Key design issues for autostereoscopic 2D/3D displays
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Abstract
Flat panel 2D/3D autostereoscopic displays are now being commercialised in a variety of applications; each with its own particular requirements. The autostereoscopic display designer has two key considerations to address to meet customer needs – the viewing interface to the display, (defined by the output window structure), and the optical component choice. Window structure determines 3D image resolution, achievable lateral and longitudinal viewing freedom, cross talk and 3D fringe contrast. Optical component selection determines the quality of the imaging of such windows, viewing distances, device ruggedness, thickness, and brightness.

Trade-offs in window design are described, and a comparison of the leading optical component technologies is given. Selection of Polarisation Activated MicrolensesTM architectures for LCD and OLED applications are described. The technology delivers significant advantages particularly for minimising nominal viewing distances in high pixel density panels and optimising device ruggedness while maintaining display brightness.

1. Introduction
Several reconfigurable autostereoscopic optical component technologies have recently emerged including active barriers[1], passive barriers[2], active lenses[3], and Polarisation Activated MicrolensesTM[4]. In this paper, the key characteristics of each class of optical technology will be compared.

The display designer also has to consider the optimum viewing interface to the display, particularly the relationship between image quality and viewing freedom – this is chiefly determined by the selection of window structure and will be considered first.

2. Autostereoscopic viewing interface
Autostereoscopic windows are the viewing regions formed around a nominal viewing distance, \( z_{nom} \) from the display within which separate left and right eye views are seen by the user. The brain fuses the images to create the impression of depth.

Autostereoscopic display performance can be quantified from measurements of window optical structure and image resolution characteristics. A photopic detector with a pupil sized (3-5mm diameter) pinhole scanned across the nominal window plane of the display[4] can determine for any point in the viewing space:

- **Cross talk**, \( \chi \) – ratio of light intensity from adjacent windows to main window intensity for each viewing position. It is the authors’ experience that \( \chi <2\% \) is desirable for high contrast images and a visibility target of \( \chi <0.3\% \) has been reported.
- **Viewing zone width**, \( \delta v \) – lateral distance over which the user can move with no pseudoscopic (reversed) image.
- **Sweet spot width**, \( \delta w \) – lateral distance for which e.g. \( \chi <5\% \),
- **Fringe contrast**, \( F \) – ratio of peak window intensity to the intensity of the gaps between the windows.

Generally window structures can be classified as either multi-view in which the emphasis is to provide increased viewing freedom (high \( \delta v \)); or two-view in which the emphasis is to provide high image quality (low \( \chi \), high \( \delta w \)).

2.1 Multi-view displays
Multi-view displays can offer wide viewing zone width, \( \delta v >50\text{mm} \), and low fringe visibility, \( F ~ 1 \) by sacrificing image resolution and cross talk performance.

2.1.1 Window structure
Reported optical configurations used include:

- **Vertical barrier/lenses** in which multiple columns of pixels are positioned under each optical element.
- **Step barriers**[3] in which a two dimensional array of slit apertures is used, each slit imaging multiple pixel columns.
- **Tilted lenses**[3] in which the number of view windows is increased by inclining lenses to the vertical axis.

In each structure, overlapping windows as shown in Fig. 1 are used to reduce \( F \) arising from imaging of the gaps between the pixel columns of the base panel.

![Fig. 1 Overlapping viewing windows for 4-view display](Image 389x429 to 514x455)

A 4-view window profile is illustrated in Fig.2, indicating \( \delta v \sim 195\text{mm} \). Multi-view displays typically have \( \chi >5\% \) over most, or all of the viewing zone. Some mitigation of the cross-talk artefact is usually achieved by reducing image disparity (total depth) and contrast.

![Fig. 2 Viewing zone for 4-view displays](Image 548x548)

2.1.2 Image resolution
In spatially multiplexed displays with typically 4-12 views, the low image resolution can result in pixel blockiness and an image stripiness artefact. In step barrier and tilted lens displays, image stripiness is reduced by trading off vertical luminance frequency with horizontal luminance frequency, using angled screen techniques similar to those well known in the printing industry. In both cases, this results in reduced vertical viewing freedom.
2.2 Two-view displays

In this class of display the emphasis is to provide high image quality (low \( \chi \)). A repeating series of left and right viewing windows are produced, as shown in plan view in Fig. 3.

![Fig.3 2-view display window structure](image)

Two-view systems, shown schematically in Fig. 4, can demonstrate \( \chi < 1\% \) (depending on the choice of optical component). By optical design, fringe contrast, \( F \) can be traded off with \( \delta w \) and longitudinal viewing zone \( \delta z \).

![Fig.4 Schematic window profile in a 2-view display](image)

Such displays generally have substantially better 3D image resolution and image quality than multi-view displays within the sweet spot region \( \delta w \), but the comparatively limited viewing freedom \( \delta z \) is not ideal. A lateral misalignment of the central viewing position of as little as \( 5\text{mm} \) can lead to viewing discomfort, suggesting that users are remarkably adept at positioning themselves centrally to displays. The viewing freedom can be substantially increased by tracking the observer position and adjusting (optically or mechanically) the window position. However, such a system is essentially for a single user and adds cost and complexity.

2.3 Comparison of viewing interfaces

Table 1 compares the typical performance of optimised 2-view and 4-view systems, using a 2" QVGA base panel.

![Table 1. Typical window characteristic comparison](image)

In cell phone displays, 2-view systems are well suited to the landscape orientation, whereas multi-view display typically require portrait mode orientation\(^1\). The constraint on \( z_{\text{nom}} \) is also determined by the choice of optical component architecture, as will be described in more detail below.

3. Display optical components

3.1 Base panel

Base panel choice is usually determined by the 2D mode requirements. In spatially multiplexed 3D displays, the optical component is arranged to image the pixel array to the windows. For each respective optical technology, this results in \( z_{\text{nom}} \) being restricted\(^2\) by the stripe pixel orientation (landscape or portrait) pixel pitch, \( p \) and glass substrate thickness, \( t \), for example as shown for a 2.0" cell phone display in Fig. 5.

![Fig.5 Simulated nominal viewing distance against pixel-optical element separation for various 3D configurations](image)

3.2 Optical technology categorisation

Switchable optical technologies for autostereoscopic 2D/3D displays can be categorised as shown in Fig. 6.

![Fig.6 Categorisation of optical technologies for autostereoscopic 2D/3D switchable displays](image)
3.3 Switchable parallax barriers
Parallax barriers limit the range of output ray angles using a patterned absorptive layer. The barrier can be formed from an active device such as a patterned TN-LC switch, or from a patterned array of λ/2 retarders and a uniform polarisation switch.

Key design considerations for parallax barrier displays include:
- Typical 3D transmission is <20% for a 4-view system, ~30% for most 2-view systems.
- 2D transmission is restricted by an additional polariser and ITO layers to ~85%.
- Diffraction effects at the barrier or pixel apertures typically limit the cross talk in switchable displays to χ >2-4%\(^4\).
- Diffraction effects (particularly arising from Fresnel diffraction in rear barrier displays) also limit the minimum fringe contrast, F that can be achieved in multi-view displays resulting in display appearing to flicker as the observer moves laterally with respect to the display.
- Active barriers typically have a comparatively high pixel-barrier separation, so z\(_{\text{nom}}\) >1100mm for a 4-view 2” QVGA panel\(^9\).
- Patterned retarder array devices have reduced viewing distance, z\(_{\text{nom}}\) ∼410mm for the same panel but have ~40% 2D transmission.
- Mixed region 2D/3D images can suffer from different 2D and 3D brightness by factors of x3-x5.

3.4 Switchable lenticular screens
Lenticular screens are arrays of cylindrical lenses aligned to the display pixels, offering substantially full brightness in 2D and 3D modes. Thus the optical properties of the lens can be tuned independently of the display brightness.

3.4.1 Active Lenses
Active microlens displays typically comprise a switchable nematic phase liquid crystal layer in contact with a surface relief solid isotropic layer.

Key design considerations include:
- With typical cell thicknesses of 60μm\(^9\) and similar isotropic polymer thicknesses such devices require high switching voltages typically >20V. The high voltage increases the complexity of multiplexing 2D and 3D zones.
- Material choices in display design typically require a driven (voltage on) 2D mode, which may cause switching difficulty across the entire lens aperture. This can leave residual image artefacts in the 2D mode.
- The nematic lensing layer typically requires a support substrate of thickness 0.5mm so z\(_{\text{nom}}\) ∼690mm for a 4-view 2” QVGA display panel.
- Thick layers of nematic liquid crystal are prone to reorient under the influence of surface pressure with relaxation times >5s. This can limit the device ruggedness and ability to remove the protective cover from the front surface of a cell phone.

3.4.2 Polarisation Activated Microlenses
In Polarisation Activated Microlens displays, the optical function of the lens is determined by the polarisation of the light passing through the lens to the observer\(^4\). As described elsewhere\(^3,9\) Polarisation Activated Microlenses using solid phase liquid crystals provide advantages of:
- Lower minimum viewing distances in multi-view and high resolution displays compared to competing technologies. For example a 2” QVGA 4-view display can show z\(_{\text{nom}}\) ∼380mm, close to a factor of two better than that achievable with active barriers and active lens devices.
- Added thickness approaching 1.0mm demonstrated\(^9\).
- High ruggedness to surface pressure
- Wide operating temperature range
- A low voltage switching component providing the ability to multiplex 2D and 3D areas.
The structure and relative merits of various Polarisation Activated Microlens architectures are described below.

3.4.2.1 ‘Type A’ architecture: LCD & OLED
In Type A architectures, a birefringent lens component is positioned between the pixel plane and output polariser of the display. For high resolution and multi-view displays, this minimises z\(_{\text{nom}}\) and maximises angular viewing zone width.

A structure suitable for an OLED display is shown in Fig. 7. Commercial OLED display pixels have an intrinsically un-polarised output but they typically use circular polarisers to increase the display contrast in ambient light. Polarisation Activated Microlenses can operate in cooperation with such polarisers so that the output is switched between 2D and 3D modes with the same contrast performance in both modes.

![Fig.7 Structure of Type A OLED device](image)

Previously, type A LCD displays operating in the normally white (NW) mode for 2D and the normally black (NB) mode for 3D have been reported\(^4,5\). In some displays, such as certain transflective mode displays, the black state polarisation is not orthogonal to the maximum transmission state. In such displays, an additional rear polarisation switch element enables NW mode operation for both 2D and 3D while providing the advantages of short viewing distance and high ruggedness.

3.4.2.2 Type B architecture
The Type A architecture can be modified by an additional polariser between the panel and lens components. The panel output polarisation is resolved onto the ordinary and extraordinary indices of the lens, providing NW contrast in both modes with minimised z\(_{\text{nom}}\).

3.4.2.3 Type C architecture
In some display structures, the spacing between pixel and optical element can be increased. The Type C architecture shown for example in Fig.8 offers a configuration with the ruggedness and image quality of Type B, but with full brightness.
A range of switchable autostereoscopic optical technologies have been developed recently, including active barriers, passive barriers, active lenses and Polarisation Activated Microlenses. Polarisation Activated Microlenses show particular advantages when using solid phase lenses of superior minimum viewing distance and compatibility with higher pixel densities. Further advantages include high device ruggedness and the ability to conveniently multiplex 2D and 3D regions over the display area. A comparison of the different optical technologies is given in Table 3.

### Table 2 Polarisation Activated Microlens architectures

<table>
<thead>
<tr>
<th>Panel type</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-LCD, TR-LCD, OLED</td>
<td>T-LCD</td>
<td>T-LCD</td>
<td>T-LCD</td>
</tr>
<tr>
<td>$z_{nom}$</td>
<td>&lt;200mm</td>
<td>210mm</td>
<td>550mm</td>
</tr>
<tr>
<td>2D efficiency</td>
<td>&gt;95%</td>
<td>45%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>3D efficiency</td>
<td>&gt;100%</td>
<td>45%</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>Contrast (2D/3D)</td>
<td>A: NW/NB</td>
<td>NW/NW</td>
<td>NW/NW</td>
</tr>
</tbody>
</table>

* Display performance based on 2.0" QVGA panel, 2-view landscape, orientation

4. Conclusion

Multi-view autostereoscopic display designs such as 4-view lenticular, step barrier and slanted lenses have been developed to offer increased lateral viewing zone width compared to 2-view implementations. While the extended viewing zone width offered by multi-view displays is clearly desirable in many applications, for the same base panel, 2-view designs can have superior image resolution, lower cross-talk, shorter nominal viewing distance and the ability to show a greater depth range effectively.

### Table 3 Comparison of reconfigurable 2D/3D optical component technologies

<table>
<thead>
<tr>
<th></th>
<th>Active barrier</th>
<th>Passive barrier</th>
<th>Active lens</th>
<th>P-A-M (Type A, solid lens)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D brightness</td>
<td>45-85%</td>
<td>45%</td>
<td>&gt;95%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>3D brightness (4-view)</td>
<td>&lt;20%</td>
<td>&lt;20%</td>
<td>&gt;95%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>Contrast</td>
<td>NW</td>
<td>NW</td>
<td>NW</td>
<td>2D:NW / 3D:NB or 2D:NW / 3D:NW</td>
</tr>
<tr>
<td>Limiting cross talk, $\chi$</td>
<td>&gt;2-3%</td>
<td>&gt;2-3%</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>$z_{nom}$ (4-view, 2&quot; QVGA)</td>
<td>1140mm</td>
<td>635mm</td>
<td>1070mm</td>
<td>520mm</td>
</tr>
<tr>
<td>Added thickness*</td>
<td>1.13mm</td>
<td>1.65mm</td>
<td>1.1mm</td>
<td>1.1mm</td>
</tr>
<tr>
<td>2D voltage</td>
<td>0V</td>
<td>0V</td>
<td>&gt;20V</td>
<td>0V</td>
</tr>
<tr>
<td>3D voltage</td>
<td>3.3V</td>
<td>3.3V</td>
<td>0V</td>
<td>3.3V</td>
</tr>
<tr>
<td>3D-2D switching response time</td>
<td>&lt;100ms</td>
<td>&lt;100ms</td>
<td>~seconds</td>
<td>&lt;100ms</td>
</tr>
<tr>
<td>2D &amp; 3D Area multiplexing?</td>
<td>x3-x5 brightness difference</td>
<td>x2-x3 brightness difference</td>
<td>High voltage multiplexing</td>
<td>Yes</td>
</tr>
<tr>
<td>Recovery time from surface pressure</td>
<td>-</td>
<td>-</td>
<td>&gt;5s</td>
<td>-</td>
</tr>
</tbody>
</table>

**Assumptions:** 130µm polariser thickness, 500µm substrate glass, 100µm polymer thickness, 65mm window width

5. References