https://doi.org/10.2352/ISSN.2470-1173.2017.5.SD&A-364

# Flat autostereoscopic 3D display with enhanced resolution using a static color filter barrier

***Silvio Jurk, Mathias Kuhlmey, Roland Bartmann, Bernd Duckstein, René de la Barré***
***Vision & Imaging Technologies***
***Fraunhofer Heinrich-Hertz-Institute, Berlin, Germany***

## Abstract

*Stereoscopic image separation can be improved with parallax barriers consisting of single color filter strips. A novel spatially multiplexed autostereoscopic 3D display design with wavelength-selective color filters is presented here. In comparison to common parallax barriers the resolution and brightness are enhanced by factor two. High quality image separation can be provided by using narrow-band RGB-backlights and bandpass barrier-filter. The newly introduced arrangement is realized as a slanted color stripe structure based on a regular RGB-display panel. In this paper we discuss the static color filter design and the influence of the barrier gaps on the uniformity of light emission.*

## Introduction

Wavelength-selective filter can be used to realize barriers for autostereoscopic displays. Common barrier type displays show different characteristics of image separation even if the same barrier pitch and ascent is used [1]. Wavelength-selective barrier displays use the primary colors for display technologies, red, green and blue. While Zhang et al. [2,3] didn't discuss the mask structure of the display and barrier, Jurk et al. [4] used vertical color filter stripes and vertical alternated colors for the pixel columns of the display. Based on slanted barrier design with horizontal alternating colors, resolution and brightness enhanced arrangements were simulated [1,7,8]. Furthermore, color filter masks can be realized by hole-structures [5,6,9]. In comparison to common barrier types with color filter transmitted light and resolution are reduced.

The combination of a *RGB* display with a wavelength selective filter barrier that is optimized for two views has special characteristics. Several combinations were found and estimated by an optimization algorithm with defined evaluation constraints [7]. Such 3D display designs operate position-adaptive if hidden subpixels are available in the sub-stripes [8, 11].

However, in the theoretical approach production tolerances of the barrier strips have to be considered. That includes for instance the overlap between the filter stripes. In practice, it is unavoidable that a black gap masks the transition between the filter strips. Such constrictions of the light transmission have an influence on the 3D display design. In the following this matter is discussed and investigated in detail.

## Design

For such novel display designs, we used stripe-shaped, wavelength-selective color filter barriers as well as *RGB*-patterned or *BGR*-patterned matrix displays. Depending on the direction of alternation of the primary colors of subpixels, a vertical [4] or a slanted [7] image splitter design was selected for our approach to produce the color balance. Here we consider the design case with a slanted barrier and two different viewing zones 1 and 2. A top view of a profile section of one subpixel row is shown schematically in FIG. 1. There, different colored light rays are emitting allocated content from the subpixel plane through the filter barrier. The colors of this display panel alternate horizontally in *RGB* order for the subpixel rows as well as in the barrier slots *F*.

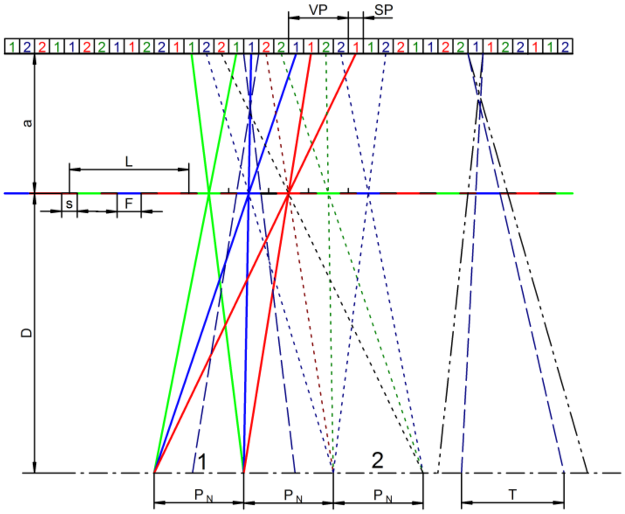

***Figure 1.*** *Schematical representation of a horizontal section through a subpixel row of the display with selected rays coming from the middle point of subpixels to construct emission properties (not true to scale, D >> a)*

FIG. 1 shows that a wavelength-selective color filter barrier with periodically alternating filter elements of period $F + s$ is arranged at a defined distance in front of the display. A filter element covers 4 subpixels in our example.

This color filter barrier only transmits the light of the subpixels with corresponding wavelengths. In distance *D* a local separation of color components of the two stereoscopic partial images is depicted. This separation is degraded by light from the two neighbored views visible in zone *T* and bounded by the gap *s*. It should be mentioned, for a good image separation, bandpass filters with narrow wavelength transmission characteristics to avoid crosstalk or interferences have to be used. This applies to the color filters of the subpixels and the barriers.

The smallest unit of this barrier construction consists of three juxtaposed monochrome barrier slots for different optical transmission areas. Since they are repeated, they can be understood as a parallel connection of three separating screens. Therefore, it is sufficient that in FIG. 1, rays of uniformly colored subpixels from the partial image 1 are shown. The corresponding subpixels of the same color are spatially separated by two subpixels of different colors. A strong separation is achieved between left (1) and right (2) picture channels. The continuity of parts for left and right images has to be assured via the neighboring rows. This is possible by slanted design choice.

Considering the center rays emitted from the subpixels of the image strip *VP*, they form their image points in two, left and right, partially overlapping zones. These zones have the width *T* and the distance *PN*. The same center rays from adjacent lines are slightly offset. The two resulting light distributions give the left and right viewing zones. Through the plane of this row it can be seen that rays from all three basic colors hit within the period *PN* and will add up to the white balance.

The convergence condition of the transmitted light rays of a sub frame [10] is derived from equation (1). The scanning distance *a* and observation distance *D* have to satisfy the condition *D*>>a.

$$R = \frac{\mathrm{D+a}}{\mathrm{D}} \tag{1}$$

The relationship between the image width *VP* and the pitch *L* of the color filter barrier can be described using the *R* factor, see equation (2).

$$L = 3 \cdot \frac{VP}{R} \tag{2}$$

Under the condition of three alternating filter colors and a uniform distribution of the gaps between the filter strips in *L* and the filter gap *s*, the filter width *F* can be determined by equation (3)

$$F = \frac{1}{3} \cdot L - s \tag{3}$$

A single subpixel produces a radiation area of width *T* at the viewing distance *D*. It corresponds to the beam construction shown in FIG. 1 and can be roughly approximated as described in equation (4).

$$T = \left(\frac{D}{a} + 1\right) \cdot (SP + F) - SP \tag{4}$$

The formula for the channel periodicity *PN* must be determined from the content design and the grid arrangement using the selected design. In our example with a strip period *F* + *s* of about 4 subpixels, *PN* is obtained from equation (5).

$$P_N = \frac{D}{a} \cdot (VP - SP) \tag{5}$$

Other image widths *VP* and a modified arrangement can affect the distribution and calculation of the zones *PN* indicated in FIG. 1. For a given strip width of 4 subpixels and *RGB* filter order in the barrier, the *PN*s are close together. The best usable eye distance *IPD* between viewing zone *1* and viewing zone *2* is obtained then.

$$IPD = 2 \cdot P_N \tag{6}$$

The gap *s* between the filter stripes influences the emission width *T* and therefore the separation of resulted views. It also decreases the crosstalk at the expense of the total brightness. To reduce Moirés and for a better vertical white balance, the image splitter will be rotated in front of the pixel panel out of the vertical. In consequence of this slope the partial images need to be arranged with an offset of one subpixel for each row.

## Investigation of sample design

In this chapter we wanted to investigate and analyze this basic arrangement by changing several parameters. For that purpose we used our simulation software with start values and calculated the best parameters of the given model. Representation of the chosen arrangement can be visualized via its internal graphic engine. FIG. 2 shows the front views of two 3D displays consisting of two displays with color filters arranged like in FIG. 1. Each color strip covers 4 subpixels per row. The left picture shows the display design without gaps and the right picture shows this display design with gaps between the filter. The gaps influence the visibility of the subpixel per row. For each row the radiated intensity with gaps is more uniformly distributed than without gaps.

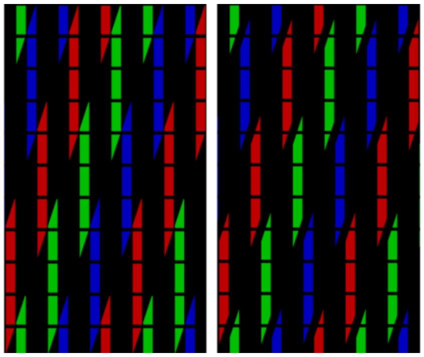

***Figure 2.*** *Front view of two 3D display designs with the same filter pitch and the same inclination angle of the barrier. Left (a) without and right (b) with gap.*

The determination of the gap sizes between each filter strip will be explained in the following in terms of distribution of visible but partially covered subpixel areas. An exemplarily chosen area of the visible structure is shown in FIG. 2a.

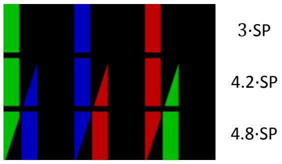

***Figure 3.*** *Detail of the alternating subpixel pattern, the visible and truncated area parts consisting of 12 subpixels for each of the 3 subpixel rows, the number of visible subpixels per row is show on the right.*

As depicted in FIG. 3 the visibility of subpixels is significant different in the three rows. This will be visible as slight texture over the whole screen. To avoid such effects FIG. 4 shows a design case with optimized gap size. The relative share for each row is equal for each color. This pattern of visible subpixel areas is valid for the whole display.

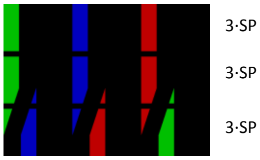

***Figure 4.*** *Pattern with visible area shares in rows for a pattern of filter stripes and gaps with optimized width and on the right the number of visible subpixels per row.*

**Table 1. Row dependent visibility of the visible subpixel areas**

| | Row m | Row m+1 | Row m+2 | Total |
|---|---|---|---|---|
| Figure 3 | 25% | 35% | 40% | 33% |
| Figure 4 | 25% | 25% | 25% | 25% |

Table 1 shows a listing of visible subpixel areas for each row by comparing FIG. 3 and FIG. 4. As a result the right choice of a gap can preserve non-uniform brightness distributions in each row. The effect of gaps can also be determined by investigating the luminance profiles. As consequence of gap structures the maximum luminance decreases. FIG. 5 shows the comparison of luminance profiles of one subpixel row by different gap widths. The luminance fluctuations of the basic design without any gaps will be compensated by using a gap that covers one subpixel, like in the results of FIG. 4.

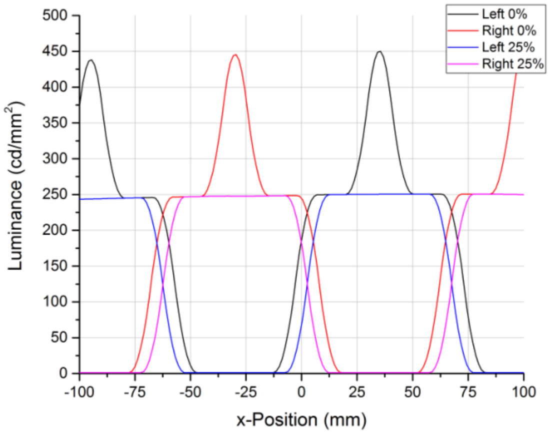

***Figure 5.*** *Luminance distribution for a single pixel row in dependence of gap width, in correspondence to FIG. 1 and 3 with D = 650 mm.*

As an important result, with 25% gaps is no position dependent luminance fluctuation visible in the viewing distance *D*. A reason for the position dependent asymmetry is that visible subpixel will be changed vertically by changing the viewing angle. Therefore, a tracking by shifting the image information, also vertically, has to be realized [8].

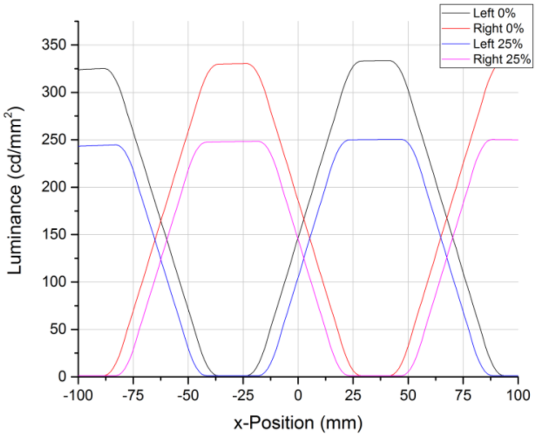

***Figure 6.*** *Luminance profile of three neighbored rows, representative for an integration of all rows, for different gap widths in percent, separated in left and right content at D = 650mm.*

An integration of visible luminance fractions over several rows is shown in FIG. 6. It is sufficient to integrate over three rows, due to a self-repeating color pattern. It is recognizable that widening the gaps also causes widening of the luminance plateau at maximum. The results of Table 1 are shown in FIG. 6 at maximum luminance. The source luminance of the display was 1000 cd/mm$^2$, and then 33% and 25% visible subpixels are in accordance to a maximum luminance of 333 cd/m$^2$ and 250 cd/m$^2$ respectively. In addition, shown in FIG. 7, the zone widths of minimum crosstalk will be expanded. In consequence the image separation will be better at the observer position.

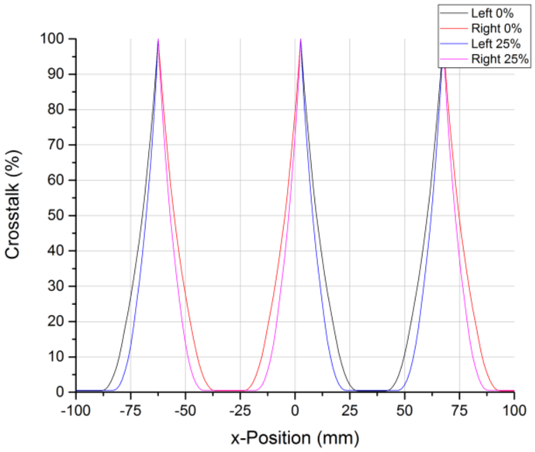

***Figure 7.*** *Crosstalk profile of three integrated rows, representative for an integration of all rows, for different gap widths in percent, separated in left and right content at D = 650 mm.*

## Results

The investigation of this arrangement shows that a general principle was found to realize a uniform light emission of all subpixel rows. It has to mentioned, for visible filter stripes that cover only three subpixels no gaps are needed. Assuming a stripe width of $VP=4\cdot SP$ a gap width of one *SP* gives row-wise compensation of brightness. Concerning both, the left and right view, a gap of $2\cdot SP$ is needed. FIG. 8 schematically clarifies this connection and shows its validity for 3 different barrier as well as pixel colors.

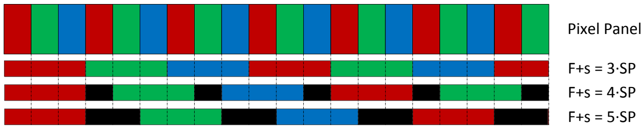

***Figure 8.*** *Schematic comparison of stripe widths at periods of 3, 4 and 5 SP.*

Further variants are depending of the order of colors. So far, we investigated the *RGB* order of filter barrier and pixel panel. For a possible *BGR* order the color allocations for the subpixels have to be adopted, if the original image is not a *BGR*. However, by using oppositional color orders like *RGB/BGR* or *BGR/RGB*, also the content allocation of each subpixel has to be adopted. In case of the right content allocation, the simulation shows that these combinations generate an image separation compared to a pure *RGB* or *BGR* order. Besides the color order, the slope of filter barrier influences the subpixel allocation or interleaving pattern of subpixels. By changing the slope of the grid also the vertical periodicity of resulted color pattern will change. As a result the length of visible, connected subpixels will change. The allocation in one subpixel row gets an offset to follow the slope, because periodicity and order in each row are the same. FIG. 9 shows the resulted structures at different parameter combinations.

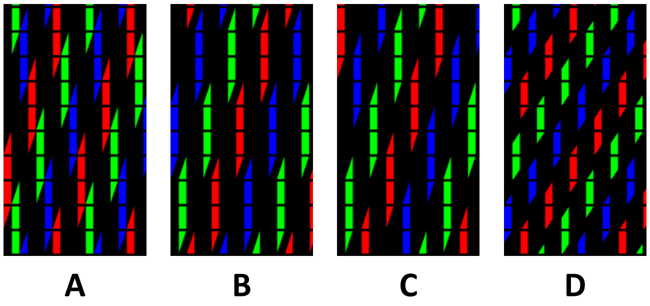

***Figure 9.*** *Different arrangements A to D, listed in Table 2.*

**Table 2. Parameter sets for the arrangements *A* to *D***

| Setting | Slope | Strip Width | Grid Pattern | Pixel Pattern |
|---|---|---|---|---|
| A | 3 Rows | 3·SP | RGB | RGB |
| B | 3 Rows | 4·SP | BGR | BGR |
| C | 3 Rows | 4·SP | BGR | RGB |
| D | 1.5 Rows | 4·SP | RGB | RGB |

From the combination of several parameters different structural arrangements arise, where the local distribution of visible subpixels over the grid was changed. This can be seen in FIG. 9 and the parameters for these arrangements are listed in Table 2.

As it was shown above, the combination *A*, which only covers three subpixels, shows a uniform distribution. A gap that couldn't be avoided is a disadvantage, due to production-orientated reasons. Combination *B* shows a result of the *BGR/BGR* color order that is similar to FIG. 4. Combination *C* shows an advantageous distribution of visible subpixel strips, due to a better illumination uniformity of the panel. Finally, combination *D* shows smaller, connected subpixel structures by using a lower slope. It can be supposed that the moving space is restricted.

## Conclusion

Flat autostereoscopic displays with stripe-shaped, wavelength-selective color filter barriers theoretically can achieve crosstalk values under two percent and up to two times higher luminance than common parallax barriers. The special color filter design ensures that about one third of the maximum light intensity is emitted from the 3D display surface. Manufacturing tolerance requires an opaque gap structure between the color filter strips. In this paper, the use of these black stripes in an advantageous manner has been proposed. In addition to the filter width and slant angle, the gap width parameter gives the designer the opportunity to homogenize the radiation characteristic of the 3D display and eliminate line-wise alternating brightness fluctuations. In future works, a further investigation of possible parameter combinations is planned. The strip width or color arrangements in combination with the slope of the grid could provide an even more optimized result of this grid type.

## References

[1] S. Jurk, M. Kuhlmey, R. Bartmann, B. Duckstein, R. de la Barré, "Flat Autostereoscopic 3D Display with enhanced Resolution using a Wavelength-Selective Filter Barrier", IDW/AD 2016,

[2] Q. Zhang, H. Kakeya, "Time-division multiplexing parallax barrier based on primary colors", Stereoscopic Displays and Applications XXV, Proc. SPIE 9011F, 2014.

[3] Q. Zhang, H. Kakeya, "A High Quality Autostereoscopic System Based on Time-Division Quadplexing Parallax Barrier", IEJCE Trans. Electron. Vol. E97-C, No.11, 2014.

[4] S. Jurk, M. Kuhlmey, R. Bartmann, B. Duckstein, R. de la Barré, "Autostereoscopic display concept with time-sequential wavelength-selective filter-barrier", Proc. SPIE 9770, Advances in Display Technologies VI, 977005 (March 7, 2016).

[5] Jae-Hyun Jung, Soon-gi Park, Youngmin Kim, and Byoungho Lee, "Integral imaging using a color filter pinhole array on a display panel", Optics Express Vol. 20, No. 17, 2012.

[6] F. Doerfel, et al., "Method and system for the three-dimensional representation", US 7,046,271 B2, 2006.

[7] M. Kuhlmey, S. Jurk, B. Duckstein, R. de la Barré, "Automated simulation and evaluation of autostereoscopic multiview 3D display designs by time-sequential and wavelength-selective filter barrier", SPIE Optical Systems Design 2015, Computational Optics, Volume: Proc. SPIE 9630, Jena, Germany, 2015.

[8] S. Jurk, M. Kuhlmey, R. Bartmann, B. Duckstein, R. de la Barré, "Flat Autostereoscopic 3D Display with enhanced Resolution using a Wavelength-Selective Filter Barrier", Fukuoka, IDW, 2017.

[9] A. Schmidt, A. Grasnick, "Multi-viewpoint Autostereoscopic Displays from 4D-Vision", SPIE Vol. 4660, 2002.

[10] R. de la Barré, K. Hopf, S. Jurk, U. Leiner, "34.1: Invited paper: "TRANSFORMERS - Autostereoscopic displays running in different 3D operating modes", SID Symposium Digest of Technical Papers, 42(1):452-455, 2011.

[11] S. Jurk, R. de la Barré, "A new Tracking Approach for XYZ-User-Adaption of Stereoscopic Content", Electronic Displays Conference, Nuremberg, 2014.

## Authors Biographies

*Silvio Jurk studied technical computer science at the University of Applied Science in Görlitz(2009) and computer science for media at HTW Berlin (2013). In 2008 he joined the Advanced Displays and Applications Group at Fraunhofer Heinrich-Hertz-Institute where he has been working on adaption procedures and display designs in the area of 3D displays. In 2015 he changed to the Capture and Display Group. His current research interests include autostereoscopic 3D displays and image based technologies.*

*Mathias Kuhlmey studied computer engineering at TU Berlin (2014) and work for Heinrich-Hertz-Institute since 2011 as a research assistant. He developed a simulation environment for autostereoscopic displays besides mathematical modeling.*

*Roland Bartmann received his diploma degree in 2002, in the physics department of the Humboldt University Berlin, and his Ph.D. degree from the Technical University Berlin, in 2009. After working in the area of neutron and x-ray optics, he changed to the display research at Fraunhofer*

*Heinrich-Hertz-Institute in 2012. His research interests include physical and liquid crystal optics and the simulation of autostereoscopic 3D displays.*

*Bernd Duckstein after receiving his degree as a graduate engineer in communications engineering at the University of Applied Sciences of the Bundespost in Berlin, Mr. Duckstein joined the Heinrich-Hertz-Institute in 1986 as research associate. Working in the 3D autostereoscopy group, he worked on many hardware, software, content and measurement issues of autostereoscopic display systems.*

*René de la Barré received his diploma in 1978 and his PhD in 1993 from the University of Mittweida (Germany). He worked for 20 years in R&D of display industries. In 2001 he joined the Heinrich Hertz Institute. Since 2003 he led the 3D display research there. In 2015 he changed to HHI's Capture and Display Group. His current research interests are design and human engineering of autostereoscopic 3D displays. He works in DIN, ISO and ICDM on autostereoscopic display topics.*