Three-panel LCOS projection systems

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Abstract — Three-panel liquid-crystal–on–silicon (LCOS) projection systems are presented with an emphasis on the commercially successful shared retarder-stack-filter (RSF) polarizing-beam-splitter (PBS) architectures. The design and operation of the specific CQ90 projection core is presented in detail, and its contrast and transmission derived. alternative three-PBS/X-cube LCOS architectures are briefly introduced and their performance is compared to that of the CQ90.

Keywords — *Liquid crystal on silicon, rear-projection television, ColorQuad, ColorSelect, retarder stack polarization optical filter.*

1 Introduction

Liquid-crystal–on–silicon (LCOS) microdisplay technology offers the greatest performance/cost ratio of all display technologies by combining the high resolution and performance of silicon VLSI with controlled liquid-crystal optical modulation. To view directly in the form of a conventional TV-like display, one or more LCOS display panels need to be projected onto a viewable screen, as shown in Fig. 1.[1] LCOS projection is non-trivial since the panels are reflective. Modulated light forms a reflected beam with a spatially varying polarization state, which occupies the same region of space as the uniform input illuminating light. Physically separating these beams while maintaining good polarization integrity required for high contrast is demanding, particularly in multiple-panel systems where color separation is also necessary.

One of the first attempts at three-panel LCOS projection used a polarizing beam splitter (PBS) to separate input and output light prior to RGB color separation and recombination.[2] A Philips prism (of the type found in early three-color TV cameras) was used for the color management but proved unsuccessful due to polarization mixing at oblique "skew" incident angles.[3] A more successful attempt separates color first, such that a single primary-color beam is directed onto and away from its modulating panel before its recombination and projection. Input beams are thus separately incident upon each panel, allowing near-equivalent architectures to the established transmissive LC system[4] to be adopted. This generic approach uses dichroic plates to separate color within the illumination before utilizing PBSs to direct light onto and away from the panels. Recombination of the imaged light is carried out with an X-cube. A variation on this approach uses angular separation of the input and output beams in an off-axis configuration.[5] This last approach has, to date, suffered from low contrast and difficulties with the registration of the individual panel images, making it less mainstream and will not be discussed further here. Of the generic 3xPBS/X-cube on-axis architectures, there are three distinct types differing in the type of PBS used. Conventional systems use MacNeille-type PBS cubes, whereas more recent systems use either wire-grid PBS plates[6] or embedded reflective polarizing films.[7] The former modified PBS system is often termed Ultrex after developments by ADO,[6] whereas the latter is known as Vikuiti™ after its development by 3M.

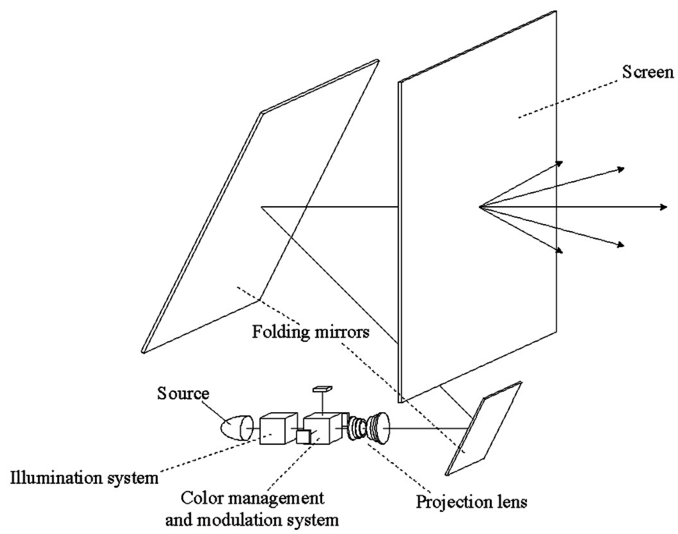

FIGURE 1 — Rear-projection TV (RPTV) system schematic.

A more-radical approach to LCOS projection is to utilize retarder stack filters[a] (RSFs),[8] which transform polarization in a color-selective manner. These laminates of stretched durable polycarbonate polymer can controllably manipulate the polarization of one color while retaining that of another. Such precise control of polarization and color allow a single PBS to be used to form input/output separation and recombination with discrete color channels between two reflective panels. All four ports of cube are therefore utilized for cost and space savings. To date, this approach forms the basis of the only commercially successful LCOS TV architecture.[9] Historically, the ColorQuad®.[10] was the first architecture of this genre to be demonstrated and commercially implemented.[11] More recently, improvements in PBS coating performance have enabled a higher-

[a]Commercially available under the trade name ColorSelect®.

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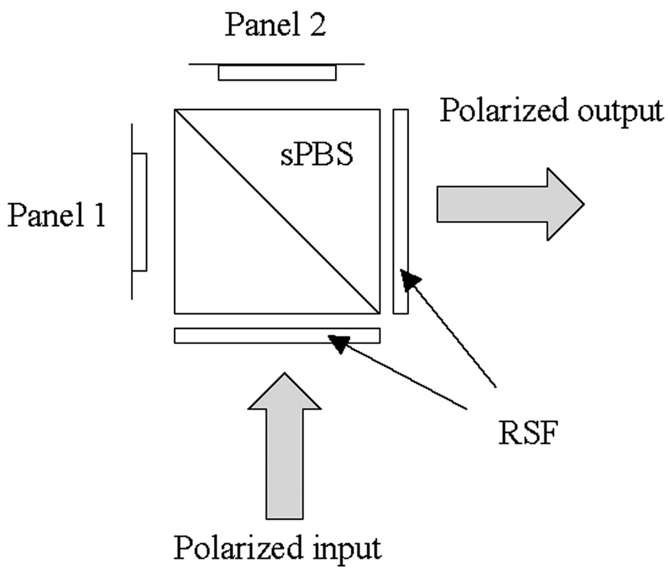

FIGURE 2 — Key two-panel shared PBS RSF splitting/combining unit.

transmitting, higher-contrast architecture with more chromatically neutral performance.[12]

This paper will describe in detail the RSF approach using the CQ90 architecture as an example. Its design, operation, and performance will be discussed; the latter being compared to the alternative on-axis architectures.

2 Design and operation of a shared PBS RSF architecture

The key architectural building block of RSF-based three-panel LCOS panel systems is a single shared PBS (sPBS) used to split and then combine light from two separate panels (see Fig. 2). Here, polarized light is input into one of the ports of the sPBS through an RSF. The sPBS then splits the light according to color-coded polarization and illuminates panels situated at the second and third PBS ports. The reflected light, altered in polarization by the panels' LC, then recombines and exits the fourth port. To avoid **p**-polarized crosstalk between channels, another RSF is placed at the output

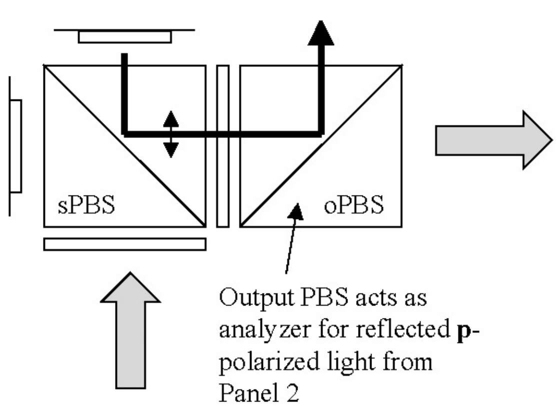

FIGURE 3 — Output PBS used as analyzer for channel 2.

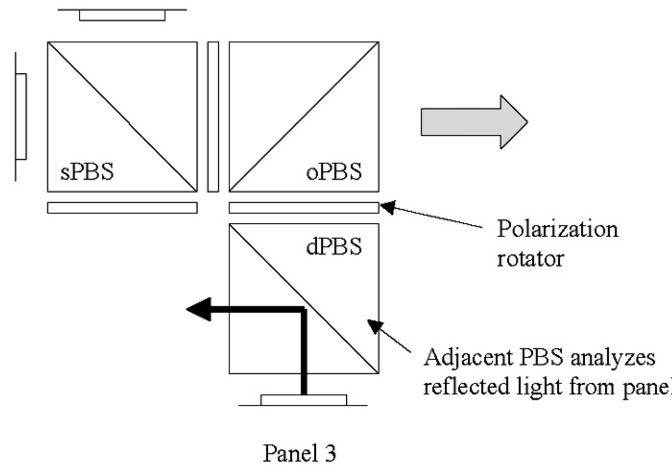

FIGURE 4 — Third channel requires PBS to analyze reflection.

to allow clean up of this unwanted polarized component by a neutral analyzer.

Expanding this approach into a three-panel system requires an output combiner, which superimposes the output light with that of a third primary. Using an output PBS (oPBS) as the combiner allows the two-panel subsystem to be analyzed in transmission, and thus ensures high contrast (see Fig. 3).

The third primary color is modulated by its own LCOS panel, requiring a dedicated PBS (dPBS) to separate input and output beams. Since the third primary-color beam reflects off the oPBS, light from the third panel must be analyzed by its dPBS. This requires a polarization rotator [RSF or 45° oriented half-wave plate (HWP)] between the dPSB and oPBS, as the polarization of the light exiting the dPBS is orthogonal to that required to reflect off the oPBS. This forces the configuration shown in Fig. 4.

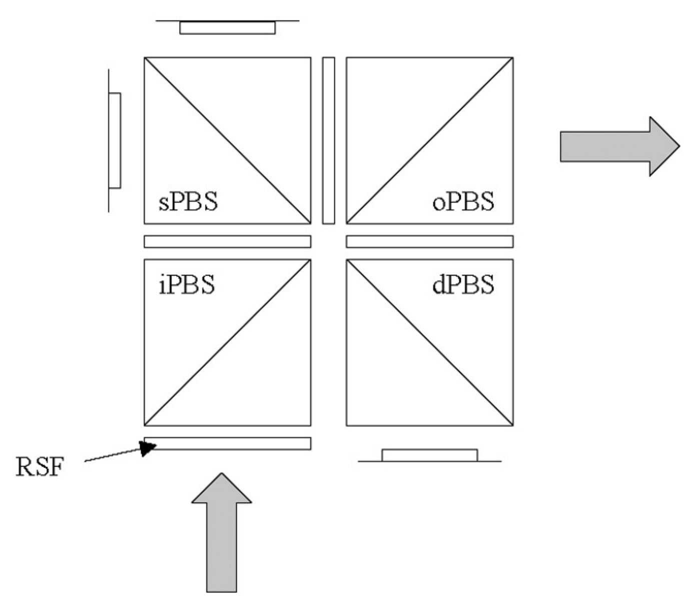

FIGURE 5 — Input PBS used with RSF to split illumination paths.

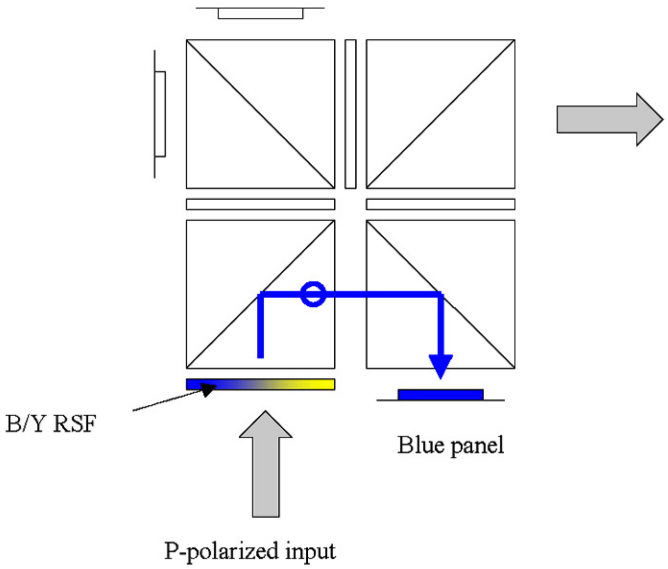

FIGURE 6 — Blue channel chosen as the biased isolated channel.

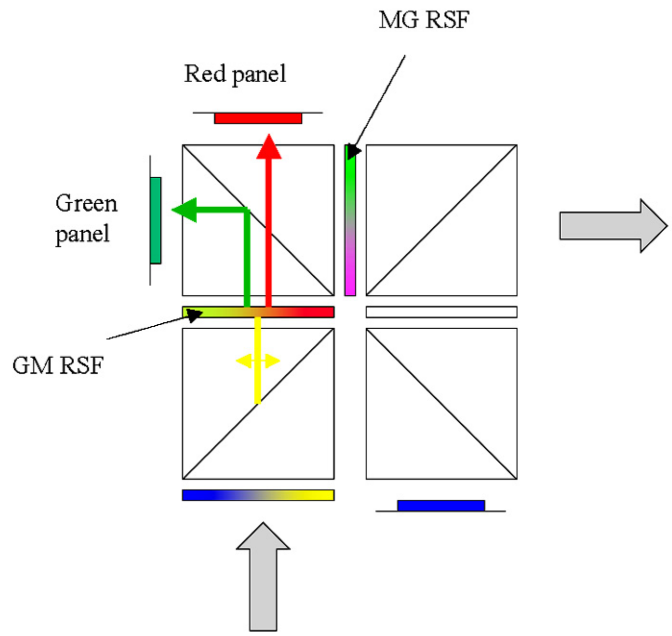

FIGURE 7 — Green panel placed opposite output to benefit phase flatness and contrast.

A fourth input PBS (iPBS) can be used to input light from a single beam into the sPBS and the dPBS (see Fig. 5). A PBS is a good choice because when used with an RSF it can ensure steep spectral transitions between color bands when high angle illumination is used. The input light can enter through one of the two free iPBS ports. For reasons of final engine physical compactness and biasing one port toward higher contrast and transmission, the port orthogonal to the output is chosen as shown in Fig. 5. Another advantage of this approach is the ability to use polarized input light-enabling standard polarization conversion techniques to be used upstream in the illumination.

There is a throughput bias since light associated with the isolated third channel transmits through only one PBS. Because reflection from PBSs are close to lossless compared with the ~5% typical transmission hit, this results in an effective 10% increase in the transmission of this channel relative to those surrounding the sPBS. For any three-color projection system, the corrected white throughput is limited by the transmission of a single, weakest color, which is typically blue for rear-projection televisions (RPTVs). Also, blue contrast is the most difficult to control with regard to contrast, which is also favored by isolation. For these reasons, blue is chosen for this third channel (see Fig. 6).

By assigning blue to this third channel, a blue/yellow (BY) RSF is the best choice for the input filter, *i.e.* one that alters the polarization state of blue while retaining that of yellow. This is from the standpoint of the largest base retarder film value that can manipulate a primary color while leaving the others alone.

Green is best placed in the port opposite the output for two reasons. First, by avoiding a reflection off the sPBS in the projection of green light, phase flatness is better and the final focused image on the screen will be likewise improved since green dominates visual brightness. Second, the contrast of the green channel is affected by the performance of the filter between the iPBS and sPBS. Because it is in the illumination path, it is possible to separate this filter from the PBSs without reducing ANSI contrast through increased back reflection. Free-standing filters have significantly reduced thermally induced stress birefringence.

By placing the green panel opposite the output, the red panel must then occupy the remaining panel port (Fig. 7). The RSFs at the input and output to this shared PBS cube are then green/red (GR) and red/green (RG), respectively. In practice, it is advantageous to make the filters green/magenta (GM) and magenta/green (MG) to minimize the number of birefringent films for a given spectral transition steepness.

As a general rule, to avoid leakage of **p**-polarized 500–700-nm yellow in the dark state from the blue channel, a blue-transmitting dichroic mirror is necessary between the blue and input PBS cubes. Also, the GM and the MG filters must not overlap more than 10% in their spectra, with the yellow transition of the GM filter being at a longer wavelength than the MG filter, to avoid unwanted 570-nm yellow light leakage from the G and R panels. As a consequence, ~570-nm light is also not present in the projected spectrum, and so saturated green and red colors are achieved without further filtering.

More specifically, for an RPTV application:

i. The yellow cut-off of the GM determines the red-color saturation and as such should be ~595 nm if an industry-standard UHP lamp is used.
ii. The yellow cut-off of the MG filter determines the longest green wavelengths and, as such, should be close to 570 nm.
iii. As explained above, the slope of these yellow transitions must ensure <10% overlap, so 10–90% slopes must be <25 nm.

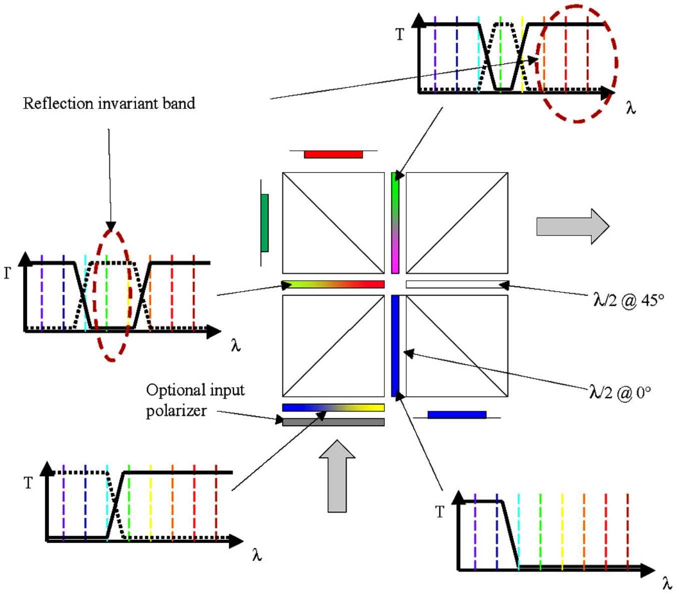

FIGURE 8 — CQ90 architecture showing filter spectral designs and skew-ray correction.

iv. The transition of the blue dichroic mirror should determine the spectrum of the blue channel. In the case of the UHP this can be anywhere between 480 and 520 nm, affecting only subtly system colorimetry and brightness. In practice, it has to be short such that the longer BY transition can ensure that the negligible **p**-polarized cyan light is incident on the blue panel (the reason for the dichroic in the first place!) and the BY transition cannot be too long to avoid making the green color too yellow. A good compromise is to have the dichroic cut-off at 495 nm and the BY to have a 510 nm cut-off.

v. The cyan cut-off of the GM and the MG filters (if shorter than that of the BY) can be ignored.

Finally, the architecture should be robust to skew-ray polarization mixing effects. Contrast is of higher priority than throughput, *i.e.* 1% less throughput is acceptable, whereas 100:1 contrast form 1% leakage is totally unacceptable. For this reason, the filters affect on contrast must be corrected. In the case of the GM filter sandwiched between PBSs, a rotationally invariant design with a HWP at 0° optimized for 550 nm is used. For the MG filter, a rotationally invariant design and half-wave designed to operate in the red is desired. For the blue channel, the output polarization rotator should have the reflection symmetry of a retarder making a single half-wave plate at 45° a suitable choice. For the input side, a half-wave at 0° between the input and blue PBS would negate adverse polarization mixing effects between these elements and hence increase blue contrast.

The final CQ90 architecture is shown in Fig. 8, where an input clean-up polarizer is included as part of the core to ensure good input polarization. Removing this polarizer is an option in systems where the input light is efficiently converted to a single polarization. The effect of removing this polarizer is to reduce blue contrast.

3 Performance

The key performance metrics of any LCOS video projection architecture is its brightness and contrast. To estimate the performance of the CQ90, and other alternative architectures, it is necessary to carefully define what is meant by brightness and contrast and how they can be related to individual component performance.

3.1 Brightness

The brightness of a projection display is its photopically weighted, spectrally corrected white output. Strictly, it is related to the radiance from the screen that is captured by the eye. Fixing screen gain and size makes the brightness directly proportional to the total output of the projection engine measured in lumens. To obtain the lumen output of a projection engine, the corrected white spectral output per unit wavelength, $W_c(\lambda)$, is measured and transformed into lumens by the following formula:

$$L = 683\int W_c(\lambda)\overline{y}(\lambda)\,d\lambda, \tag{1}$$

where $\overline{y}(\lambda)$ is the CIE color-matching function.[13]

Corrected white corresponds to a neural hue consistent with a black body radiating at a given temperature. For video projection systems, this temperature can be between 6500 and 10,000K, corresponding to the limiting (x,y) color coordinates (0.31, 0.32) and (0.28, 0.29), respectively. Common white-light sources used for projection do not in general produce a suitable white output due to their innate emission spectra and chromatic attenuation within the engine. The industry-standard ultra-high-pressure (UHP) mercury source is typically weak in red emission, whereas less common xenon lamps are deficient in blue. To correct white, those colors that are in excess have to be attenuated either passively or actively at the modulating panel. The transmission of the system is then determined by the weakest or limiting color. Comparing brightness between systems is a matter of determining their relative transmission of their weakest color. For most commercial RPTV systems, this is blue. This is somewhat surprising as there is a surplus of blue from the industry-standard UHP source. It is a result of increased blue attenuation in almost all components, including those external to the engine such as the cabinet fold mirrors and screen, which is further exacerbated by the hot, blue rich white requirements of current display systems.

The absolute brightness of the system shown in Fig. 8 is dependent on many system-dependent parameters, not least being the power of the source. For the purpose of comparison, the transmission of the weakest color blue though the core can be estimated, where the core is defined as the color-management and modulating systems and excludes the polarization conversion, homogenizer, relay, and imag-

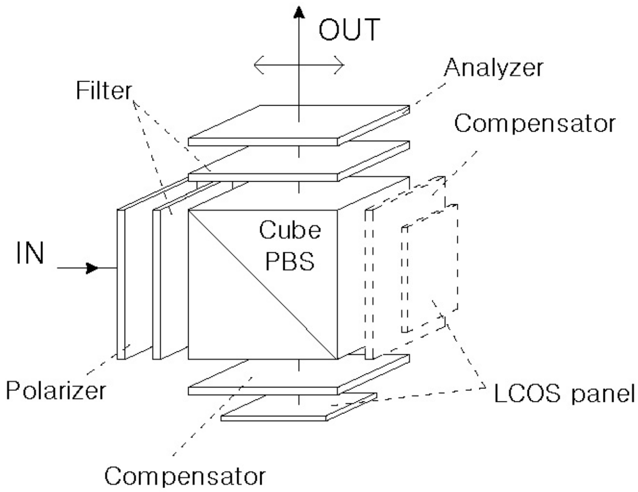

FIGURE 9 — Generic modulation system schematic.

ing systems typical of all projectors. It is also assumed for the sake of comparison all systems considered project the same white and primary RGB colors with similar UHP lamps at the typical 2.8 illumination $f_{/\#}$.

The blue transmission of the CQ90 core can only be described in Eq. (2) by the product of the transmission of the components in the blue path.

$$T_{CQ90} \sim T_{pol} \cdot T_{BY} \cdot \overline{R}_s \cdot \overline{T}_{DM} \cdot T_{\lambda/2} \cdot \overline{R}_s \cdot \eta_p \cdot \overline{T}_p \cdot T_{\lambda/2} \cdot \overline{R}_s. \quad (2)$$

The description and typical angle averaged values of individual product terms in Eq. (2) is given in Table 1 together with those relating to alternate systems. Angle averaging, denoted by a bar, is only applicable to components with significant angular-dependent performance.

Inserting the values of Table 1 into Eq. (2) yields a relative CQ90 core transmission of ~54%. Removing the input polarizer increases its transmission by ~10–60%.

3.2 Contrast

Contrast is the photopic ratio of full white to full black output. In general, it is dominated by leakage in the dark or black state, which results from unwanted polarization mixing between polarizer and analyzer as is the case for all LCD display systems. In LCOS systems, the polarizer and analyzer are combinations of pre- and post-polarizing components flanking a PBS, and the entire subsystem is called the modulation system. The generic modulating system is shown in Fig. 9.

Current systems demand high contrast (>1000:1) and corresponding low leakage, allowing the separate contributions to be considered independent. Each term represents leakage due to one aspect assuming the remainder of the system is ideal and leak free. In this way we can express the contrast of the system as the following sum since normalized leakage is the reciprocal of the associated contrast.

TABLE 1 — Typical angled averaged component transmissions.

Symbol	Component throughput	Value (%)
R_m	Fold mirror (in reflection)	97
T_{pol}	Clean-up polarizer	90
$T_{BY}, T_{MG}, T_{\lambda/2}\ldots$	RSF	98
$\overline{R_s}$	MacNeille PBS in reflection	99
$\overline{R_{BL\_s}}$	Birefringent-layer PBS in reflection	99
$\overline{R_{WG\_s}}$	Wire grid PBS in reflection	90
$\overline{T_{DM}}$	Dichroic mirror	98
η_p	Panel	70
$\overline{T_p}$	MacNeille PBS	95
$\overline{T_{BL\_p}}$	Birefringent-layer PBS	99
$\overline{T_{WG\_p}}$	Wire grid PBS	90
$\overline{R_{X-cube}}$	X-cube reflection	94

$$\frac{1}{C_{sys}} \approx \frac{1}{C_{ideal\_panel}} + \frac{1}{C_{ideal\_PBS}} + \frac{1}{C_s}. \quad (3)$$

I. The first term of this expression can then be further split into two independent terms:

$$\frac{1}{C_{ideal\_panel}} = \frac{1}{C_{coating-only}} + \frac{1}{C_{pre-cond}}, \quad (4)$$

where $C_{coating\_only}$ quantifies the leakage from non-ideal PBS coatings. That is the extent to which the PBS reflects one polarization and transmits its orthogonal counterpart. This term also incorporates the performance of any pre- and post-clean-up polarizers and any non-ideal polarization filter performance in systems sharing a single PBS. C_{pre_cond} is an additional term necessary when there is a geometrical rotation between the polarization axes of any clean-up polarizers and the PBS. This is seen when a sheet polarizer is used in conjunction with MacNeille-type PBS.

II. The second term of Eq. (1) can be split into two dependent terms:

$$\frac{1}{C_{ideal\_PBS}} = \frac{1}{C_{compensation}} + \frac{1}{C_{AR}}, \quad (5)$$

TABLE 2 — Contrast terms for the CQ90 and various 3xPBS/X-cube architectures. Here, ∞ implies negligible leakage.

Contrast factor	Determined by:	Three-panel architecture			
		CQ90	3xPBS/X-cube		
			MacNeille	MB	WG
$C_{coating\_only}$	PBS $\overline{T}_s$, $\overline{R}_p$ and RSF δ where applicable	8500	10,000	8,000	∞
$C_{pre-cond}$	Geometric mismatch between polarizing components	∞	15,000	∞	∞
$C_{compensation}$	QWP or c-/a-compensation of VA LC	9,000	9,000	∞	∞
C_{AR}	Reflection off PBS and compensator component/air interfaces	8,000	8,000	∞	∞
C_s	Scattering including depolarizing diffraction from panel	3,000	3,000	3,000	3,000

where $C_{compensation}$ is the contrast associated with non-ideal compensation of the LCOS panel. In the most general case, $C_{compensation}$ includes

1. On-axis leakage due to the incomplete compensation of any residual in-plane retardance in the LC in the panel's off-state.
2. Off-axis leakage due to the uncompensated LC birefringence seen by off-axis rays.
3. Off-axis leakage due to uncorrected non-orthogonal polarizer and analyzer optic axes.

For the majority of three-panel systems a vertically aligned (VA) LC mode is used because this yields the best contrast and most-effective compensation.

C_{AR} is the contrast due to non-ideal anti-reflection coatings adjacent to the compensator.

III. C_s is the contrast limit of practical systems due to scattering effects at the panel and off any other optical components making up the system.

Estimation, calculation, and measurement of each of these terms for a given system is involved and described in detail elsewhere.[14] Here, we will use the results of Ref. 14 to estimate specific system performance.

As with all shared PBS architectures where green is one of the shared color bands, the ideal panel $CQ90_{ideal\_panel}$ contrast is primarily determined by the PBS coating and filter performances as described by the expression

$$C_{coating\_only} \sim \frac{1}{2 \cdot \overline{R}_p \cdot \delta + 2 \cdot \overline{T}_s}, \tag{6}$$

where $\overline{R}_p$ is over the shared red and green color bands only and $\overline{T}_s$ is only in the yellow wavelength region separating red and green. δ is the leakage of the green/magenta (GM) RSF in the green, and also the red leakage of magenta/green (MG). In most cases, the $\overline{T}_s$ term can be neglected relative to the larger first term. Taking a value for $\overline{R}_p$ of 0.02 and δ of 0.003 yields a contrast $C_{coating\_only}$ ~ 8500.

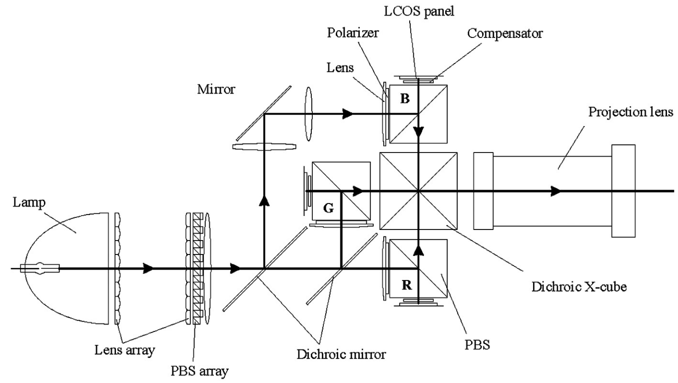

FIGURE 10 — MacNeille-based 3xPBS/X-cube three-panel LCOS projection system.

The remaining terms are derived by complex system modeling.[14] The complete set of terms relating to all the other contrast terms [Eqs. (3)–(5)] are then generic to many other systems and are quantified in Table 2.

Since the GM and MG filters are compensated for off-axis polarization effects between successive PBSs, the pre-conditioning leakage term is negligible. The overall system contrast is then 1500.

4 Alternative three-panel LCOS projection systems

Alternative on-axis architectures employ three PBSs for each of the primaries incorporating dichroic-coated MacNeille (MN), multi-layer birefringent (MB), or wire-grid (WG) PBSs.

4.1 MacNeille-based 3xPBS/X-cube system

First commercialized in 1998 by JVC in the G1000 projector, this system offers good performance as exemplified by the recent Nikon architecture incorporated into the Sony Qualia projector.[15] Its generic structure is shown in Fig. 10, which includes the standard polarization converted illumination system common to most commercial LCOS systems including the CQ90.

Light is collimated from a UHP arc lamp using a reflective parabolic mirror before encountering paired fly's-eye lens arrays. Each rectangularly shaped lens pair acts to sample the incoming beam and form superimposed images in the plane of the panel. The irregular intensity profiles of each sample are then averaged to form a uniform illumination patch. At the exit of the second lens array is typically a linear array of PBSs with alternate 45° oriented half-wave strips that act to transform the non-polarized input light into a uniformly polarized beam. A series of dichroic plates then separate the red, green, and blue components of the illumination, which reflect off cube MacNeille PBSs onto the modulating LCOS panels. The reflected beam is analyzed in transmission by the same PBSs before being combined pro-

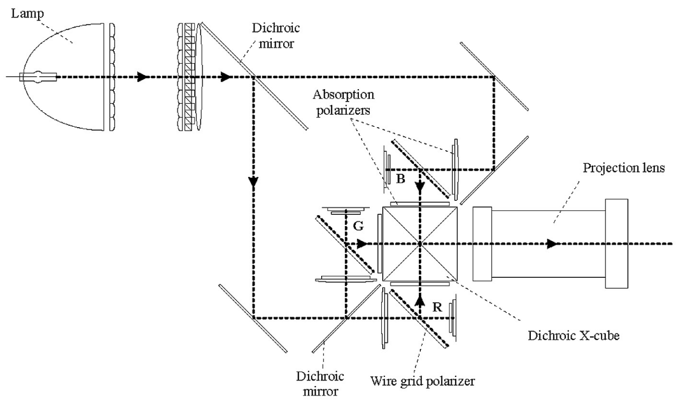

FIGURE 11 — Wire-grid 3xPBS/X-cube LCOS projection architecture.

jected light from the two other channels by an embedded dichroic-coated X-cube. The emerging light is then imaged with projection optics onto a screen.

To achieve the desired contrast level, clean-up polarizers are required at the input of the PBSs, which improves contrast at the expense of throughput and brightness. Also present are 45°-oriented half-wave plates between the red and blue PBSs and the X-cube, preconditioning the polarization for maximum X-cube efficiency.

In the MacNeille system of Fig. 10, the blue transmission of the core is closely approximated by the product of the individual component angle averaged transmissions and expressed as

$$T_R \sim \overline{T}_{DM} \cdot R_m \cdot T_{pol} \cdot \overline{R}_s \cdot \eta_p \cdot \overline{T}_p \cdot T_{\lambda/2} \cdot \overline{R}_{X-cube}. \quad (7)$$

By using the typical component values of Table 1, a relative core transmission of ~52% is obtained.

Regarding contrast, the separate terms of Eqs. (1)–(3) are summarized in Table 2 for the MacNeille 3xPBS/X-cube system where zero-order uniaxial quarter-wave plates (QWPs) are used to compensate both panels and off-axis geometric effects caused by the 45°-oriented PBS coating. Substituting these values into the Eq. (1) yields an overall system contrast of ~1400.

4.2 Multi-layer birefringent 3xPBS/X-cube architecture

This approach uses film derived from the 3M material DBEF,[16] and the assembled core is marketed with the Vikuti™ trade name. The architecture is essentially that of Fig. 10 in its physical make-up. The main advantage of this PBS is its higher transmission and contrast over the more-conventional MacNeille counterparts. High transmission is achieved by avoiding in most cases an input clean-up polarizer. With suitable optimized material, $\overline{T}_p$ can be >99%, which with efficient polarization conversion can yield sufficient system contrast. It remains to be seen whether part-to-part variation forces a clean-up stage to avoid system variation. The contrast is high since the optic axes of the uniaxial material within the film determine the Eigen polarization states. The ray-independent polarization axes show none of the geometric rotations characteristic of the MacNeille cubes and avoids having to use QWPs as compensators. This simplification yields higher intrinsic contrast. Even when QWPs are used as panel generic panel compensators, the lack of geometric rotation increases net compensation loss. Pre-conditioning of the polarization by any clean-up polarizers is also compatible with the polarization axes of the cube for all rays negating any corresponding leakage.

Its core transmission is given by

$$T_{MB} \sim \overline{T}_{DM} \cdot R_m \cdot \overline{R}_s \cdot \eta_p \cdot \overline{T}_p \cdot T_{\lambda/2} \cdot \overline{R}_{X-cube}. \quad (8)$$

since it is possible to avoid using the input clean-up polarizer. Evaluating this for the higher transmitting $\overline{T}_p$ value yields a relative transmission value of 60%. Introducing a clean-up polarizer would reduce this to ~54%.

Without a clean-up pre-polarizer, the contrast of the system is heavily dependent on the film properties. Actual measurement of selected cores delivered a contrast of ~8000 using mirrors and QWPs,[14] which when combined with the expected 3000 contrast limits of the panel due to scattering and diffraction effects, yields an overall contrast C_{sys} of ~2200.

4.3 Wire-grid-based 3xPBS/X-cube system

Wire-grid PBSs also avoid geometric polarization rotations and allow higher contrast that the MacNeille equivalent. They are, however, plate beam splitters that at present cannot be embedded in glass. For this reason, they are used in a reflection-imaging configuration with the metal grid facing the modulating panel. The resulting architecture is therefore more complex physically as shown in Fig. 11.

By using post clean-up polarizers, high contrast can be achieved up to the 3000:1 limit imposed by panel scattering. Although able to achieve very high contrast, the absorption of light by the metal layer can, however, lead to reduced throughput and system brightness. The core transmission is effectively that of the MacNeille architecture attenuated by the lower transmission and reflection properties of the metal coating. Good estimates make both $\overline{T}_p$ and $\overline{R}_s$ close to

TABLE 3 — Brightness and contrast of three-panel LCOS architectures. Transmissions all assume a single clean-up polarizer.

Contrast factor	Three-panel architecture			
	CQ90	3xPBS/X-cube		
		MacNeille	MB	WG
Brightness (%)	54	52	54	45
Contrast	1500	1400	2200	3000

90%, yielding a core transmission given by Eq. (9) of ~40% (see Table 1):

$$T_{WG} \sim \overline{T}_{DM} \cdot R_m \cdot T_{\lambda/2} \cdot T_{pol} \cdot \overline{R}_s \cdot \eta_p \cdot \overline{T}_p \cdot T_{pol} \cdot R_{X-cube}. \quad (9)$$

With a slight reduction in the contrast performance the input clean-up polarizer can be removed, improving the transmission to ~45%.

5 Summary, conclusions, and discussion

The design and operation of the shared PBS CQ90 architecture is described and compared in performance to alternative on-axis three-panel LCOS projection engines. Brightness and contrast is defined and estimated for all systems using a generic approach. The estimated relative performance is given in Table 3. From the table, the multi-layered PBS approach appears to yield the best compromise between transmission and contrast; however, the high transmission, compact nature, and low cost of established shared PBS architectures make it attractive, especially as future auto-iris implementations relax system contrast levels and favor higher transmission. Auto-irises attenuate the source for dark imagery, including the off-state. A further advantage of the CQ90 architecture is the short back focal length comprising two high-index cubes which allow cost-effective off-axis lens designs[17] used in thin cabinet RPTV implementations. It remains to be seen, however, which architecture will become the future industry standard.

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