

## 39.2: Polarization Conversion System Using a Polymer Polarization Grating

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### Abstract

We describe a new Polarization Conversion System (PCS) concept, particularly well suited for pico-projectors, employing a polymer polarization grating thin-film, fly-eye lens, and lowered halfwave plate. We demonstrate improved polarization-conversion in the PG-based PCS, leading to enhanced brightness (12%) and color-uniformity (20%) as compared to a conventional PBS-based PCS.

### 1. Introduction

Projection display systems can be largely divided into illumination and projection subsections. Illumination optics transfer light from the source onto the light modulator (ie, microdisplay), whereas projection optics project the modulator's image onto a screen. Illumination optics can usually be decomposed into three parts: collimation lens, integrator, and relay lens. The light source normally emits light into all directions (ie, the entire hemisphere) from a small area, and for this discussion is assumed to be unpolarized (ie, a lamp or light-emitting-diode (LED)). The role of collimation lens, therefore, is to collimate and direct the spreading light onto the integrator.

The integrator typically accomplishes two jobs crucial to achieving good image quality and projector efficiency: it transforms the cross-sectional area of the beam from circular to rectangular, and it simultaneously homogenizes the spatial intensity profile. Two kinds of integrators are generally available for projectors: one employs a long light-guide that functions via total-internal-reflection, and the other is much more compact and employs a Fly-Eye Lens (FEL) that functions via refraction. The final part of the illumination system is usually the relay lens, which focuses the reshaped beam onto the light modulator.

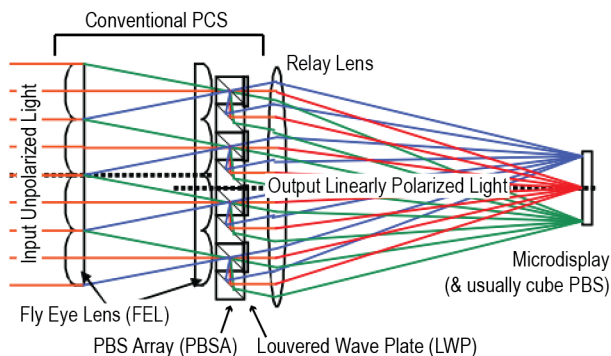


Figure 1 – Optical layout with conventional PCS.

Three kinds of light modulators are most commercially significant: Digital-Light-Processor (DLP), Liquid Crystal on Silicon (LCoS), and High Temperature Poly-Silicon (HTPS). Both HTPS and LCoS panels utilize liquid crystal (LC) technology, and therefore require polarized light. In HTPS systems, a polarizer is arranged to polarize the light incident on the panel, with an additional polarizer to analyze the outgoing light. LCoS systems usually use a Polarizing Beam Splitter (PBS) to simultaneously polarize and analyze the light into and out of the modulator, because the display is reflective. Since DLP panels employ micro-mirrors to modulate light, they most commonly use unpolarized light directly. Nevertheless, note that the majority of 3D projection systems must use polarized light even when they use DLP panels.

### 2. Background

LCoS, HTPS, and 3D projector systems require polarized light. However, the vast majority of viable light sources emit unpolarized light, which requires some sort of conversion to polarized light. The simplest way uses a polarizer, which transmits the desired polarization but either absorbs or reflects the unwanted polarization. In order to overcome this > 50% loss of power, a subassembly called the Polarization Conversion System (PCS) has been developed to use convert and then transmit the unwanted polarization [1-2]. The most popular use a FEL, a PBS-Array (PBSA), and a halfwave plate, as illustrated in Figure 1. This operates by focusing input light onto a PBSA, which transmits P linear polarization and reflects S polarization onto a reflector that redirects it forward. A broadband Louvered (half)Wave Plate (LWP) converts the P polarization to S, so that the output is in principle all S polarization. Note that while this PCS approach roughly maintains the beam area, the output has double the divergence angle in one dimension.

The transmittance of the PBS (both in the PBSA and the polarizer/analyzer cube) is highly sensitive to the incidence angle (Figure 2). At 45° incidence angle to the beam splitting surface, the PBS operates well, but noticeable degradation begins even at ±5° deviation from this. Furthermore the effect does not have symmetry; compare the 35° incidence angle (with 80-85% output) with the 55° incidence (with 60-70% output). When a 3-color LED (RGB) light source is used, as is very common, a dichroic mirror is also employed (not shown in Figure 1, but understood to precede it). The performance of this dichroic mirror is also moderately sensitive to incidence angle (Figure 3).

The FEL and relay lens combination causes off-axis light in the horizontal plane to spatially spread across the light modulator in the horizontal dimension, causing unwanted brightness- and color-variation. Furthermore, the thickness of the PBS array

makes these worse. The light passing through the FEL in the vertical plane is focused to the center of the light modulator (Figure 3). This light passes the PBS surface at 45° and performs very well. Nevertheless, this PCS has three problems: non-ideal throughput, brightness uniformity, and color uniformity.

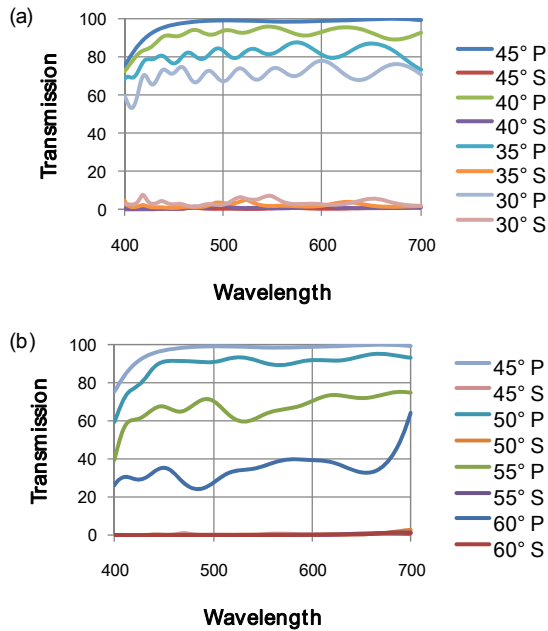


Figure 2 – PBS transmittance sensitivity to incident angle and polarization: (a) angles ≤ 45°. (b) angles ≥ 45°.

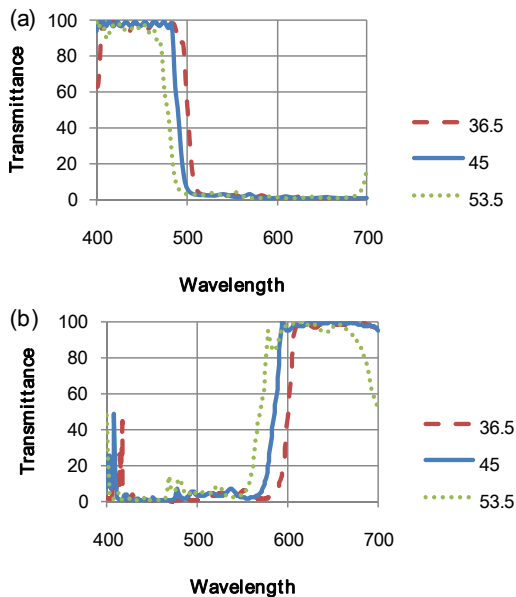


Figure 3 – Dichroic mirror transmittance sensitivity to incident angle: (a) Blue-reflect-yellow. (b) Cyan-reflect-red.

### 3. Polarization Gratings (PG)

Here we describe how to advance beyond these limitations with a novel, diffractive, thin-film, polarizing beam splitter, used to

accomplish polarization conversion with improved throughput, and brightness- and color-uniformity.

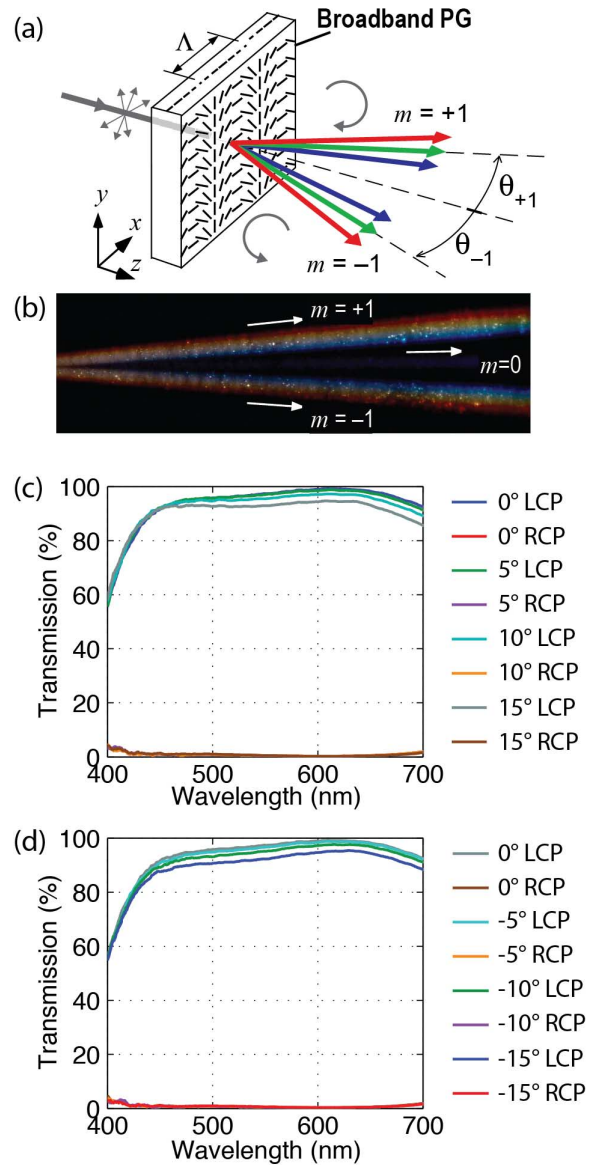
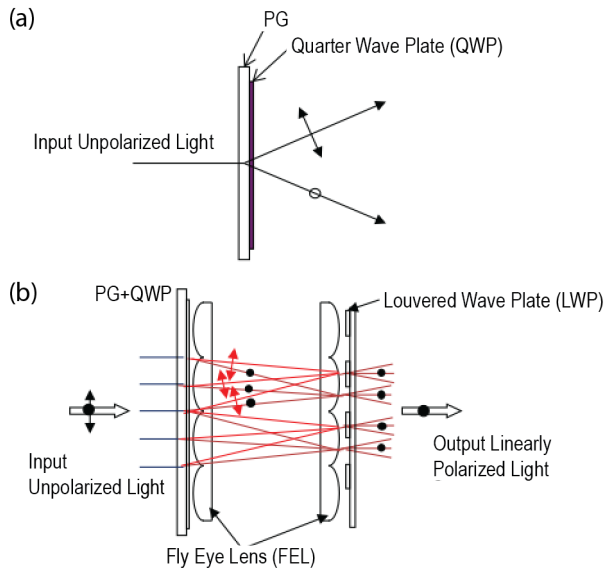


Figure 4 – Broadband polarization gratings (PG) functionality: (a) Diffraction behavior and geometry. (b) Photograph of unpolarized, white LED light diffracted by a PG. Measured PG transmittance sensitivity to incident angle and polarization for (c) + angles and (d) - angles.

The PG employed here is a member of the class of birefringent diffractive optical elements [3-4] comprised of a spatially periodic birefringence – in this case formed with an LC polymer material [5-7]. It functions as a thin-film beamsplitter, where incident light is angularly separated into two, forward-propagating, orthogonal, circular polarizations. As illustrated in Figure 4(a) and photographed in Figure 4(b), its output is governed by the classic grating equation ( $\sin\theta_m = m\lambda/\Lambda + \sin\theta_{in}$ , where  $\Lambda$  is the grating period,  $m$  is the grating order, and  $\theta_m$  and  $\theta_{in}$  are the diffracted and incidence angles). Details of the LC microstructure and holographic fabrication can be found elsewhere [7].



**Figure 5 – New PG-based PCS concept: (a) Diffraction behavior and geometry of PG+QWP. (b) Overall polarization conversion behavior, PG+QWP+FEL+LWP.**

The diffraction efficiency spectra, polarization behavior, and angular sensitivity of this PG [4-5] are notably different than conventional phase or amplitude gratings. Light diffracted from broadband PGs [7] is directed almost entirely into their first ( $m=\pm 1$ ) diffraction orders for most of the visible wavelength range. These first-orders naturally have orthogonal circular polarizations, but a quarterwave can be added to convert them to horizontal and vertical polarization.

Most notably for this discussion, this broadband PG has low angle dependence. We measured the polarized transmittance of a PG (4.17  $\mu\text{m}$  period) with  $\pm 2^\circ$  divergence input light for a range of incidence angles, shown in Figure 4(c) and 4(d). As compared to the PBS sensitivity in Figure 2, the PG is substantially improved in its throughput and polarization contrast over a much larger angle range. The diffraction transmittance remains high (> 90%) within modestly oblique angles of incidence ( $\sim \pm 20^\circ$  [4]).

Note that an entirely different use of polymer PGs in projectors is also being studied [6], that essentially replaces all polarizing

elements with PGs and directs both polarizations into the LC microdisplay simultaneously. While this prior approach presents several advantages, it requires significant re-design of the optical light engine. It should be clear that the new PCS described here is broadly applicable to practically any HTPS or LCoS projector with little modification.

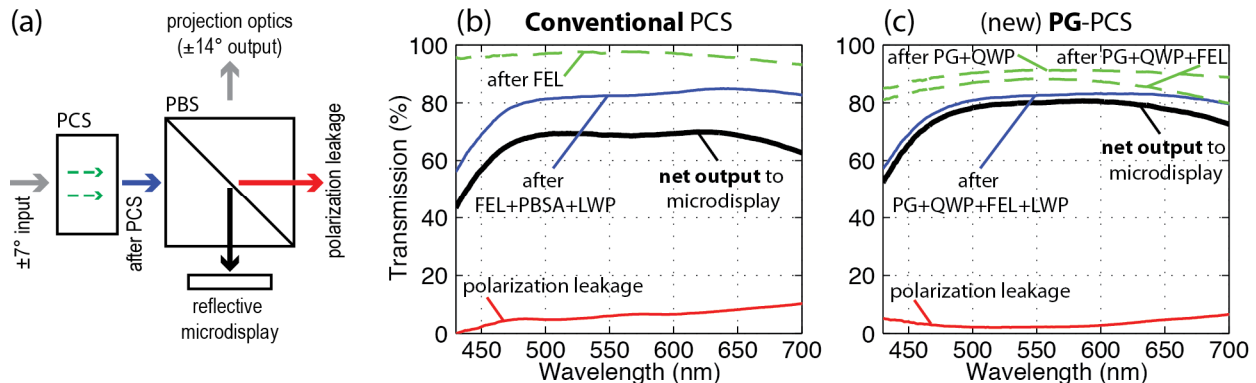
#### 4. Concept and Results of PG-based PCS

We note that the superior angle insensitivity of PGs enables an improved PCS design. By combining a broadband PG with a broadband Quarter Wave Plate (QWP), the two transmitted diffraction orders become linearly polarized (P and S), as illustrated in Figure 5(a). When nominally collimated, unpolarized light is diffracted by the broadband PG+QWP, it is focused by the FEL onto the LWP. Note that because the two orthogonally polarized beams from the PG have different propagation angles, they become spatially separated after the FEL. The LWP is therefore arranged to convert one of these beams to the opposite polarization, resulting in a nominally uniform linear polarization.

We assembled this PG-based PCS, and measured its performance as compared to the conventional PCS. In both, we used a FEL with 7x12 array, 1x0.58 mm<sup>2</sup> pitch, and  $f/\# \sim 2$ . In the conventional PCS, the PBSA had 17 layers and 1 mm pitch, and where the LWP strips (0.5 mm width) were laminated directly on the PBSA prims. The new PG PCS employed a broadband PG [7] with 4.17  $\mu\text{m}$  period ( $\pm 7.3^\circ$  diffraction angle at 530 nm) formed with LC polymer RMS03-001C from Merck Chemicals Ltd, a broadband QWP from ColorLink Japan Ltd, and a LWP laminated on its own substrate. BBAR anti-reflection coatings were used.

The measurement setup is illustrated in Figure 6(a): unpolarized white light with  $\pm 7^\circ$  symmetric divergence angle was directed through the PCS and then directed into the PBS polarizer/analyzer. The transmittance was measured before and after the PCS (and its sub-elements) using an integrating sphere capturing the whole output beam (within  $\pm 14^\circ$  and  $\pm 7^\circ$  divergence angle). Results are graphed in Figure 6(b) and 6(c).

The most important result (black curve) is that while the conventional PCS has a peak net output of  $\sim 70\%$  sent toward the microdisplay, the new PG-PCS manifests  $\sim 80\%$  transmittance. This may best be understood as a consequence of the more uniform angular sensitivity of the PG itself, as compared to the PBSA. It is interesting to note that the blue curves, which are



**Figure 6 – Measured PCS throughput performance: (a) Layout of PCS and PBS, indicating measurements. (b) Conventional PCS, with peak at  $\sim 70\%$  useable transmittance. (c) PG-PCS, with peak useable transmittance improved to  $\sim 80\%$ .**

measured immediately after each PCS, are similar in both cases, while the black curves (total useful transmittance) are not. We observe that this is due to the larger “sidelobes” from the PBSA, where light is scattered into larger angles that are not incident onto the microdisplay.

To evaluate the performance of this PG-based PCS concept as compared to the conventional PCS, we made a small projector with a 0.29” LCoS panel, which could accept either one. Shown in Figure 7(a) with the PG-PCS, the volume of optic engine is 10 cc in both cases. The projection lens has 75% brightness uniformity at 0.7 field (Figure 7(b)).

We found that the low angle dependence of the broadband PG improves brightness uniformity. This is furthermore promoted in the new PCS because the LWP is positioned immediately after the FEL, without the thickness of the PBSA. With the conventional PCS, our projector set has 60% brightness uniformity (9 points) with standard deviation 0.03. When we install the new PG-PCS, brightness uniformity reaches 70% with standard deviation 0.04. This is almost the limitation of brightness uniformity.

As expected, the PG-PCS manifests higher projector brightness (9.1 ansi-lumens) compared to the conventional PCS (8.1 ansi-lumens), both at 1 W of electrical power. This is a 12% improvement in brightness, graphed in Figure 7(c). Note that the contrast ratio is about 200:1 for both cases, largely independent of the PCS since the PBS acts as the polarizer and analyzer.

The symmetrical angle dependence of the broadband PG improves color uniformity by 20%. The conventional PCS projector gives high duv (0.020), but the new PG-PCS projector gives improved duv (0.015), graphed in Figure 7(d).

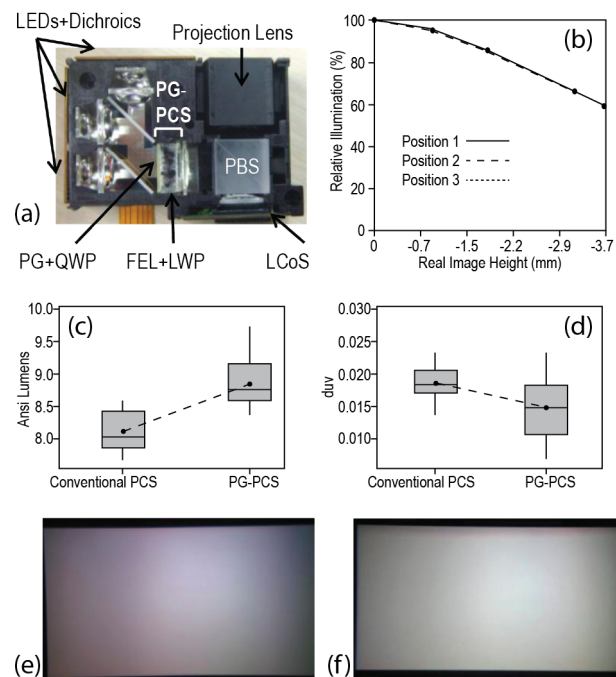
Throughout these comparison tests, the brightness at the center of the projected images in both cases was nearly identical (44 lux at 1 Watt and 30 inch screen size). The reason is related to the fact that the center of the image maps the on-axis angles that passed through the PCS – and in both cases this light is efficient. It is primarily the off-axis light that is notably improved by the PG, as discussed above, leading to a more uniform image (Figure 7(e-f)).

The new PG-PCS has an additional benefit. The conventional PCS needs at least two separate alignment steps: the FEL and PBSA must be aligned, and PBSA and LWP must be aligned. However, the new PG-PCS does not require alignment of the broadband PG to the FEL, and only needs alignment between FEL and LWP. In our tests so far, tact-time has been reduced to 35 sec from 55 sec, and the alignment defect-fraction has been reduced to about 10% from 70%.

## 5. Conclusion

The new PG-PCS is one of the best options for projectors that require polarized light, because it achieves high polarization conversion. It also manifests improved brightness (ansi-lumens) and color uniformity (duv), as compared to a PBSA-based PCS.

This concept enabled us to demonstrate a compelling and practical energy efficient portable projector.



**Figure 7 – PCS comparison in prototype LCoS pico-projector: (a) Photograph. (b) Relative illumination of projection lens. Measured (c) improved brightness and (d) decreased color difference of PG-based over conventional PCS. Comparison of projected image from projector with (e) conventional and (f) PG-PCS.**

## 6. Acknowledgements

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## 7. References

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