Holographic video display based on guided-wave acousto-optic devices

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ABSTRACT

We introduce a new holo-video display architecture ("Mark III") developed at the MIT Media Laboratory. The goal of the Mark III project is to reduce the cost and size of a holo-video display, making it into an inexpensive peripheral to a standard desktop PC or game machine which can be driven by standard graphics chips. Our new system is based on lithium niobate guided-wave acousto-optic devices, which give twenty or more times the bandwidth of the tellurium dioxide bulk-wave acousto-optic modulators of our previous displays. The novel display architecture is particularly designed to eliminate the high-speed horizontal scanning mechanism that has traditionally limited the scalability of Scophony-style video displays. We describe the system architecture and the guided-wave device, explain how it is driven by a graphics chip, and present some early results.

Keywords: synthetic holography, 3-D display, holographic video, acousto-optic devices

1. INTRODUCTION

The fundamental engineering challenge in designing a holographic video display relates to achieving a high enough space-bandwidth product to meet the image size and view angle requirements for the viewer. A large view angle is possible only with very small diffraction fringes (and thus small pixels), while a large image translates to a large light modulator; therefore in simple terms what's necessary are a massive number of very small pixels. It is in some cases possible to use optics to trade off one of these for the other to some extent, for example by magnifying a display that is higher-resolution than needed, or by demagnifying a large modulator to get small enough effective pixel size, but passive optics can't simultaneously increase size and angle. Because of the practical limitations on devices that can currently be fabricated it is commonly necessary to use either or both of scanning (re-using a smaller device for more than one region of the image) or tiling (using multiple copies of a small device). See for example Sato, *et al.* [1] and Slinger, *et al.* [2]

Recent research in holographic video at the MIT Media Laboratory has added a new constraint to the design space. We are seeking to construct a display for consumers, which means that (unlike our earlier systems) the display must be at least standard television resolution, quiet, reliable, compact, manufacturable for at most a few hundred dollars, and capable of being driven by the graphics hardware of a PC or game console (rather than specialized hardware). A vast amount of 3-D visual data now exists, particularly in the gaming world (though most is rendered for 2-D viewing), and we feel that autostereoscopic or volumetric displays could easily take advantage of this resource if they could be manufactured inexpensively. The widespread adoption of such displays would also spark innovation in 3-D capture of real-world scenes.

In this paper we present a new display architecture that we feel is capable of meeting these requirements, and indeed solves a fundamental problem that has limited the Scophony video display architecture for over 70 years.

2. EARLIER ARCHITECTURES

The two earlier generations of displays at the MIT Media Laboratory were variations on a 2-D diffractive display architecture that dates from the 1930s, called the Scophony system.

2.1. Scophony

In a 2-D Scophony display, an electrical sinusoidal oscillation is converted to a compression wave which changes the index of refraction in some material and thus creates a sinusoidal phase grating. Amplitude-modulating this sinusoidal carrier with a video signal changes the amplitude of a diffracted beam of light; the latter is then scanned by rotating or oscillating mirrors to form a video image.[3]

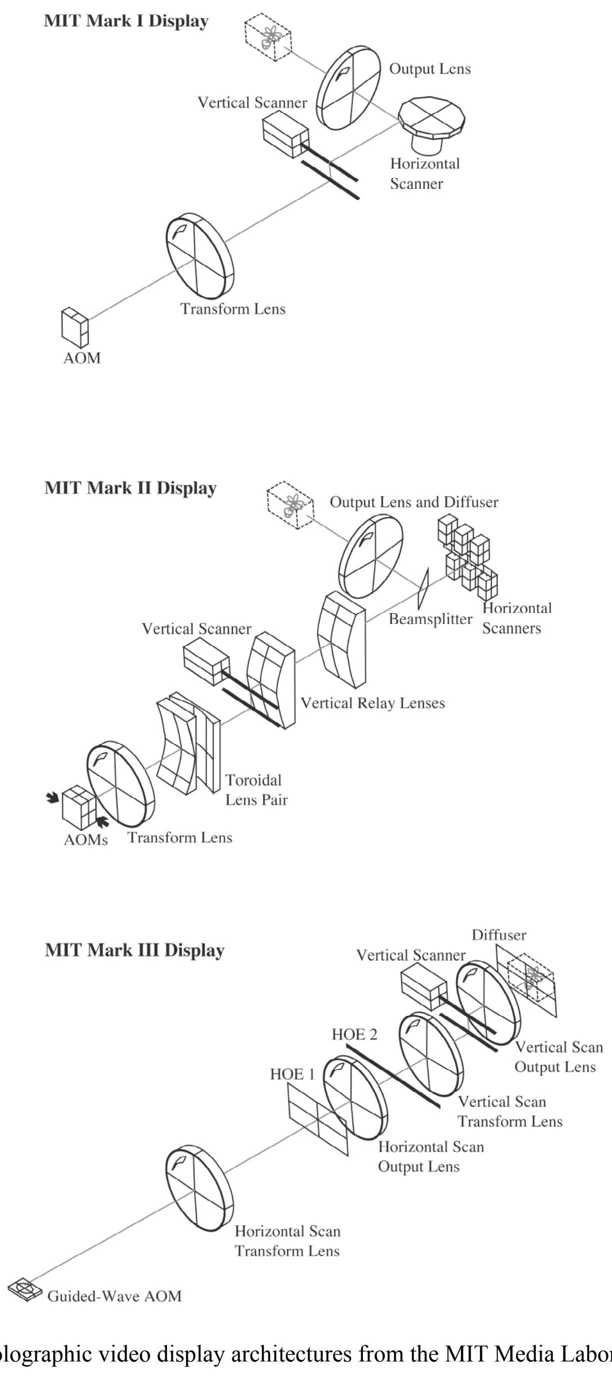

Fig. 1. Three generations of holographic video display architectures from the MIT Media Laboratory.

Besides the need for a monochromatic light source (to enable sharp focus) the major limitation of such a display system stems from the fact that the grating pattern is moving with the speed of sound through the diffractive material. To create a stable image, the diffracted light must be imaged in a mirror moving in the opposite direction, a requirement that makes scaling such a system difficult.

2.2. MIT Mark I

If a Scophony-type display is driven not with a single amplitude-modulated sinusoid but a superposition of many gratings at different frequencies it can output light in multiple directions. Then we can think about the output of the acousto-optic modulator (AOM) as one "holo-line" of a horizontal-parallax-only (HPO) holographic image.

The first-generation MIT display ("Mark I") (Figure 1) [4] was fundamentally a standard Scophony architecture, with a 50 MHz bandwidth TeO_2 AOM driven by a 32,768 x 192 raster; the video signal was multiplied by a 100 MHz sinusoid and lowpass filtered to retain the lower sideband. The view volume was 25 mm × 25 mm × 25 mm (W × H × D) and the view angle 15°. The vertical scanner was a galvanometer and the horizontal scanner a polygonal mirror. A Thinking Machines CM2 performed the computation.

2.3. MIT Mark II

In order to scale up the image size such that both a viewer's eyes could fit into the view zone with some added look-around, St.-Hilaire *et al.* increased the space-bandwidth product of the system by using 18 TeO_2 AOM channels in parallel, and thus outputting a group of 18 adjacent scan lines.[5] The vertical scanner then moved in 18-line steps to scan out 144 lines, each having 262,144 samples. The view volume was 150 mm × 75 mm × 150 mm and the view angle 30°. Because of the difficulty of making a single horizontal scanner wide enough to meet the requirements, Mark II used a synchronized linear array of galvanometric scanners. The 18 video channels were initially generated by a compact dataflow computer called Cheops,[6] and in later work the display was driven by three dual-output PC video cards.[7]

The use of parallel AOMs and a segmented horizontal scanner gave Mark II a modular character that was intended to allow scale-up of the system, admittedly at the expense of more video input channels and more synchronized mirror-drive circuitry.

3. THE MIT MARK III ARCHITECTURE

3.1. Proof-of-concept system

Because of the modular architecture of Mark II, it is easy to see how one might scale that system to allow very large view volumes. But the system is already physically large (about the size of a dining table top) and expensive, so in thinking about how to make a higher-quality display we have departed from a direct extrapolation of Mark II's design and instead sought to center our new display on a single, inexpensive, very high bandwidth light modulator, and a novel optical design that eliminates the horizontal mirror and as many optical elements as possible.

We have undertaken construction of a first version of a complete, packaged monochrome display system that is capable of being driven by one (dual-output) PC video card. The target specifications for the first system are:

- 440 scan lines, 30 Hz
- 24° view angle
- 80 mm × 60 mm × 80 mm (W × H × D) view volume
- approximately 1.5 m total optical path length, folded to fit into a relatively shallow box

We anticipate further generations of this design that will increase the view volume and view angle, and add full color.

3.2. Guided-wave light modulator

A light-modulation technology that appears to us to be particularly suitable for our purposes is the guided-wave acousto-optic modulator, which we will refer to as a guided-wave scanner (GWS).[8] Such a device is easily made from a slab of $LiNbO_3$ that has been acid-treated to create a subsurface waveguide through proton exchange, and then patterned on the surface with aluminum transducers. Yet this simple device – which we believe could be produced in quantity at prices approaching those of the rather similar surface acoustic wave (SAW) devices currently on the market

for a few dollars – can have over 1 GHz of usable bandwidth, can diffract light along two axes,[9] and can rotate the polarization of the diffracted light so that the undiffracted portion can be blocked with a polarizer. Although the vertical diffraction angle available is perhaps too small to be usable for the vertical scanning of a video display, we propose to apply it in conjunction with holographic optical elements to solve the horizontal scanning problem inherent in past Scophony-architecture displays. We provide details on this novel approach in the next section. The basic approach is also very likely to prove appropriate for compact and inexpensive 2-D video projection applications.

The guided-wave scanner is composed of two sets of aluminum, interdigital transducers which straddle a region of proton-exchanged lithium niobate. The scanner uses two sets of transducers to create surface acoustic waves that first deflect light horizontally, via Bragg diffraction, and then vertically by means of mode-conversion.

The device achieves Bragg diffraction through a set of five phased-array transducers which launch a holographic pattern of acoustic waves at the Bragg angle of the light traveling in the waveguide. Because these transducers each have several phase-shifted acoustic emitters, they are able to steer the acoustic pattern to meet the Bragg angle of light over an angular range corresponding to an acoustic bandwidth of 200 MHz per transducer.

A second set of simple (not-phased) transducers creates a pattern of sound waves that meets light traveling in the waveguide "head-on." Over a particular range of acoustic frequencies, this collinear interaction can "bump" the light into a leaky mode via polarization-rotating mode conversion. This leaky-mode light passes through the waveguide interface and finally exits from the edge of the substrate. This second, collinear interaction can be used to scan light vertically over an angle corresponding to approximately 70 MHz of acoustic bandwidth.

We construct the GWS by first proton exchanging a region of the $LiNbO_3$ substrate to create a surface waveguide and then patterning transducers. This proton exchange step is usually accomplished by masking the substrate with SiO_2, and then immersing the substrate in a >200° C melt of benzoic acid for a time period ranging from a few minutes to a few hours depending on the desired waveguide depth. In our case the substrate is immersed in a 250° C melt for 30 minutes for a waveguide depth of approximately 1 micron. Finally, we remove the SiO_2 mask and photolithographically place aluminum transducers on the proton exchanged $LiNbO_3$ substrate using a negative resist lift-off process.

Readers desiring more detail on our device fabrication process may find reference [10] of interest.

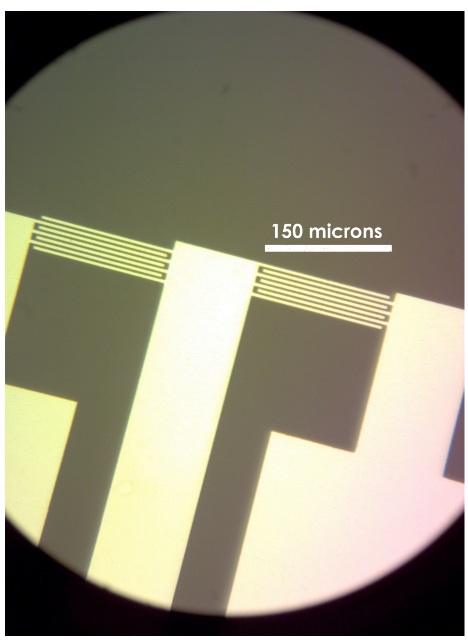

Fig. 2. Close-up of phased transducer on surface of guided-wave device.

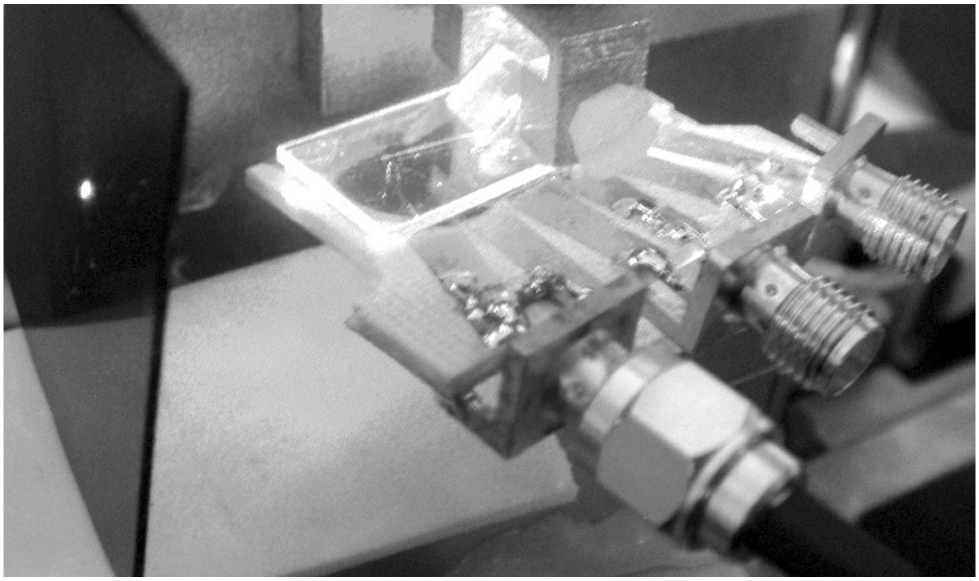

Fig. 3. Guided-wave device (center) undergoing testing.

3.3. Optical path

We have designed our initial system for operation with 510-532 nm semiconductor laser illumination. The requirement for the Mark III optical design is to place the diffracted light from the modulator at the correct position over time to present a proper display. The optics must scan the GWS aperture to produce a holo-line, un-do the motion of the diffraction pattern to render the holo-line stationary, demagnify the GWS aperture to create a wide field of view, and tile the holo-lines vertically to create a raster image.

The optics consists of a Bravais lens system, a modified telephoto Fourier transform system, two holographic optical elements (HOEs), a demagnifying transform lens, and a vertical scanning subsystem. The Bravais system magnifies the GWS's vertical scan angle while forcing the scan still to appear to come from the GWS location. The telephoto Fourier transform system converts the diffraction fringes' linear motion into rotational motion thereby allowing the fringes to be descanned later by an optical element that creates a reverse rotation. The telephoto system is modified to reduce the overall length of the optical path for efficient packaging of the system. The HOE works in conjunction with the GWS's vertical scan capability to make stationary the holographic fringes without using moving parts. The HOE simultaneously scans the GWS aperture, which is narrower than a full holo-line. The HOE is followed by a transform lens to convert the rotational scan of the GWS aperture into a linear motion to form a holo-line. The transform lens also magnifies the holo-line's field of view. A second HOE removes the vertical scan component introduced by the GWS's vertical scanner. The holo-line is then tiled vertically with a slow-moving galvanometer-based vertical scan subsystem to form a complete frame of holo-video.

The light emitted from the GWS first passes through a modified Bravais system to magnify the GWS's vertical scan angle 10X while forcing the scan to still appear to come from the GWS's position. As a consequence of this effect (and unlike in Mark II), the horizontal and vertical scans both appear to emanate from the same location and following optical elements can remain spherical rather than needing to be separate cylindrical lenses for each axis. The Bravais system is modified so the beam remains collimated.

The light then passes through the modified telephoto Fourier transform lens system. We used a telephoto arrangement with multiple elements since a single lens will not have a sufficient focal length. The telephoto arrangement also reduces the front focal distance and allows fine tuning of the focal length by adjusting the spacing between the telephoto elements. The telephoto system is modified so as also to reduce the back focal distance thereby reducing the overall length of the system.

The Mark III optics include novel HOEs that work in conjunction with the GWS's vertical scan capability to scan the GWS aperture and track the holographic fringes without moving parts. Since the hololine is horizontal parallax only, no image information is carried vertically, and the vertical direction can be temporarily used to encode the desired GWS's aperture postion along the hololine. The first HOE is designed such that the amount of horizontal deflection varies continuously with vertical position (analogous to a mirror with a helical surface, but transmissive rather than reflective). The GWS's aperture is scanned vertically onto the HOE; the HOE then scans the aperture horizontally. The vertical scan rate (and therefore the horizontal scan speed) is adjusted to track the motion of the holographic fringes rendering them stationary. A second HOE must then remove the vertical encoding introduced earlier. This solid-state scanning feature results in a more robust, inexpensive, and scalable system than designs using the traditional Scophony solution of moving mirrors.

4. DRIVING MARK III

A single NVIDIA Quadro FX 4500 graphics processor performs the rendering and fringe computations and generates the video signals for the Mark III display. Mark III treats six video lines of 4096 samples as a single holo-line of 24,576 samples (and thus must divide the horizontal sync signal by six before using it to advance the position of the vertical scanner). Because this display is monochrome, as in our earlier work we treat the dual RGB outputs of the graphics chip as six independent frame buffers operating with 400 MHz pixel clock (and thus 200 MHz of bandwidth). Five of these channels drive the horizontal transducers of our GWS with the image information for each holo-line and the sixth drives the vertical transducer with a fixed pattern on each holo-line consisting of a sinusoid whose frequency linearly increases from the beginning of the holo-line to the end. The starting frequency and chirp rate of this sinusoid can be changed in software to adjust the "horizontal hold" implemented by the HOE discussed in the preceding section.

As shown in Figure 4, each of the five horizontal transducers has a bandwidth of 200 MHz and a center frequency of $(200n + 160)$ MHz for $1 \leq n \leq 5$; in each case we take one of the video channels from the graphics processor (which have a 400 MHz pixel clock and thus a 200 MHz bandwidth) and upconvert the signal by multiplying it by a sinusoid at the top of the band $(200n + 260)$ and then lowpass filtering it with a cutoff at that same frequency to retain only the lower sideband. The vertical transducer has a bandwidth of 70 MHz and a center frequency of 460 MHz, so the carrier frequency and filter cutoff are set to 495 MHz.

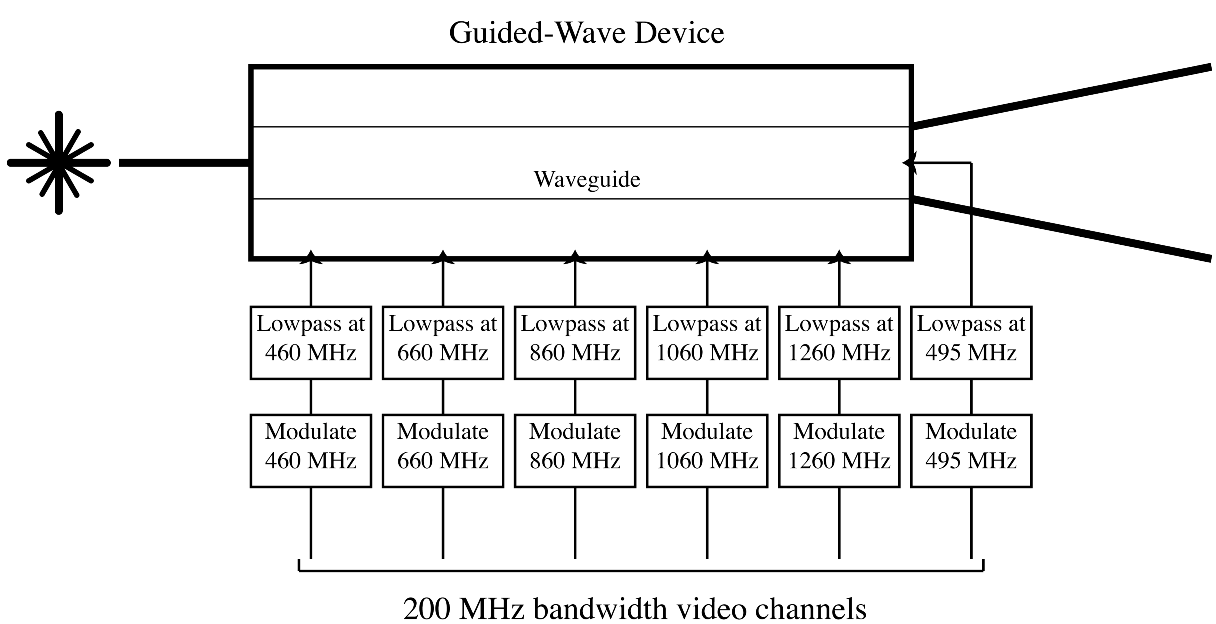

Fig. 3. Five video channels control horizontal diffraction of light passing through the device, and a sixth provides vertical diffraction.

Rendering for this display is very similar to the method discussed in reference [7] above, though here each channel does not represent a separate scan line but rather all channels must carry different frequency ranges (and thus different diffraction angles) for the same scan line.

5. PROJECT STATUS

As of the date of publication, we have fabricated and tested several iterations of GWS design, and device testing indicates that these devices should be able to meet the target requirements for the display system. The optical system is under construction, and rendering software from our previous work is being converted to drive the new system. We are also beginning design work on a scaled-up display system with a larger view volume.

6. CONCLUSIONS

While this system design is in many ways a descendant of previous MIT holo-video displays, the new focus of this work on simplifying and cost-reducing holo-video displays has resulted in the novel application of 2-D guided-wave devices to displays. We anticipate that this field will prove a fertile one for both 3-D and 2-D video displays.

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