Research Trends on Holographic 3D Display Devices

Display devices with a huge number of pixels and a fine pixel-pitch will be needed for three-dimensional (3D) television (TV) to display a more natural 3D images without requiring the viewer to wear special glasses. One such device that our laboratory is conducting research on is a holographic device called a spatial light modulator (SLM). In this article, we discuss the performance requirements for a holographic 3D display, the current trends in SLM research, and our research on new SLMs.

1. Introduction

Ultra-high definition TV such as 8K Super Hi-Vision (8K) provides a sense of reality and presence not available with current forms of TV, by making it seem as though the viewer is “actually there” or objects are actually right in front of them. The beginning of 8K test broadcasting in 2016 is approaching, and developments are advancing at a rapid pace toward full deployment in 2018. Farther into the future, 3D TV will likely be the successor to 8K, and promises new levels of realism; in particular, we have high hopes for spatial 3D imaging technology, which displays natural 3D images without requiring special glasses. In fact, we are engaged in R&D on new devices that display holographic 3D images.

Art museums and exhibitions already feature 3D photographs and artwork that appear to float in air. These images are holograms, -from the Greek “holos,” meaning whole-, which is a 3D display technique that allows the light wave-fronts scattered from an object to be recorded and later reconstructed so that an imaging system (an eye or a camera) can see 3D image of the object. Holography has a long history. It was invented in 1948 by D. Gabor as a way of improving the resolution of electron microscopy, but together with the invention of lasers, it has greatly expanded the field of optics. Currently, it is used for displaying art work like those described above and in the optical components of CD and DVD players. Holograms are also widely used to prevent forgery of familiar items such as paper money and credit cards. The holographic images also contain no inconsistencies related to focal accommodation, binocular parallax or convergence of the eyes. For these reasons, holography is said to be the ultimate 3D display technology.

The basic principles of holography are discussed in the article, “Research Trends in Spatial Imaging 3D Video,” in this issue.

2. Holographic 3D Display Devices: SLM

A normal hologram is a recording of an interference pattern of light scattered from the object and so-called reference beam, and it replays a static image with all the characteristics of light waves, including phase, amplitude, and wavelength going through the recording medium. To display moving images, an electronic display device capable of changing the interference pattern in real time is needed. A spatial light modulator (SLM) is the key component to such a display. Furthermore, we call the display of 3D images using SLMs “electronic holography.”

2.1 Performance Requirements for SLM

To display 3D moving images, the main performance requirements of the SLM are as follows.

i. fine pixel pitch
ii. huge number of pixel (large size)
iii. high-speed response
iv. low power consumption
v. compact (thin and lightweight)

The pixel pitch of the SLM must be sufficiently smaller than the wavelength, \( \lambda \), of visible light. The viewing-zone angle, \( \psi \), which determines the range of angle through which the reproduced image can be viewed, can be calculated from the maximum diffraction angle, \( \phi \), of the SLM. The smallest interference pattern that can be displayed by an SLM with a pixel pitch \( p \) has a pattern cycle of two pixels, or \( 2p \). The relationship between the viewing-zone angle, \( \psi \), maximum diffraction angle, \( \phi \), and pixel pitch, \( p \), is given by the following equation.

\[
\psi = 2\phi = 2 \sin^{-1} \frac{\lambda}{2p}
\]

Equation (1) shows that the object light can be reproduced within an angle of \( 2 \phi \) from the center, which is the direction of propagation of the reference beam. To reproduce 3D images at an angle smaller than \( \phi \), the intervals in the interference pattern can be widened on the SLM. Figure 1 shows the relationship between viewing-
zone angle and pixel pitch calculated from Equation (1). Here, we see that for practical angles of 30° or more, the pixel pitch must be 1.2 μm or less*. Hologram recording materials normally have very high resolution of at least 1000 lines/mm and can produce pixel pitches of 1 μm or less, so they can display 3D images viewable over a wide angle (See also section 2.2 regarding the LCOS and DMD in Figure 1).

3D displays must be able to show images that are big enough for the intended purpose, and this means the SLMs must have a huge number of pixels (and cover a large area). Thus, a common issue for all holographic display devices is that they must simultaneously have a narrow pixel pitch (or high resolution) for a wide viewing-zone angle and many pixels for a large-enough image. For example, a 1-μm pixel pitch means there are 1,000 pixels per mm. A 2-mm-square SLM would thus have as many pixels as two high-definition screens, while an 8-mm-square SLM would have as many pixels as two 8K screens. This illustrates that the features of SLMs for 3D displays will have to be extremely fine.

A way of supplying enough drive current for this extreme number of pixels must also be developed, and it must be slim, lightweight, and compact enough not to make the display bulky.

### 2.2 Features and Issues of SLMs for Holographic Display

SLMs can be divided into the following three types on the basis of how they write the information

i. Electrically addressed SLM: Information corresponding to the interference pattern in the form of an electrical signal is sent to and “written”, i.e., the SLM changes its characteristics in response, on the SLM.

ii. Optically addressed SLM: The information is written using a laser beam or is an optical image from a compact display device.

iii. Electron-beam-addressed SLM: The information is written using a scanning electron beam in a vacuum.

Figure 2 shows three different types of SLM for electronic holography, and Table 1 lists the features and issues of each. Electrically addressed SLMs (Figure 2(a)) use thin-film transistors (TFTs) or metal-oxide-semiconductor field-effect-transistors (MOS-FETs) to drive the SLM directly. Typical devices are liquid crystal SLMs and digital micro-mirror devices (DMD)*5.

The interference signal is input to these SLMs directly as a video signal, and 3D video can be produced simply by exposing the SLM to light. However, the pixel pitch of these SLMs is currently between 5 and 10 μm, which is not fine enough to display interference patterns at visible light wavelengths (Figure 1). Even when using liquid crystal on silicon (LCOS) technology,

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* For a wavelength, λ, of 640 nm.

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![Figure 1: Relationship between pixel pitch and viewing-zone angle (for light wavelength of 640 nm)](image)

### Table 1: Features and issues of major SLMs for electronic holography

<table>
<thead>
<tr>
<th>Type</th>
<th>Example device</th>
<th>Features</th>
<th>Issues</th>
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</thead>
<tbody>
<tr>
<td>Electronically addressed SLM</td>
<td>LCOS, DMD, etc.</td>
<td>- Electronic signal can be input directly</td>
<td>- Increasing resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Motion display possible</td>
<td>(current pixel pitch is 3.5-20 μm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Compact (small, lightweight)</td>
<td>- Increasing screen size</td>
</tr>
<tr>
<td>Optically addressed SLM</td>
<td>Organic photorefractive materials, etc.</td>
<td>- High resolution (1,000 lines/mm or greater)</td>
<td>- Equipment such as electronically addressed SLM is needed to form interference pattern, resulting in a large system.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Large-size</td>
<td>- Motion display</td>
</tr>
<tr>
<td>Electron-beam-addressed SLM</td>
<td>EBLSLM*, etc.</td>
<td>- Electronic signal can be input directly</td>
<td>- Increasing resolution (currently 80 lines/mm or less)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Motion display possible</td>
<td>- Large-size, because vacuum equipment is required</td>
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* Electron-beam-addressed SLM

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*5 An optical device with 10-μm-square micro-mirrors arranged in an array. Light can be switched ON and OFF by controlling the position of the mirrors.
the smallest pixel pitch is currently 4.8 μm \(^6\) and the visible field is only about 7.6°. Recently, an 8K LCOS \(^6\) was developed with 3.5-μm pixel pitch. While this display has a visible field of 10°, it is still insufficient for a practical display. Compared with hologram recording materials, electrically addressed SLMs have significant issues, including low resolution, resulting in a narrow viewing-zone angle that makes 3D viewing difficult, and conjugate light \(^7\), which interferes with the reproduced images. The advent of ultra-fine SLMs with very small pixels and pitches may resolve these issues.

Optically addressed SLMs (Figure 2(b)) use materials whose optical characteristics change when exposed to light, such as photo-refractive \(^8\) or photo-chromic \(^9\) materials. Recently, research has been particularly active on 3D displays using optically addressed SLMs made from organic photo-refractive materials. This type has very

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\(^6\) An optical device with liquid crystals for each pixel that are controlled by a drive voltage using MOS-FET switching transistors on a silicon substrate.

\(^7\) Light with phase rotated 180 degrees relative to that of the reproduced image.

\(^8\) A material that produces a space charge when exposed to light, and the space charge causes a local change in the refractive index due to electro-optical effects.

\(^9\) A material that undergoes a reversible change in color when exposed to light.
promising characteristics compared with electrically addressed SLMs. One is that it is easier to reach a resolution equivalent to that of hologram recording materials because the pixels are not separated. Another is that it is easier to scale the display area because the materials are simply coated on a substrate. The experiments have already been reported on using an optically addressed SLM and the holographic stereogram method\(^\text{10}\) to display static images on large-area displays\(^\text{7,8}\). A major issue with this approach is the method used to input and rewrite the interference pattern. Many experiments using electrically addressed SLMs to produce the interference pattern have been reported, but future developments will depend on whether the requisite number of pixels can be attained. Other issues include the need to supply a separate optical system for high-resolution writing and the resulting increase in system size. Finding a way of displaying video rather than just still images is also a major issue.

In electron-beam-addressed SLMs (Figure 2 (c)), a beam from an electron gun is modulated by an electrical write signal and conventional electro-optic crystals or oil film are used as the optical modulation material\(^\text{9-11}\). Experiments in which these devices displayed 2D images holographically have been reported\(^\text{9,10}\), but the resolution was inadequate, and the devices were bulky because the method only works in a vacuum.

3. Spin-SLM

We are conducting R&D on an SLM with a huge number of pixel and a fine pixel pitch of 1 μm or less, with the goal of achieving an ideal 3D video display with a wide viewing-zone angle. This new electrically addressed SLM is called a Spin-SLM\(^\text{12}\), and it is controlled with the magneto-optic effect\(^\text{11}\) and spin transfer switching\(^\text{12}\). It has greatly improved viewing characteristics relative to earlier devices.

3.1 Basic Structure and Features

The Spin-SLM basically consists of a pinned layer (ferromagnetic thin film), a spacer layer (non-magnetic thin film), and an light modulation layer (ferromagnetic thin film) between a lower electrode and an upper transparent electrode (Figure 3). The middle layer can be one of two types: a non-magnetic metallic thin film exhibiting giant gagneto-resistance (GMR) or a very thin insulator exhibiting tunnel magneto-resistance (TMR).

The Spin-SLM uses magnetic materials that give it a memory function, and it can be driven by a simple circuit. As shown in Figure 3, the direction of magnetization (up or down) of the light modulation layer is controlled by the direction of a pulse current. If linear polarized light is incident on the upper transparent electrode, the plane of polarization of the reflected light is rotated depending on the magnetization direction in the light modulation layer. This device holds great promise for realizing both ultra-fine pixels and high-speed response.

3.2 Development Status

Figure 4 illustrates the state of development of the Spin-SLM at our laboratory. Research began in 2010, with prototyping of a single sub-micron GMR-type element. In 2012, we prototyped a linear array passive-matrix drive\(^\text{13}\), GMR-type Spin-SLM with 1×10 pixels and a 1-μm pixel pitch and demonstrated spin transfer

\(^{10}\) A phenomenon whereby, when linearly polarized light is incident on a magnetized material, the reflected light is el- liptically polarized with an inclined major axis.

\(^{11}\) A technique that changes the direction of magnetization of a magnetic material by injecting electrons of a certain spin direction into it.

\(^{12}\) Operation by selecting plus and minus electrodes.

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Figure 3: Structure and operating principles of Spin-SLM
The GMR element of this SLM consisted of a pinned layer composed of layers of terbium-iron-cobalt (Tb-Fe-Co) alloy and Co-Fe alloy, a spacer layer of silver (Ag), and a light modulation layer of gadolinium and iron (Gd-Fe). Each pixel of the Spin-SLM is surrounded by an insulating layer, and spin transfer switching can be controlled without cross-talk affecting neighboring pixels.

As mentioned above, to display 3D moving image, the Spin-SLM needs to have a huge number of pixels. In 2012, R&D on the drive method shifted from the passive-matrix to an active-matrix (AM) driven method. Figure 5 shows the basic structure of the device. The optical modulation elements are layered on top of the drive element transistors for each pixel. As the pixel pitch of the AM spin SLM decreases, the transistor drive current decreases, and as a result, it uses TMR-type light modulating elements able to operate at low drive currents. The TMR elements replace the spacer layer of the GMR element with a magnesium-oxide (MgO) layer. The current density of spin-transfer-switching is 1.0 MA (10⁶ A/cm²), which is one tenth that of the GMR element. We have already prototyped a TMR spin SLM 2D-array structure (5×10 pixels, 5 μm pitch) and shown that individual pixels can be selected, and spin transfer switching and light modulation is possible on them. We are currently developing a device with a smaller pixel pitch and many more pixels.

3.3 3D Imaging Reconstruction Using a Ultra-high Definition Holography

To verify that a 3D holographic display can be built using a spin-SLM 2D array, we created a hologram (a magnetic hologram) by forming a fixed 2D pattern on the magneto-optic material used in the spin SLM, and tested 3D image reproduction over a wide viewing-zone angle (Figure 6). A computer generated hologram (CGH) was computed using a near-field approximation of Kirchoff-Fresnel diffraction in the Fresnel range.
As shown in Figure 6, the 3D object was the Japanese character, 「イ」, inscribed on two perpendicular surfaces. The hologram was 10 mm × 10 mm with 10K × 10K pixels (pitch-size was 1 μm), and the object was placed just 0.5 mm from the hologram surface. It was designed for a reference beam incident at a horizontal angle of 0° and elevation of 10°, and the 3D image was viewable within a range of 36.9°.

The 2D fixed pattern for the static hologram was formed by microfabrication of the magneto-optic thin film. The optical systems included a He-Ne laser (λ = 632.8 nm) and a CCD camera able to move in an arc centered on the hologram. The front of the object was defined to be 0° and photographs of the hologram over the range from 18° to the left to 18° to the right in an arc are shown in Figure 6. The narrow pixel pitch of 1 μm resulted in a wide enough field of view to display the large motion parallax, and 3D images can be viewed directly. The actual field of view was close to the computed value (36°), confirming that 3D images with a wide viewing angle can be reproduced. These results show that it will be possible to display 3D motion video with a wide visible field in the future if we can increase the number of pixels of the spin-SLM to the same range as the 10K × 10K magnetic hologram of this experiment.

4. Conclusion
This article described research on SLMs for electronic holography. It gave an overview of the required performance and features of major types of SLM and described current R&D on spin-SLMs that exploit spin transfer switching and magneto-optic effects. To date, an AM-driven TMR spin-SLM 2D array with a pixel pitch of 5 μm has been prototyped and its basic operation has been verified. However, a 3D motion display with a wide viewing-angle 3D object will require the development of an electronic device with many more pixels and an even finer pitch. In the future, we will focus on increasing the efficiency of spin transfer, reducing the drive current so we can soon develop a display with a finer pixel pitch and more pixels.

Some of the research on the spin SLM was conducted under contract with NICT as part of the “R&D on Ultra-realistic Communication Technologies using Innovative 3D Video Technologies” project. (Hiroshi Kikuchi)

References