Portable 3D Laser Projector Using Mixed Polarization Technique

Kaan Akşit, Osman Eldes, *Student Member, IEEE*, Selvan Viswanathan, *Senior Member, IEEE*, Mark O. Freeman, and Hakan Urey, *Senior Member, IEEE*

***Abstract*—This paper introduces a new twist on stereoscopic displays—one that has similarities to existing methods in that it utilizes both polarization and color to present different stereo 3D perspectives to each eye, but by combining the use of polarization and color, it avoids weaknesses associated with previous methods. This new method is named Mixed Polarization 3D. Color imbalance artifacts associated with anaglyph methods of 3D are avoided by alternating the colors presented to each eye. Flicker, associated with polarization-sequential 3D, or the need to increase the frame rate to at least 120 Hz to avoid this perceived flicker, is avoided in mixed polarization 3D by presenting both eyes with 3D information in every single frame. It is particularly aimed at use in scanned laser projectors where all three primary colors (R, G, B) are already polarized and simultaneously displayed. Like other polarization-based approaches, it requires the use of a polarization-preserving screen and inexpensive passive polarization glasses. The 3D display needs just a single handheld mobile projector coupled with an active polarization rotator, thus the image registration problems with two projectors is avoided.**

***Index Terms*—Stereo vision, mixed polarization, portable projectors.**

TABLE I
COMPARISON OF STEREOSCOPY METHODS (ASSUMING MINIMUM 60 HZ PER EYE REFRESH RATE AND A FLICKER FREE IMAGE)

Method	Hardware options	Pros / Cons
Anaglyph	60 Hz projector; Any surface; Color coded glasses	(+) Simple hardware, (+) Standard refresh rate, (+) passive glasses, (-) Loss of color
Polarization multiplexing	120 Hz projector + polarization rotator (or two 60 Hz projectors); Polarization maintaining surface; Passive polarized glasses	(+) Passive glasses, (-) High refresh rates (or image registration problem), (-) Special screen requirement
Time multiplexing	120 Hz projector; Any surface; Active shutter glasses	(-) Active glasses are expensive, require battery, (-) High refresh rate
Mixed polarization	60 Hz projector and polarization rotator; Polarization maintaining surface; Passive polarized glasses	(+) Standard refresh rate, (+) Passive glasses, (-) Special screen requirement

I. INTRODUCTION

THE most common stereoscopic display approaches are color-multiplexed (using anaglyph glasses), polarization-multiplexed, and time-multiplexed, which are reviewed under [1]. In the anaglyph method, the viewer wears a pair of colored glasses so that the left and right eyes each receive non-overlapping parts of the visible spectrum, with different stereo views of the 3D scene coded in each partial spectrum. From this information, the brain synthesizes a full-color 3D scene. Several types of anaglyph color schemes are available, the most common being red-cyan color colored glasses [2]–[4]. The main drawbacks of this type of display are the loss of color information, challenges in obtaining the correct color balance, binocular rivalry [5] and reproduction, and the high degree of crosstalk between the two eyes [5], [6].

In the polarization-multiplexed approach, the polarization state of the light corresponding to each image in the stereo pair is made mutually orthogonal. One common setup of polarization-multiplexed approach consists passive polarization glasses, a projector with a liquid crystal polarization rotator with at least 120 Hz refresh rate, and a polarization maintaining screen. A straightforward way of building a polarization-multiplexed setup is to employ two projectors with projected light in orthogonal polarizations, and one projector for left-eye images and the other projector for the right-images [7] and [8]. Alternative operation modes of this technique are described in [1]. Passive glasses with orthogonal polarizers for the left and right eyes blocks the image not intended for that eye. A single projector operated at a minimum of 120 Hz refresh rate with an active polarization rotator to rotate the polarization in between frames has also been demonstrated [9]–[11] and is commercially available for 3D TVs. The main drawback of these schemes is the increased frame rates and the blanking times required between switching cycles to reduce the crosstalk. Patterned micro-polarizers and patterned retarders have also been employed, particularly for 3D TVs, to achieve polarization multiplexing at the expense of resolution [12], [13].

In the time-multiplexed approach, each eye receives light only on alternate frames which leads to flicker unless the frame rate is increased to at least twice the frequency where flicker is not perceived. Those displays are typically operated at 120 Hz or greater. The viewer is required to wear battery-powered active shutter glasses, which are synchronized to the content being displayed, [14]. Active glasses are more costly and heavier than inexpensive passive glasses, and require careful handling. All of the described techniques with their hardware options, advantages and disadvantages are tabulated under Table I.

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K. Akşit, O. Eldes, and H. Urey are with the Electrical Engineering Department, Koç University, Istanbul 34450, Turkey (e-mail: hurey@ku.edu.tr).

S. Viswanathan and M. Freeman are with Microvision Inc., Redmond, WA 98052 USA (e-mail: selvan_viswanathan@microvision.com and mark_freeman@microvision.com.

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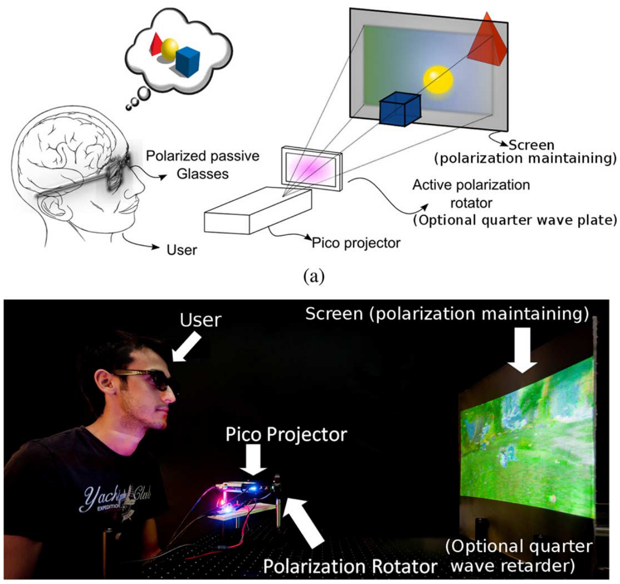


(a)

(b)

Fig. 1. (a) Single pico projector 3D display system. (b) Photograph of the overall system during operation.

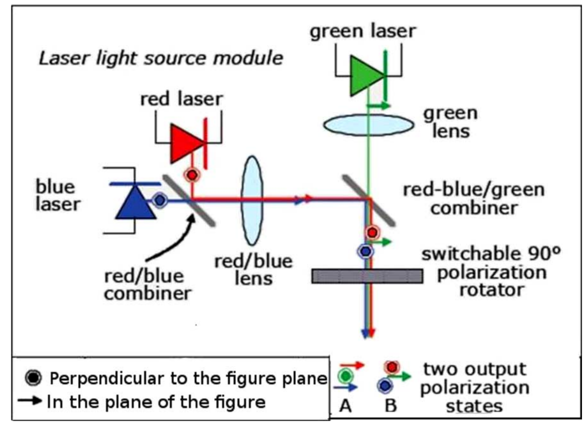
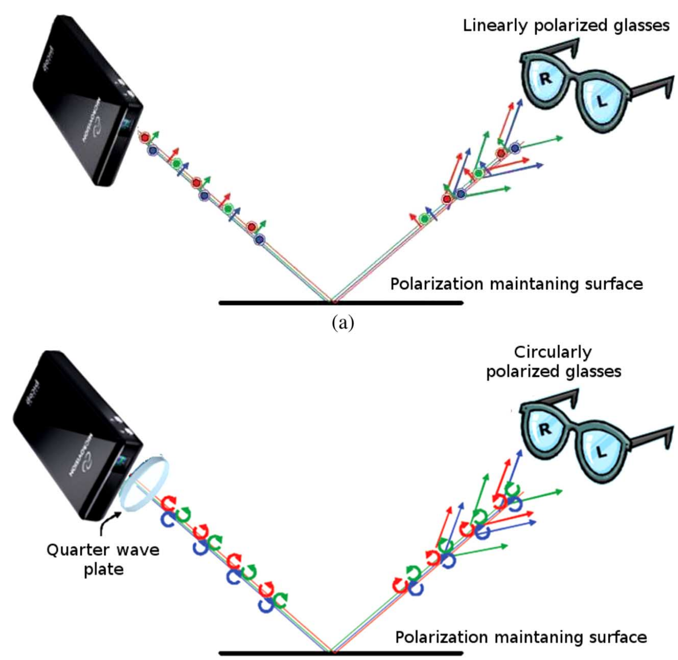


Fig. 2. System sketch showing laser light source module with two orthogonal polarization states.



(a)

(b)

Fig. 3. (a) Polarization state of the light at different stages. (b) Polarization state of the light at different stages with a quarter wave plate.

This paper introduces a new method for 3D projection displays one that has similarities to the existing methods discussed above in that it utilizes polarization and color-multiplexing to present different stereo 3D perspectives to each eye, but by combining the use of polarization and color, it avoids the weaknesses associated with previous methods. The method described does not employ color filter multiplexing as used anaglyph displays but utilizes the fact that the colors are separated over alternate frames. This new method is named mixed-polarization 3D. It is particularly aimed at use in a single, handheld, scanned laser projectors where all three primary colors (R, G, B) are simultaneously displayed using already polarized lasers [15]. Microvision's PicoP™ handheld pico projector is a good example of this type of scanned laser projector [16]. Unlike [7] and [8], a single projector is used, so an image registration problem on the image plane caused by multiple projectors is avoided. Furthermore, the image retention problem that is present in [8] is solved by using a laser scanning system. The use of lasers provides infinite focus, wide color gamut and a simplified mobile solution where no projection optics are required. Section II discusses the key components and provides a Jones calculus analysis of the system, Section III discusses the content creation, Section IV discusses the test results and Section V discusses the options for polarization maintaining screens.

II. Concept of the Display

The system contains four different elements as illustrated in Fig. 1(a): 1) a scanned laser pico projector; 2) an active polarization rotator coupled to the projector; 3) a polarization maintaining screen; and 4) passive polarized glasses.

The scanned laser light from the pico projector passes through an active polarization rotator and then is incident on a polarization maintaining screen. A user with polarized glasses views the light beams reflected from the polarization maintaining screen such as a silver screen. Fig. 1(b) shows the latest prototype from our test-bench which is adaptable to both linearly polarized scheme and circularly polarized scheme, the latter requiring additional quarter wave plates.

The pico projector contains red, green, and blue laser light sources, a MEMS scanner and drive electronics. Fig. 2 illustrates layout of the laser module and the associated combiner optics that result in different polarization states in the combined beam. The red and blue lasers are shown to be polarized perpendicular to the plane of the figure while the green laser is polarized in the plane of the figure. The current bench top prototype system shown in Fig. 1(b) has the polarization rotator after the pico projector, but it can also be embedded in the system before the MEMS scanner as shown in Fig. 2. In the embedded case, the polarization rotator acts on the beam before it is scanned by the MEMS scanner, the beam passes through it at fixed angle of incidence which improves the performance of the polarization

TABLE II

POLARIZATION VECTORS AT DIFFERENT STAGES WITHOUT A QUARTER WAVE PLATE (FAST AXIS OF THE POLARIZATION ROTATOR AT 45° ANGLE WITH LASER AXIS IS USED AS THE REFERENCE COORDINATE AXIS TO AVOID MATRIX ROTATIONS IN THE JONES CALCULUS)

	Jones Matrix	Frame i		Frame i+1	
		Red & Blue	Green	Red & Blue	Green
After Laser Combiner	-	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$
Polarization Rotator (R)	$\begin{cases}L_{R_i}=\begin{bmatrix}0&1\\-1&0\end{bmatrix}\\L_{R_{i+1}}=\begin{bmatrix}1&0\\0&1\end{bmatrix}\end{cases}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}-1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$
Polarization Maintaining Screen (PMS)	$L_{PMS}=\begin{bmatrix}1&0\\0&1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}-1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$
Left Eye (Left eye linear polarizer, LLP)	$L_{LLP}=\begin{bmatrix}\frac{1}{2}&\frac{1}{2}\\\frac{1}{2}&\frac{1}{2}\end{bmatrix}$	$\begin{bmatrix}0\\0\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}-1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\begin{bmatrix}0\\0\end{bmatrix}$
Right Eye (Right eye linear polarizer, RLP)	$L_{RLP}=\begin{bmatrix}\frac{1}{2}&-\frac{1}{2}\\-\frac{1}{2}&\frac{1}{2}\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\begin{bmatrix}0\\0\end{bmatrix}$	$\begin{bmatrix}0\\0\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$

TABLE III

POLARIZATION VECTORS AT DIFFERENT STAGES WITH A QUARTER WAVE PLATE (FAST AXIS OF THE POLARIZATION ROTATOR AT 45° ANGLE WITH LASER AXIS IS USED AS THE REFERENCE COORDINATE AXIS TO AVOID MATRIX ROTATIONS IN THE JONES CALCULUS)

	Jones Matrix	Frame i		Frame i+1	
		Red & Blue	Green	Red & Blue	Green
After Laser Combiner	-	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$
Polarization Rotator (R)	$\begin{cases}L_{R_i}=\begin{bmatrix}0&1\\-1&0\end{bmatrix}\\L_{R_{i+1}}=\begin{bmatrix}1&0\\0&1\end{bmatrix}\end{cases}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}-1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$
Quarter Wave Plate (QWP)	$L_{QWP}=\begin{bmatrix}1&0\\0&-j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}-1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$
Polarization Maintaining Screen (PMS)	$L_{PMS}=\begin{bmatrix}1&0\\0&1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}-1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$
Left Eye (Left handed circular polarizer, LHCP)	$L_{LHCP}=\frac{1}{2}\begin{bmatrix}1&-j\\j&1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\begin{bmatrix}0\\0\end{bmatrix}$	$\begin{bmatrix}0\\0\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$
Right Eye (Right handed circular polarizer - RHCP)	$L_{RHCP}=\frac{1}{2}\begin{bmatrix}1&j\\-j&1\end{bmatrix}$	$\begin{bmatrix}0\\0\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}-1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	$\begin{bmatrix}0\\0\end{bmatrix}$

rotator. Also, by operating on the pre-scanned laser beam, the size and cost of the polarization rotator can be minimized.

The active polarization rotator is synchronized with the frame rate of the projector such that it switches state during the off time between frames (i.e., scanner retrace time). Thus mixed polarization states of lasers are alternated for successive frames with red and blue having in-plane polarization and green having out-of-plane polarization in frame i, and then flipping in frame $i+1$ so that red and blue have out-of plane polarization and green has in-plane polarization. Any type of polarization rotator could be used; we chose a ferro-electric liquid crystal rotator. It acts as a half-wave retarder with its fast axis lined up with the polarization in the ON state and rotated by 45 degrees in the OFF state. The incident light is therefore unaffected in the ON state and rotated by 90 degrees in the OFF state. The polarization rotator is synchronized with the refresh rate of the pico projector which is typically around 60 Hz.

The mixed-polarization method introduced in this paper takes advantage of the perpendicular relationship between the polarization state of the red and blue lasers and that of the green laser in Microvision PicoP display engine. The polarization states of this system can be analyzed using Jones calculus, [17]. The analysis is carried out for the green channel and the blue/red channels separately and tracks only the polarization direction without taking the beam power and efficiency of the components into account. The method is suitable for two different approaches: 1) using linear polarization illustrated in Fig. 3(a) and 2) using circular polarization, illustrated in Fig. 3(b). In the circular polarization case, QWPs are placed to convert the linear polarization into circular polarization and vice versa.

Tables II and III show the Jones matrices of the system components and the Jones vectors for the all color channels after each component in the system. The fast axis of the QWP in cir-

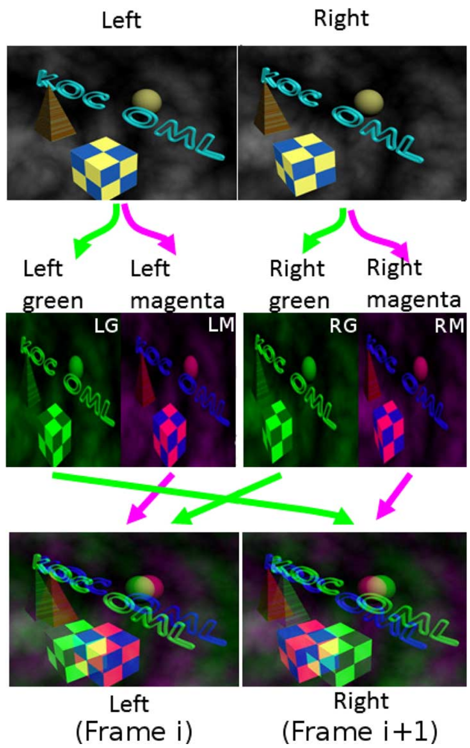


Fig. 4. Demonstration on how single frame is modified.

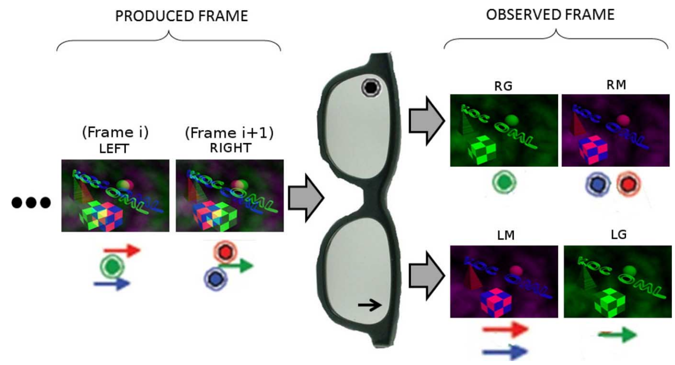


Fig. 5. Frames produced in Fig. 4 are displayed as demonstrated in the paper.

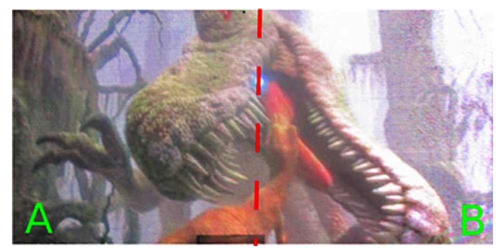


Fig. 6. Photograph of a view from the screen. (A) Left eye image seen through the polarizer. (B) Superimposed left and right images seen with a naked eye.

cular polarization and the polarization rotator case are identical and chosen to be the reference axes of the whole system to avoid rotation matrices in the analysis and to provide ease of understanding.

A polarization maintaining diffuser screen is necessary to avoid depolarization of the light. The reflected light from the screen arrives at the polarized glasses. In the linear polarization case, the passive glasses contains two linear polarizers with perpendicular polarization states at $\pm 45°$ angles to the coordinate axis. In the circular polarization case, the passive glasses contains left and right handed circular polarizers. Circular polarization is generally preferred as it allows more head tilt without crosstalk. The passive glasses act as polarization analyzers and separate left and right eye images. The polarization filters are assumed ideal without any crosstalk.

As a result, the left eye receives the green channel while the right eye receives the red and blue channels in one frame. In the next frame, the left eye receives the red and blue channels while the right eye receives the green channel.

III. Content Creation

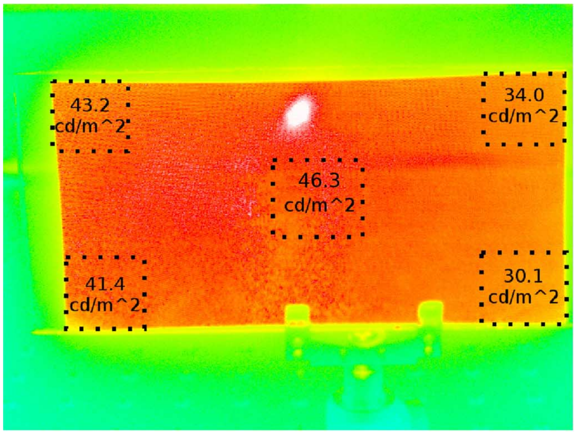
The operating scheme requires specially encoded video or image sources to provide stereoscopic vision. Conventional frame-compatible stereoscopic content contains two images per frame, one for each eye. In the mixed polarization scheme, the green channel is interchanged between the stereo image pairs to create a modified stereoscopic content. Fig. 4 illustrates the required content modification.

Note that the conversion operation is straightforward and can be performed in real-time. We modified the content with the help of scripts developed both in MATLAB and Python. Thus the conversion can run across different operating systems and platforms. Fig. 5 explains how a user receives the modified stereoscopic content with the glasses.

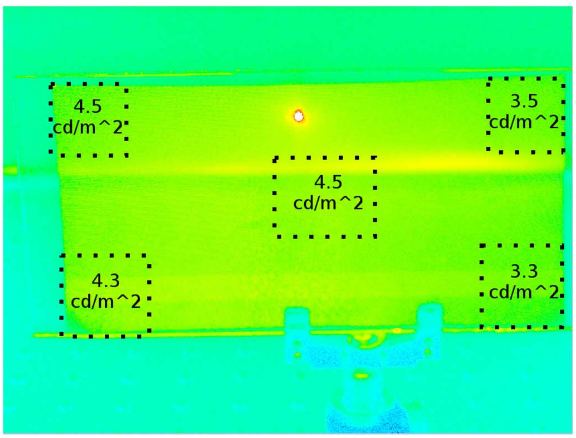
IV. Results and Discussions

The display system shown in Fig. 1(b) was built to demonstrate the mixed polarization 3D approach. The elements used were a scanned laser pico projector from Microvision [18], an active polarization rotator from Micron Tech. [19] (driver model DR-95) coupled to the projector, a polarization maintaining screen from SilverFabric-UMA [20] and passive polarized glasses. The 3D content shown in Fig. 6 was convincing and high-quality. In [21], it was stated that the flicker sensitivity of a human eye appeared to be set by a chromatic channel below 3 Hz and an achromatic channel above this frequency. Thus, a 30 Hz chromatic flicker provides better performance than 30 Hz luminance flicker. During the experiments it was noted that there is no noticeable flicker in the display. When the images were projected onto a partially reflective microlens array screen [22] which has the properties of both maintaining polarization and eliminating laser speckle, then the image quality was even better due to lower speckle contrast.

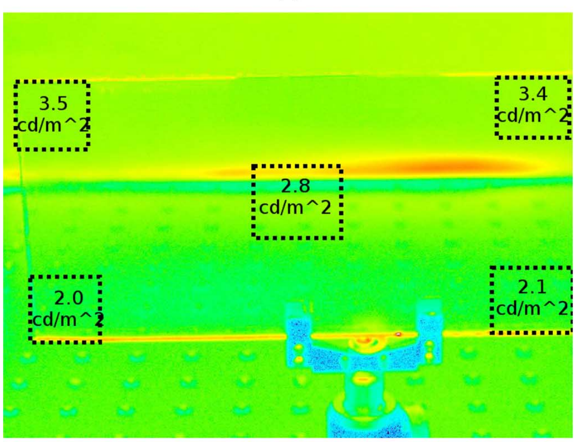
Crosstalk performance of a stereoscopic display is an important measure in providing true stereoscopic vision to the users. Using the system shown in Fig. 1, system crosstalk analysis was performed using a black image in one eye and a white image in the other eye. A microlens array screen at about 30 cm from the pico projector and a polarizer film in front of a calibrated camera from Radiant Imaging at a distance 120 cm from the screen were used. Two images were captured by orienting the polarizer in appropriate angles for left and right eyes. Fig. 7 (false-color)



(a)



(b)



(c)

Fig. 7. Sample photographs of the light projected onto a microlens array screen. (a) Luminance level of the left eye (White screen). (b) Luminance level of the right eye (Black screen). (c) Luminance level of the ambient (Pico projector is off).

shows the luminance distribution in each eye. The ratio of the average luminance in both eyes were presented under Table IV.

We also measured crosstalk per each state of the rotator using the test bench illustrated in Fig. 8. The power meter, shown in Fig. 8, was placed at a point corresponding to the center of the projected image. Note that the measurements were made for each state of the polarization rotator, thus polarization rotator stays in one state during each measurement. A portion of the

TABLE IV
AVERAGE CROSSTALK VALUES OF THE EACH SAMPLE REGION ON THE MICROLENS SCREEN SHOWN IN FIG. 7

Regions	White Image (W)	Black Image (B)	Ambient (A)	Crosstalk
Upper Left	43.2 cd/m^2	4.5 cd/m^2	3.5 cd/m^2	2.58 %
Upper Right	34.0 cd/m^2	3.5 cd/m^2	3.4 cd/m^2	0.32 %
Lower Right	30.1 cd/m^2	3.3 cd/m^2	2.1 cd/m^2	4.30 %
Lower Left	41.4 cd/m^2	4.3 cd/m^2	2.0 cd/m^2	5.83 %
Center	46.3 cd/m^2	4.5 cd/m^2	2.8 cd/m^2	3.95 %
Total	39.0 cd/m^2	4.0 cd/m^2	2.7 cd/m^2	3.39 %

*Crosstalk is calculated using $(B - A)/(W - A)$ equation.

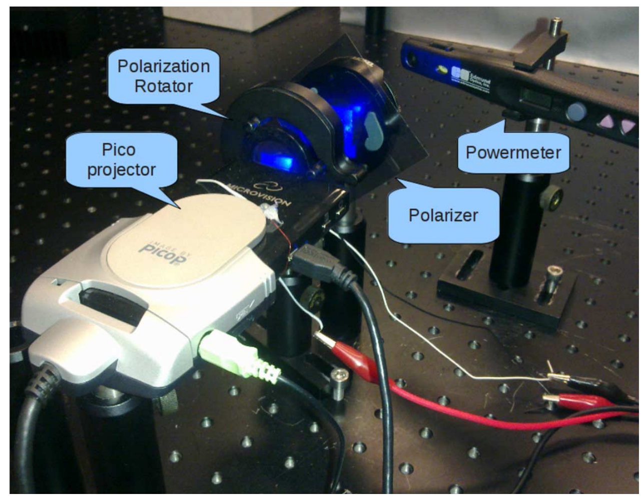


Fig. 8. A picture of the experiment bench.

TABLE V
POWER MEASUREMENTS ("NONE" REPRESENTS THE CASE WHEN POLARIZATION ROTATOR IS REMOVED FROM THE BEAM PATH.)

Rotator state	Polarizer	Red only	Green only	Blue only
On	Left	82 μW	1.11 μW	35.5 μW
On	Right	4.76 μW	62.5 μW	0.6 μW
Off	Left	8.48 μW	59.7 μW	0.47 μW
Off	Right	76.1 μW	3.17 μW	35.1 μW
None	Left	91.7 μW	1.2 μW	47.9 μW
None	Right	3.32 μW	75 μW	1.45 μW

projected content goes through the polarization rotator and the linear polarization filter. The transmitted power was measured using a power meter from Edmund Optics.

The experiment was repeated for each color channel. Note that the effect of the polarization maintaining screen was neglected for this experiment and the polarization maintaining screen was assumed to be ideal. Table V presents the measured values from the power meter. During the experiment, it was observed that the polarization states of green and red color channels are orthogonal to each other. But the polarization state of blue has an additional angular difference of 4° with respect to red. Photometric weights of red and green dominate over blue and therefore the polarization rotator and the linear filters should be aligned with respect to red and green to achieve good crosstalk attenuation levels.

The radiometric crosstalk ratio is the direct ratio between the unwanted and wanted content. For example with the rotator in the "ON" state and with the left eye polarizer, the radiometric

TABLE VI
CROSSTALK LEVELS: RATIO OF DESIRED TO UNDESIRED LIGHT POWERS

Rotator state	Polarizer	Photometric crosstalk ratio	Radiometric crosstalk ratio
On	Left	4.0 %	0.9 %
On	Right	2.4 %	8.6 %
Off	Left	4.5 %	15.0 %
Off	Right	12.5 %	2.9 %

TABLE VII
CONTRAST RATIO FOR EACH COLOR CHANNEL: THE RATIO OF SWITCHED-ON TO SWITCHED-OFF BRIGHTNESS

	Red	Green	Blue
Left	10:1	54:1	75:1
Right	16:1	20:1	59:1

crosstalk ratio is $1.11\ \mu\text{W}/(82\ \mu\text{W} + 35.5\ \mu\text{W}) \times 100 = 0.9\%$. The photometric weights of the wavelengths used are 23.2% for red, 75.0% for green and 1.8% for blue (RGB: 643 nm, 530 nm and 446 nm respectively). The photometric crosstalk ratio is the ratio of undesired light to desired light for a particular state of the rotator and for a particular eye [23]. For example with the rotator in the "ON" state and the left eye polarizer, the photometric crosstalk ratio is $1.11\ \mu\text{W} \times 0.75/(82\ \mu\text{W} \times 0.23 + 35.5\ \mu\text{W} \times 0.02) \times 100 = 4.0\%$. Table VI presents the full set of calculated crosstalk ratios.

From Table VI, the average crosstalk level for left eye during the operation can be calculated as follows: The unintended luminance using photometric weights is $(8.48\ \mu\text{W} \times 0.23 + 1.11\ \mu\text{W} \times 0.75 + 0.47\ \mu\text{W} \times 0.02 = 2.79\ \mu\text{W}$. The intended luminance using photometric weights is $(82\ \mu\text{W} \times 0.23 + 59.7\ \mu\text{W} \times 0.75 + 35.5\ \mu\text{W} \times 0.02) = 64.35\ \mu\text{W}$ and finally the ratio between the unintended luminance and the intended luminance is the calculated crosstalk value for left eye which is $2.79\ \mu\text{W}/64.35\ \mu\text{W} \times 100 = 4.3\%$. Similarly, the crosstalk value for the right eye during operation was calculated as 5.4%. In [24] it is stated that the image distortions caused by crosstalk percentages up to 5% are hardly noticeable and the same source suggested that ideally the designers should keep the crosstalk below 2%. Additionally, [25] suggested that the most of the depth perception is maintained at crosstalk levels below 4%.

The power of red in the "ON" state and the "OFF" state for left eye was 82 and 8.48 μW, respectively. Therefore, the contrast ratio of this case can be defined as 10:1. Using this approach, the contrast ratios for each color channel are shown in Table VII.

The prepared test benches both in Microvision and in Koç University was viewed by many testers (>100 people) and all of the testers have stated that the quality level of the stereoscopic display is good and satisfactory.

V. POLARIZATION MAINTAINING SURFACES

We also performed experiments comparing various surfaces for their polarization-maintaining properties. Sometimes people have the mistaken impression that the polarization-maintaining "silver screen" for observing 3D is expensive. Here, we demonstrate that this need not be the case. Different surfaces such as micro lens array screen, duct tape, a commercial silver screen and metallic laptop surface were illuminated with linearly polarized light (using a single color channel of the pico projector), see Fig. 9(b). Another photograph as in Fig. 9(c) is taken with a linear polarizer in front of the camera which is orthogonal to the polarization state of the illumination source. Illumination values of the cases in Fig. 9 are tabulated in Table VIII. A "zoomed out" version of Fig. 9(b) can be seen in Fig. 9(a). As seen in Fig. 9, duct tape, silver screen and metallic laptop surface are suitable for this technique. Likewise, one can also use non-scattering surfaces such as micro lens array based beam expanders, which are also polarization maintaining [27]. There are a number of options for back projection polarization maintaining screens as well.

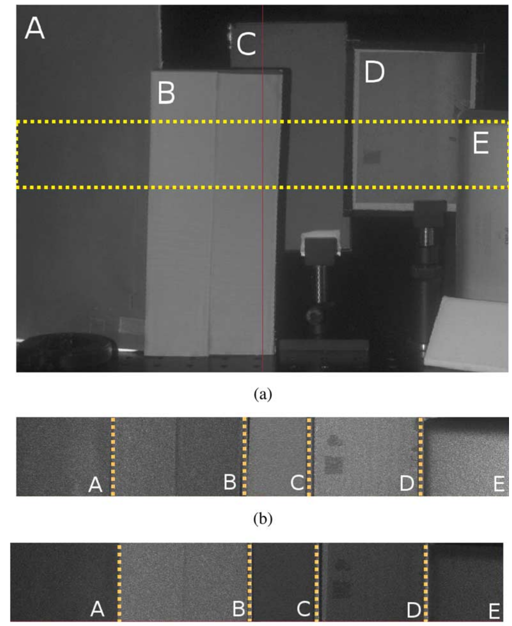


Fig. 9. (a) A photograph of surfaces, region of interest is shown (A: Silver Screen; B: Duct tape; C: New generation micro lens array screen from Microvision; D: Old generation micro lens array screen from Microvision; E: Surface of a tablet computer (Apple iPad). (b) Sample regions from a photograph of the illuminated surfaces. (c) Sample regions from a photograph of the illuminated surfaces with a cross polarizer in front of the camera.

TABLE VIII
MEASURED BRIGHTNESS (CD/M^2) OF THE REGION OF INTERESTS SHOWN IN FIG. 9

	A	B	C	D	E
Figure 9b	4.936	14.166	9.546	12.532	11.891
Figure 9c	0.545	1.961	0.590	0.673	0.598
Ratios	10	7	20	20	20

VI. CONCLUSION

We have successfully demonstrated a novel glasses-type stereoscopic pico projector based projection display with an active polarization rotator. The prototype operates on source 3D content with a display refresh rate value of 60 Hz without any noticeable flicker effect. It was also demonstrated that there are several usable surfaces such as micro lens array screens, silver screens and even duct tape or the surface of a tablet computer. In other words, with a little creativity, one can find suitable surfaces for polarization-based 3D display in everyday environments. As conventional stereoscopic content cannot be used directly in this approach, a script was written for on the fly conversion and off-line conversion of the video. The average crosstalk level is measured as 4.3% for left eye and 5.4% for right eye. Viewers generally agreed that the current level of crosstalk did not degrade the 3D experience. The techniques and hardware described in this paper can easily be incorporated into the pico projector engine. This new approach opens a path for displaying and sharing 3D content with a mobile device.

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Kaan Akşit received the B.S. degree in electrical engineering from Istanbul Technical University (ITU), Turkey in 2007, the M.Sc. degree in electrical power engineering from RWTH Aachen University, Germany, in 2010, and is currently working toward the Ph.D. degree in electrical engineering at Koç University, Turkey.

Since the summer of 2010, he has been with the Optical Microsystems Laboratory, under Dr. Urey's guidance, at Koç University, where he works in High Efficiency Laser based Multi user multi modal 3D display (HELIUM3D) project, funded through the European Commission Seventh Framework Programme (EC-FP7). In 2009, under Dr. Cennini's guidance, he joined visual experiences group at Philips' research center, the Netherlands, to complete his master thesis.

Mr. Akşit was a key member of ITU's solar car team in 2006 and 2007, the team won several trophies including best design and first place at the Scientific and Technical Research Council of Turkey's (TÜBİTAK) solar car races.

Osman Eldes (S'11) received the B.S. degree in electrical and electronics engineering (with high-merit scholarship) from Koç University, Istanbul, Turkey, in 2012.

He is currently working at Optical Microsystems Laboratory at Koç University, Istanbul, Turkey, as an undergraduate researcher since February 2010. He works on High Efficiency Laser based Multi user multi modal 3D display (HELIUM3D) project of European Commission Seventh Framework Programme (EC-FP7). In summer of 2011, he has worked as intern at Microvision Inc., Redmond, WA.

Mr. Eldes is a member of SPIE.

Selvan Viswanathen (M'99–SM'11) received the B.E. in electronics and communications from Mangalore University, India, in 1994 and the M.S. in electrical engineering from the University of Southern California, Los Angeles in 1997.

He is currently the Systems Lead for Advanced Applications at Microvision, Redmond, WA. He has several pending patents and published conference papers and has also conducted workshops and presented invited topics at various industry events. He has previously held senior technical roles in startups developing Optical Switches and Broadband Loop Carriers and has also served in leadership roles in starting up and leading technology development at off-shore design centers in India. As a research assistant during his graduate program, he was also the lead designer on a DARPA funded project to develop a CMOS-based MEMS micro-robotic array. His current areas of research interest include user interfaces and usability models of Pico Projectors.

Mark Freeman received the B.Phys. degree (with High Distinction) from the University of Minnesota, in 1977, the M.S.E.E. degree from the University of Illinois, in 1979, and the Ph.D. degree from the University of Wisconsin, in 1988.

He is currently the Director of Advanced Development and Head-Up Displays at Microvision, Inc., Redmond, WA. During his career, he has also worked at the Industrial Technology Research Institute (ITRI Labs) in Taiwan, developing pickup-head technologies for optical disk drives, served as the Taiwan Technology Analyst for the Asian Technology Information Program (ATIP), served on the faculty at the University of Colorado researching optical signal processing technology, and worked at the General Electric Corporate Research Laboratories, Schenectady, NY. He has published upwards of 50 research papers and has about 40 issued patents in the U.S. and Taiwan.

Hakan Urey (M'92—SM'09) received the B.S. degree from Middle East Technical University, Ankara, Turkey, in 1992, and the M.S. and Ph.D. degrees from Georgia Institute of Technology, Atlanta, in 1996 and 1997, all in electrical engineering.

He is currently Professor of Electrical Engineering at Koç University, Istanbul, Turkey. After completing his Ph.D., he joined Microvision Inc., Seattle as Research Engineer and he played a key role in the development of the scanning display technologies. He was the Principal System Engineer when he left Microvision in 2001 to join the department of Electrical and Electronics Engineering at Koç University, where he established the Optical Microsystems Research Laboratory (OML). He has published more than 40 journal and more than 100 conference papers, six edited books, four book chapters, and he has 23 issued and several pending patents. His research interests are in MEMS, micro-optics, MOEMS system design, and laser based 2D/3D display and imaging systems.

Dr. Urey received the Werner Von Siemens Faculty Excellence Award in 2006 from Koç University, Distinguished Young Scientist award from the Turkish Academy of Sciences in 2007, and the Encouragement Award from the Scientific and Technical Research Council of Turkey (TÜBİTAK) in 2009. He is a member of SPIE, OSA, IEEE Photonics Society, and the vice-president of the Turkey chapter of IEEE Photonics Society.