Progress in Microdisplay Optics

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Microdisplay optics

- LCOS LCD mode
- Projector optics - PBS, color separation filters, color recombination filters, projection lens
- Lamp - spectrum, collimation, polarization conversion, homogenizer
- Near eye optics - aspheric lens
Optical budget

- 9600 Lm is available from a 150W arc lamp
- 1200 Lm can be projected in the best DLP and transmittive LCD systems, <800 Lm for LCOS
- Why? Limited acceptance angle of the optical elements (etendue or F# matching)
- Improvement can be made from the lamp side (smaller divergence angle), and/or from the optical elements side (larger acceptance angles)
LCOS fabrication

- **Front-end for electrical functions**
  - Full integration of display drivers and DAC
  - High breakdown voltage techniques
  - Standard 0.5 μm CMOS process

- **Back-end for optical performance**
  - Surface planarization by CMP and light shield
  - High reflectivity final metal with special surface treatment
  - Pixels gap filling techniques
  - Modified 0.35 μm CMOS process

3M2P process
SEM pictures of pixels

- DVD resolution (704x576)
- 9.6 µm pixels
- 86% fill factor
- Direct view

- XGA resolution (1024x768)
- 13.8 µm pixels
- 91% fill factor
- Projection
Packaged LCOS panel
Surface reflectance

![Graph showing surface reflectance as a function of wavelength. The graph includes lines for different materials: Al metal, Al compound, oxide/nitride, and dielectric mirror. The x-axis represents wavelength (nm) ranging from 450 to 750, and the y-axis represents surface reflectance (%) ranging from 0 to 100.]
Resolvable pixels showing stability

HKUST XGA Display
1024 x 768 Resolution
13.8μm Pixels

No timing jitter - advantage of digital driving scheme
Projected image on the screen
Projected image on the screen
LCOS LCD optical modes

- Traditional LCLV - 45° hybrid field effect (HFE) mode (Hughes)
- Normally white operation - TN-ECB mode (Sonahara 1989)
- MTN (Wu 1995)
- MTB (Kwok 1997)
- Other LCD modes in use: VA, ferroelectric, PDLC, ...
Unified picture of all reflective LCD modes

Observation:
At any voltage \( T = T(\alpha, \gamma, \phi, \delta) \)
For a single polarizer reflective display \( R = R(\alpha, \phi, \delta) \)

Therefore, T or R can be plotted as a function of 2 variables by fixing the third or fourth variable - parameter space
Reflective displays

For reflective display with one polarizer

\[ R = \begin{pmatrix} \cos \alpha & \sin \alpha \end{pmatrix} \cdot R \cdot M^* \cdot R^{-1} \cdot M \cdot \begin{pmatrix} \cos \alpha \\ \sin \alpha \end{pmatrix}^2 \]
Parameter Space Diagrams for Reflective Displays

Twist angle

$d\Delta n$

$\alpha=0^\circ$

TN-ECB-1

TN-ECB-2

TN-ECB-3

HFE

RTN

RSTN
Parameter Space Diagrams for Reflective Displays - effect of change in polarizer angle
Relationship between various MTB modes
(Mixed TN-Birefringence modes)

0.9 reflectance contour for various polarizer angles

- SCTN
- MTN
- TN-ECB

Twist Angle

$\Delta n$
Both NW and NB modes are possible (//--// polarizers)

NB or NW can be reversed by changing polarizers. Better nomenclature: in-well and out-of-well modes
Electro-optic curve of in-well and out-of-well modes

//--// polarizers
# In-well and out-of-well modes

<table>
<thead>
<tr>
<th></th>
<th>Normally white (NW)</th>
<th>Normally black (NB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct view</strong></td>
<td>Out-well, dark state at intermediate voltage</td>
<td>In-well, bright state at high voltage</td>
</tr>
<tr>
<td><strong>Projection</strong></td>
<td>In-well, dark state at high voltage</td>
<td>Out-well, bright state at intermediate voltage</td>
</tr>
</tbody>
</table>

Note: No retardation film
Normally black modes with PBS (Out-of-well modes)

Dark state ($V=0$) of NB RTN modes with diff. twist angles

Bright state ($V=2V$) of NB RTN modes with diff. twist angles
Optical engine

- New PBS + new trichroic prism assembly (TPA)
New TPA reduces s-p split of dichroic coating

Angle of incidence reduced to 16°. (Traditional Philips prism has AOI of >24°)
Calculated results for $\theta = 16^\circ$ and $30^\circ$

Why is s-p split important?
Color fidelity, light efficiency
Good Color Fidelity for TPA
- Experimental Results

Negligible S-P Polarization Split
Acceptance angles of optical coatings in PBS and TPA

Acceptance angle: F/3.8 optics => ±5° in glass

PBS, dichroic filters, LCOS panels
Broadband, large acceptance angle PBS is difficult to achieve
New PBS - Li design

\[70^\circ\]
New PBS (52°)
More detailed data for 52° PBS

Coating: 25 layers
New PBS (45°)
More detailed data for 45° PBS

Transmission of P Polarized light

Coating: 19 layers

Center for Display Research
Color separation/recombination coatings

Color shift of 10nm. Loss of color fidelity and some intensities
Color saturation measurements

Green not quite green
Measured color coordinates

Includes the effects of the halogen light source and the TPA.

Cannot be improved no matter how hard we tried!
Color saturation is not quite NTSC

Reason: the UHP lamp does not have enough red color output!

*Same problem no matter which color separation/recombination scheme is used
120 W Philips UHP lamp output spectrum

Other arc lamps are no better!

Have to compromise between G and R
Color coordinates as a function of $\lambda_{\text{cutoff}}$

CIE 1931 Color Coordinates of Philips Lamp

Blue CutOff: 500nm
Red CutOff: 572-584nm

Need more red continuum emission
Acceptance angle of LCOS panels

- Not an issue with present PBS designs (10° acceptance angle)
- Strongly dependent on operating voltages and LCD modes
Viewing angle of MTB mode
- importance of operating voltage

3V
±4° for CR = 125

4V
±10° for CR = 250
Projected image on screen
Summary

- Much detailed optimization needed for LCOS projectors
- Steady progress is being made to improve the acceptance angle of all the optical elements and this has direct implication on the system brightness (optical efficiency)
- Improvement is also made from the lamp side - smaller etendue