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Light Field Modulation Using A Double-Lenticular Liquid Crystal Panel

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Abstract

The ultimate goal of constructing an autostereoscopic display is to reproduce exact light fields of 3D scenes on the display's surface. However, most existing autostereoscopic displays can only reproduce inexact light fields. Filling the gap between them has been a major target of research.

In this paper, we present a light field modulator consisting of a liquid crystal panel, a light diffuser, and a pair of lenticular sheets. The modulator will modify the intensity of light passing through it. When combined with a color filter, the modulator can also modify the color tone. Since the modification depends on the light's propagation direction, the modulator can be tuned to improve the quality of the light field from being inexact to being nearly exact.

To further investigate the modulator's capability, we put it in front of a multilayer display. The light fields reproduced by a multilayer display are only approximate especially when the display is tailored to cover a wide viewing zone. We observe that the modulator can mitigate the occurrence of artifacts in the outputted light fields. We also observe that monochromatic fields can be converted into color fields using the modulator.

Introduction

Modulation is a common technology frequently employed in signal processing. It usually refers to the process of changing some properties of periodic waveforms such as light, electric, and acoustic signals. In 3D display research, holographic displays use spatial light modulators (SLMs), which modify the phase and amplitude of light emitted from a coherent light source[1]. If we think of modulators as the devices that slightly change the status of propagating media, not necessarily limited to waveforms, many optical components fall into this category. For example, refractive elements, such as micro-lens arrays or lenticular sheets, can be viewed as modulators, which change the direction of light propagation. Liquid crystal panels change the amplitude of light, which is also an example of modulation. We will combine such components to construct modulators that correct and improve the quality of light fields emitted from autostereoscopic displays.

One of the ultimate goals of autostereoscopic display research is to construct display devices that exactly reproduce the light fields of 3D scenes[2]. Existing autosterescopic displays are known to reproduce only approximate or inexact light fields. In order to fill the gap between exact and inexact fields, we propose to combine a liquid crystal (LC) panel, a light diffuser, and a pair of lenticular sheets. This specific combination of optical components is called light field modulator, whose structure is similar to that of double-lenticular screen used in multi-projector displays[3]. The light field modulator can modify the intensity of light passing through the modulator. The modification can be done for each light's propagation direction, though the angular resolution of light field controllable by the modular is limited. Even if the modification achievable with a single modulator might be slight, it does contribute to incrementally updating and improving the quality of the light field, which will be demonstrated through simulation-based studies.

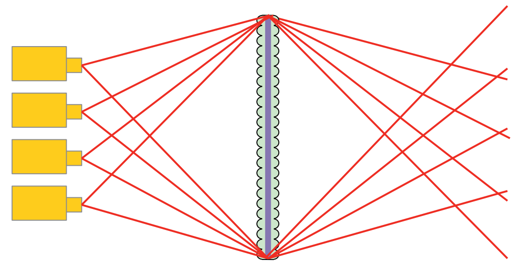

Figure 1. *Multiprojector display: A double-lenticular screen is used to transform the sparse light field produced by an array of projectors to a dense light field suitable for autostereoscopic viewing.*

The proposed modulator can work cooperatively with computational displays such as multilayer displays. When a light field modulator containing a color LC panel is used in conjunction with a monochromatic multilayer display, the monochromatic light field emitted from the display will be converted into a color light field. We will also show successful or nearly successful examples of such conversion.

Construction of Light Field Modulators

In signal processing, modulation is the process of varying one or more properties of a periodic waveform called the carrier signal, with a modulating signal that typically contains information to be transmitted. Depending on the types of varying process, modulation is usually classified into amplitude modulation, frequency modulation, phase modulation, and polarization modulation. Here we construct a device, called light field modulator, that enables us to modulate the amplitude of light fields. The device contains a liquid crystal panel as its component, which also changes the phase and polarization state of light that passes through the panel. However, for the simplicity of explanation, we will not discuss such aspects of modulation in this paper.

Components of Light Field Modulators

In designing light field modulators, we are inspired by existing autostereoscopic displays called multiprojector displays. As shown in Figure 1, a multiprojector display consists of an array of projectors and a double-lenticular screen. The double-lenticular screen is constructed by sandwiching a light diffuser with a pair

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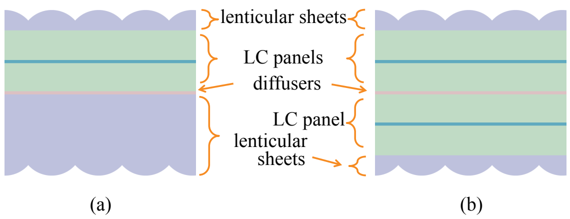

Figure 2. *Two variations of light field modulators : (a) modulator with 1 LC (liquid crystal) panel, (b) modulator with 2 LC panels.*

of lenticular sheets[4, 5]. The light emitted from the projectors is refracted and diffused by the double-lenticular screen. Referring to Figure 1, the light field on the right of the screen is dense, whereas the field on the left side is sparse. This sparse to dense transformation enables us to deliver autostereoscopic images to viewers looking at the screen from the right side.

We will slightly change the design of double-lenticular screen to construct light field modulators. By inserting a liquid crystal panel between the pair of lenticular sheets, the screen is now given the ability to control the intensity of light passing through the screen. The intensity control will be dependent on the direction of incident light since the lenticular sheets refract the light as in lenticular displays.

Variations of Light Field Modulators

Figure 2(a) provides a cross-sectional view of the proposed light field modulator. It consists of a liquid crystal (LC) panel, a light diffuser, and a pair of lenticular sheets. The LC panel is a thick component comprised of glass substrates and a LC layer. The light diffuser is a thin film. In Figure 2(a), the LC panel exists only on one side of the diffuser.

We may introduce an additional liquid crystal panel to the light field modulator. Figure 2(b) shows such a configuration of light field modulator, where two LC panels are attached to both sides of the diffuser. With an additional liquid crystal panel, more flexible control of directional light's intensity would become possible. However, the flexibility is obtained at the expense of reduced light intensity since LC panels will block some portion of light.

These two configurations of modulators are compared with each other in the simulations to be explained in later sections.

Optics of Light Field Modulators

Figure 3 illustrates the optical characteristics of light field modulators. Here we discuss two typical cases. In both cases, rays of light coming from the top are refracted, diffused, and refracted at boundaries of lenticular sheets and diffusers. The major difference between cases (a) and (b) is on how the diffusers change the directions of rays. In case (a), the diffuser slightly changes the rays' directions; the directions of diffused rays are limited within a narrow range, and after being refracted by the lower lenticular sheet, these rays form another set of parallel rays. In contrast, in case (b) the diffuser abruptly changes the rays' directions; the diffused rays spread so wide that even after being refracted by the lower lenticular sheet, these rays still continue to spread. The

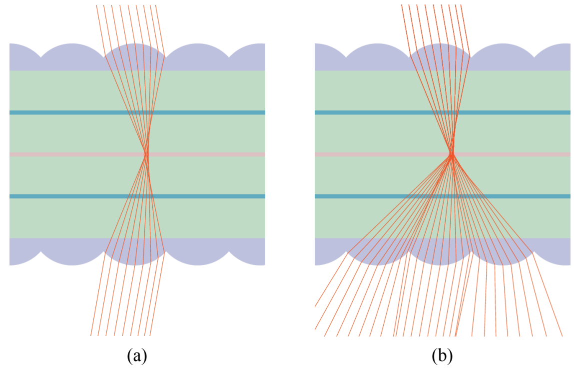

Figure 3. *Parallel rays of light passing through the modulators. Two typical cases are shown here, where (a) directions of diffused rays are limited in a narrow range, (b) diffused rays spread wide.*

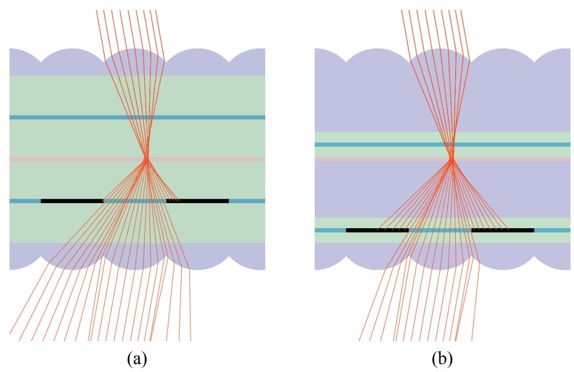

Figure 4. *The lower LC panels are used as light shutters. Black portions in the LC layers will block light, which contribute to narrowing the directions of light rays. Thick LC panels (a) are less effective than thin LC panels (b).*

spreading of light will lead to an undesirable phenomenon such as excessive blur[6].

It is important to choose appropriate diffusers in constructing light field modulators. One could preferably customize the diffuser in accordance to the lens pitch and focal length of lenticular sheets. Alternatively, one could also consider using the liquid crystal panels as light shutters. The latter method is illustrated in Figure 4, where black portions in lower LC layers will block spreading light thus narrowing light's propagation directions. How effective the shutters work depend on the thickness of LC panels incorporated in the modulators. Apparently thin panels produce better results than thick panels. However, such panels are so fragile that they are not always available.

Using Light Field Modulators

The proposed light field modulators are simple extensions of double-lenticular screens. These can be placed in front of autostereoscopic displays to slightly modify the light fields emitted from the displays. However, it should be noticed that light field modulators cannot be made "transparent". As shown in Figure 3, pairs of lenticular sheets change the light's propagation direction regardless of the pixels' status in LC panels. Pixels in LC panels can only control the directional intensity of the light fields emitted

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from autostereoscopic displays.

For the light field modulators to work properly, it is therefore necessary to coordinate the roles of autostereoscopic displays and light field modulators. The following pseudo code roughly describes how such coordination could be done. Here $D[x]$ and $M[y]$ are functions representing the transformations of light passing through an autostereoscopic display and a light field modulator. These functions depend on parameters x and y. The combination of two functions $M[y](D[x](R))$ represents the light field emitted from the modulator, which should be as close as possible to the light field L given as input. This pseudo code will be used in the next section, where combinations of light field modulators and multilayer displays are to be studied.

Procedure 1 Given the light field L to display and the light source R, optimize the parameters of autostereoscopic display $D[x]$ and light field modulator $M[y]$.

$x \leftarrow 0$ (initialize)
$y \leftarrow 0$ (initialize)
repeat
  find y' such that $|M[y'](D[x](R)) - L|$ will be minimum
  $y \leftarrow y'$
  $L' \leftarrow M[y]^{-1}(L)$
  find x' such that $|D[x'](R) - L'|$ will be minimum
  $x \leftarrow x'$
until convergence

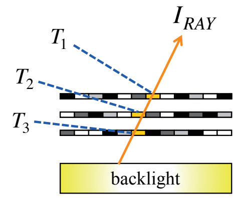
Light Field Modulators Combined with Multilayer Displays

To examine the capabilities of light field modulators, autostereoscopic displays must be prepared as the test beds. We will employ multilayer displays for this purpose since they are auto-stereoscopic and computational. The parameters of multilayer displays are determined only through computation, which in fact consists of a series of optimization procedures. Such displays will fit well with the computational framework described in Procedure 1.

Introduction to Multilayer Displays

A multilayer display is an autostereoscopic display constructed by stacking multiple liquid crystal panels on top of a light source[7]. Multilayer display is sometimes confusingly called light field display, as it emits approximate light fields from the its surface. The light source of multilayer display is usually omnidirectional. However one can combine directional light source with a multilayer display. Such a display is called tensor display, and can achieve better approximation to the given light field than ordinary multilayer display[8].

For a multilayer display to be autostereoscopic, a light field should be mapped to layers of panels. The mapping requires computation, and can be viewed as a kind of optimization problem, where pixels in panels act as variables, and light rays act as constraints. Referring to Figure 5, a constraint is generated for each ray in the light field, where I_{RAY} represents the intensity of the ray, and T_{123} represents the transmittance of pixels that the ray passes through. The number of constraints (i.e., rays) are usually much larger than the number of variables (i.e., pixels). An approximate



$$T_{123} = T_1 + T_2 + T_3 - c(T_1T_2 + T_2T_3 + T_3T_1)$$

$$I_{RAY} = T_{123}\, I_{BACKLIGHT}$$

Figure 5. *Multilayer display: The relationships between pixels' transmittance and light field form a large set of simultaneous equations, whose solution is sought using a numerical method.*

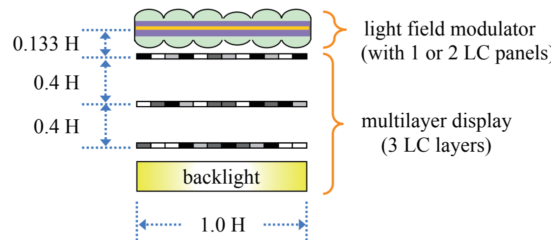
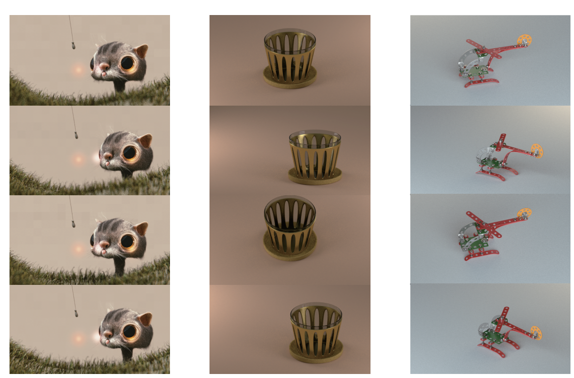


Figure 6. *Combination of a multilayer display and a light field modulator used in simulations.*

solution satisfying these constraints is computed by applying numerical methods.

Simulation Setups

The capabilities of light field modulators are evaluated using a multilayer display. As shown in Figure 6, the multilayer display consists of 3 liquid crystal layers and an omnidirectional backlight. Each layer has 640×480 square pixels, and each pixel can be further decomposed into 3 sub-pixels. The separation between layers is $0.4H$, where H represents the width of the layer. As for the light field modulator, we will test two types of modulators; one with 1 LC layer, and the other with 2 LC layers. The resolution of LC layers in the modulators is also 640×480. The lens pitch of lenticular sheets is 2 pixels wide, i.e., 6 horizontally aligned sub-pixels are covered by each lenslet in the sheets.



(a) (b) (c)

Figure 7. *Light fields used for the simulation. 4 representative images are shown for each field: (a) cat, (b) glass, and (c) helicopter.*

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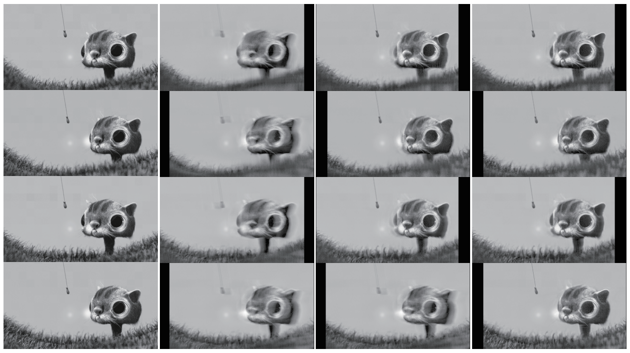


(a) (b) (c) (d)

Figure 8. *Simulation results for the "cat" scene: (a) exact views, (b) multilayer display, (c) multilayer display and modulator (1 LCD panel), and (d) multilayer display and modulator (2 LCD panels).*

Light fields of 3 sample scenes are mapped onto the combination of multilayer display and light field modulator. The representative images are shown in Figure 7. Each light field consists of 117 images representing the parallel projections of a 3D scene. The directions of projection is restricted within the ranges $-6^\circ \sim +6^\circ$ (horizontally), and $-4^\circ \sim +4^\circ$ (vertically).

(a) (b) (c) (d)

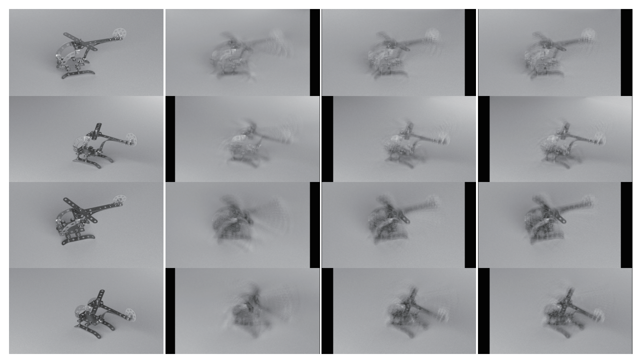
Figure 9. *Simulation results for the "glass" scene: (a) exact views, (b) multilayer display, (c) multilayer display and modulator (1 LCD panel), and (d) multilayer display and modulator (2 LCD panels).*

Based on these setups, we have conducted 2 types of simulations. The aim of the first simulation is to test whether the spatial resolution of light fields emitted from the display is improved by the addition of a light field modulator. This test is done with monochromatic light fields. In the second simulation, on the other hand, monochromatic light fields are converted into color fields using a light field modulator. For this purpose, color filters are attached to the liquid crystal panels in the modulator. While the light fields emitted from the multilayer display is monochromatic, after passing through the color filters in the modulator, color light fields are generated.

Simulation 1: Improving Spatial Resolution of Light Fields

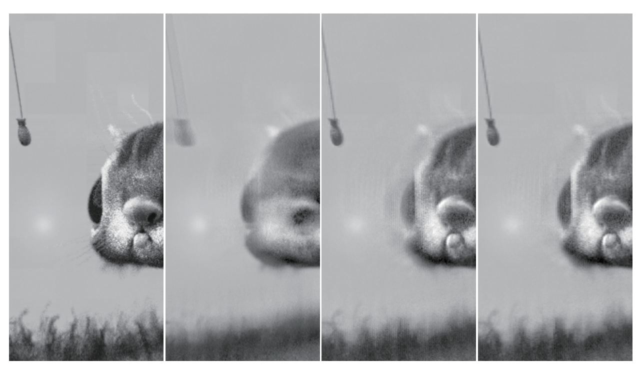
Figures 8-10 show the results of simulation using monochromatic light fields. In all these figures, (a) corresponds to the exact views of 3D scenes, (b) to the views from the multilayer display (without any modulators), (c) to the views from the combination of multilayer display and modulator with one LC panel, and (d) to the views from the combination of multilayer display and modulator with two LC panels. Looking at the images in Figure 8(b), for example, degeneration from the exact views in Figure 8(a) is observable. These images are apparently blurred; artifacts are also visible in these images. The images in Figure 8(c) are sharper than those in Figure 8(d); slight differences are still observable between Figure 8(a) and Figure 8(c), but they are very close to each other. The images in Figure 8(d) look almost the same as those in Figure 8(b) at this scale, but if we check the magnified views shown in Figure 11, we notice that the occurrence of artifacts is reduced in Figure 11(d).

Comparing the images in Figure 8 and Figure 9, we find that the overall image quality is lower in Figure 9. It seems to indicate that the "glass" scene is more difficult to display than the "cat"



(a) (b) (c) (d)

Figure 10. *Simulation results for the "helicopter" scene: (a) exact views, (b) multilayer display, (c) multilayer display and modulator (1 LCD panel), and (d) multilayer display and modulator (2 LCD panels).*



(a) (b) (c) (d)

Figure 11. *Magnified views of simulation results for the "cat" scene: (a) exact views, (b) multilayer display, (c) multilayer display and modulator (1 LCD panel), and (d) multilayer display and modulator (2 LCD panels).*

scene. Nevertheless, we notice some quality improvement in images shown in Figure 9(c) and Figure 9(d) from those in Figure 9(b). Such improvement is less observable in Figure 10, where even with the assistance of light field modulators, views from the display are significantly blurred.

Simulation 2: Converting Monochromatic Fields into Color Fields

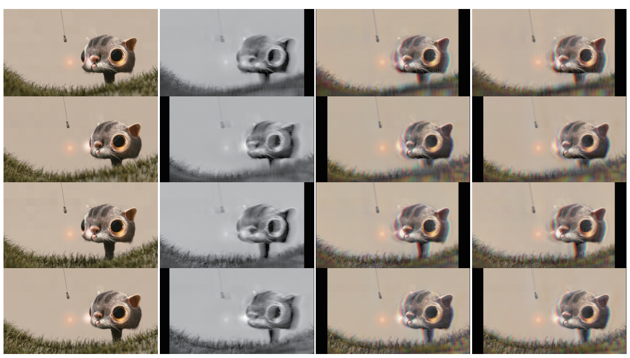
Figures 12-14 show the results of simulation using color light fields. As before, images labelled (a) corresponds to the exact views of 3D scenes, (b) to the views from the multilayer display (without any modulators), (c) to the views from the combination of multilayer display and modulator with one LC panel, and (d) to the views from the combination of multilayer display and modulator with two LC panels. Since the multilayer display used for this simulation monochromatic, it produces only gray views. Images shown in Figures 12(b)-14(b) are the same as those in Figures 8(b)-10(b).

The monochromatic light fields emitted from the multilayer display is colored by the light field modulators. An successful example of coloring can be seen in Figure 12, where images in Figure 12(c) and Figure 12(d) convey the color tone shown in Figure 12(a). Looking at the magnified views shown in Figure 15, we notice that artifacts are visible in Figure 15(c) and Figure 15(d). The difference between Figure 15(c) and Figure 15(d) looks small.

Turning out attention to Figures 13 and 14, we find that colored views in (c) and (d) are more degenerated than the corresponding gray views shown in Figures 9 and 10. The degeneration could be accounted for by the fact that the effective resolution of LC panels in the modulator is reduced by the introduction of color filters.

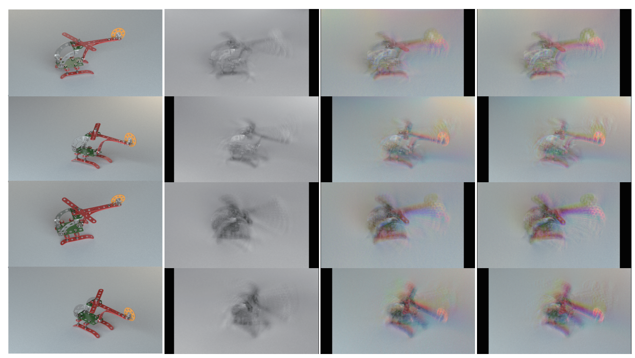
Concluding Remarks

In this paper, we proposed light field modulators consisting of a light diffuser, and (one or two) liquid crystal panels, and a pair of lenticular sheets. The modulators can modify the intensity of light fields in a direction-dependent manner. Simulation-based studies have shown that such modulators could be used for improving the spatial resolution of the light fields emitted from autostereoscopic displays. In our experience, the occurrence of artifacts in the light fields is reduced by adopting the modulators. When color liquid crystal panels are incorporated into the mod-



(a) (b) (c) (d)

Figure 12. Simulation results for the "cat" scene: (a) exact views, (b) multilayer display, (c) multilayer display and modulator (1 LCD panel), and (d) multilayer display and modulator (2 LCD panels).

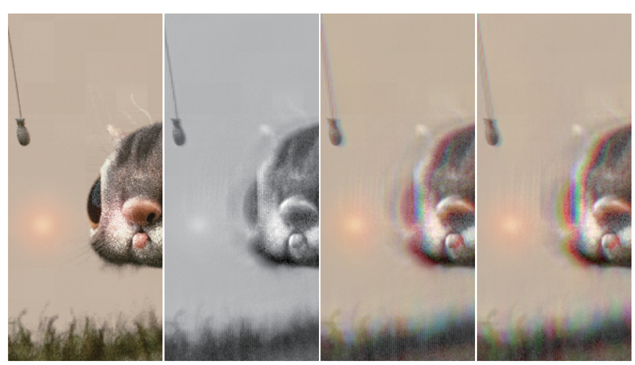


(a) (b) (c) (d)

Figure 14. Simulation results for the "helicopter" scene: (a) exact views, (b) multilayer display, (c) multilayer display and modulator (1 LCD panel), and (d) multilayer display and modulator (2 LCD panels).

(a) (b) (c) (d)

Figure 13. Simulation results for the "glass" scene: (a) exact views, (b) multilayer display, (c) multilayer display and modulator (1 LCD panel), and (d) multilayer display and modulator (2 LCD panels).



(a) (b) (c) (d)

Figure 15. Magnified views of simulation results for the "cat" scene: (a) exact views, (b) multilayer display, (c) multilayer display and modulator (1 LCD panel), and (d) multilayer display and modulator (2 LCD panels).

ulators, monochromatic light fields can be converted into color fields with the assistance of the modulators.

We have not constructed physical implementations of proposed modulators. This is left for future research. Improving the performance of modulators by mitigating aliasing phenomena is also an important issue. Another interesting directions to proceed is to investigate various combinations of modulators and autostereoscopic displays. There are many types of autostereoscopic displays other than multilayer displays. Finally, the proposed light field modulators can be extended using microlens arrays. This extension will provide greater degree of flexibility in combining the modulators with autosterescopic displays.

Acknowledgments

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Author Biography

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