Waveguide Panel Display Using Electromechanical Spatial Modulators

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Abstract

A novel micro-electro-mechanical system (MEMS) approach in waveguide panel displays (WPD) is described. High efficiency electromechanical spatial modulators, based on the use of frustrated total internal reflection, were demonstrated. Potential applications of the new display in HDTV using solid-state light emitting diode (LED) as a light source are discussed.

Introduction

Optical waveguides have long been sought as low-lose and low-cost media to construct panel displays.[1] One important issue is how to effectively extract light from the waveguides in the process of forming images. Electro-optical effect, thermal-optical effect, acoustic effect, and thermally generated bubbles have been described as methods of light extraction.[2] These methods, in one way or another, suffer from being inefficient for extracting light, being too slow for high resolution video display applications, and being too complicated for making low cost products. Therefore, an efficient, fast, and simple way of light extraction is needed.

Recent development in the field of MEMS has provided us with inspirations for new approaches. Lukosz and coworkers demonstrated SiO_2 micromechanical optical modulators for causing phase shift of light waves in waveguides.[3] This was achieved by changing a gap between an optical waveguide and an optical modulator and, thus, disturbing light propagation in the waveguide. Stern recently proposed the use of micromechanical modulators to construct flat-panel displays.[4] In his proposal, light extraction is caused by light scattering on a roughened SiN_x modulator surface.

In this presentation, we describe waveguide panel displays using highly efficient reflective electromechanical modulators.

Operation Principle

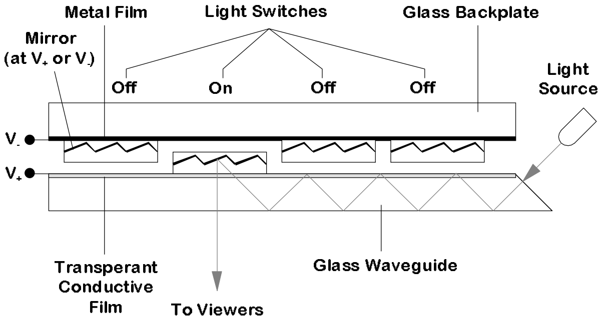

Figure 1. Schematic illustration of the operation principle of a WPD.

Figure 1 schematically illustrates the construction of the new display device. A light beam from a light source is coupled into a waveguide at one end. It then propagates along the waveguide until reaching a location where an optical modulator, which we call light switch, is on. Light switches are made of a transparent material. The on and off states of a light switch is determined by the gap between the lower surface of the modulator and the upper surface of the waveguide. When the gap is large, as compared to the wavelength of the light beam, the light beam propagates along the waveguide without being disturbed and therefore the light switch is off. However, when the gap is sufficiently small, the light beam tunnels though the gap, enters the light switch, and the light switch is on. In order to extract light efficiently from the waveguide into free space, reflective mirrors are embedded inside each light switch. The mirror plans are tilted at a proper angle so that the light beams are reflected perpendicularly out of the display screen. The mirrors are segmented to reduce the thickness of the modulator. The light switches are electrostatically actuated. Actuation voltages are

ISSN0098-0966X/98/2901-$1.00 + .00 (c) 1998 SID

applied through a transparent conductive film on the upper surface of the waveguide, a metal film on the back-plate, and the metal-mirror films embedded in the light switch.

A power transmission coefficient, the ratio of the powers of the tunneled light and the incident light, as a function of an air gap was calculated and the result is shown in Figure 2.[5] According our calculation, when the gap is less than 10 nm, more then 99% of all visible light tunnels through the gap. When the gap is larger than 1,500 nm, less than 0.01% of the visible light tunnels through the gap. Therefore, light switching takes place when the gap is varied between 10 and 1,500 nm. By using highly reflective mirrors in the light switches shown in Fig. 1, an overall light extraction coefficient of better than 90% can be achieved.

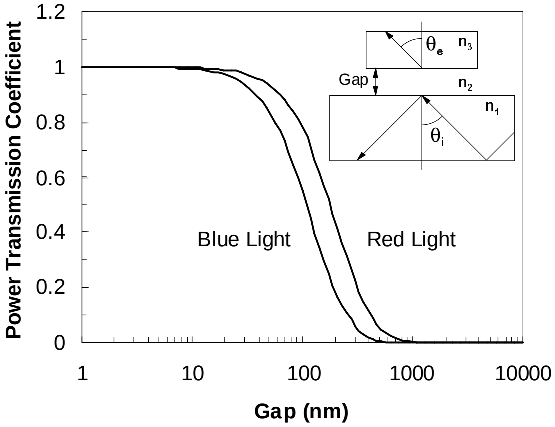

Figure 2. Light (TE mode) tunneling from one glass medium (medium 1) through an air gap into another glass medium (medium 3). The following parameters are used in the calculation: for red light: $\lambda_o=720$ nm, $n_1=n_3=1.512$, $n_2=1$, $\theta_i=45°$; for blue light: $\lambda_o=450$ nm, $n_1=n_3=1.524$, $n_2=1$, $\theta_i=45°$.

Results

Working devices based on the principle shown in Fig. 1 have been demonstrated. Figure 3 illustrates the construction of a concept device. Surface-micromachining processes were used to fabricate the device.[6] A 0.5-mm thick glass (BK-7 from Schott) substrate was used as a planar waveguide. A transparent-conductive indium-tin oxide (ITO) film was deposited on the glass surface for applying an electrical bias. On top of the ITO film, a SiO_2 film was deposited as an insulating layer. Light switches were made of a polyimide material (PI-1111 from DuPont). Each light switch consists of three layers. The first layer is a TiO_2-pigment-embedded polyimide film of 3-μm thick. This layer serves as a light diffuser. The second layer is a Cr/Au/Cr metal film of total 3,000 Å thick, serving as an electrical conductor and an optical reflector. Chromium provides a good adhesion to polyimide and gold provides a good electrical conductivity. The third layer is a polyimide film, which balances the stress in the first polyimide film to maintain a flat light-switch structure. The width of each light switch is 230 μm and the pitch distance between adjacent light switch is 300 μm. The light switches are strip-shaped suspended beams that are affixed through end anchors onto the glass substrate. The gap between a freestanding light switch and a substrate surface is 1.2 μm. A right-angle prism (BK-7 glass) was bonded to the glass substrate and was used as a light coupler. From Fig. 3, the simplicity of the device structure is obvious. Simple device structures can potentially be fabricated by using low-cost production processes.

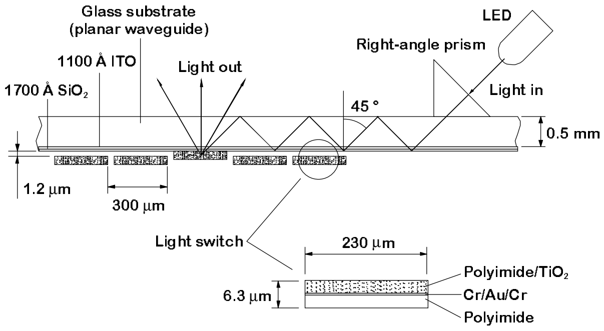

Figure 3. A schematic cross-section view of a concept device. The optical modulators are made of a light-diffusive polyimide material that contains TiO_2 pigment particles.

Figure 4 demonstrates light extraction and spatial modulation functions of the electromechanical light switches. As the light switches were turned on, one at a time, the movement of a light bar was clearly observed, as indicated by arrow marks in Figs. 4a, 4b, and 4c. Actuation voltage used in this experiment was 10 V. Further reduction on the actuation voltage is expected as low stress materials are used and improvements on mechanical structures are made.

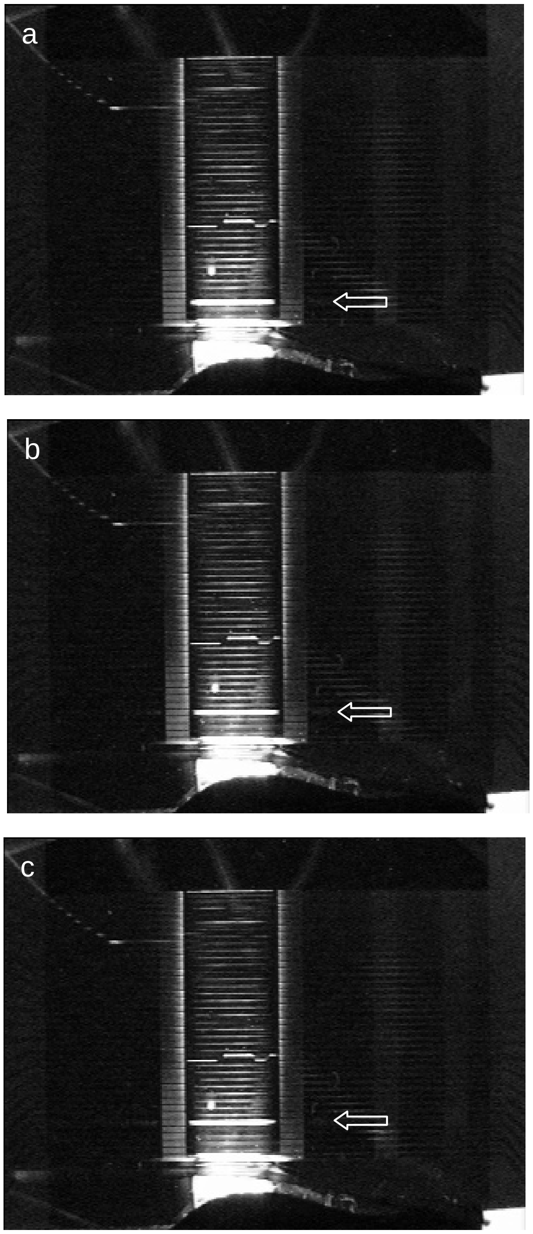

Figure 4. Photographs showing light extraction and spatial modulation in an electrostatically driven device. Figure (a), (b), and (c) illustrate three light switches, as pointed by arrow marks, being turned on one at a time. An actuation voltage of 10 V was used. The bright areas at lower-middle region of the images are due to a stray light from a light coupler.

The device structure shown in Figs. 3 and 4 proves to be robust. All testing experiments of the devices were conducted in ambient condition. No stiction problem was observed during the test. We attribute this to the hydrophobic surface property of the polyimide material used. The material (PI-1111 from DuPont) is a fluorinated polyimide and its chemical structure is believed to have contributed to the desired surface property.

Operational devices containing light switches with segmented reflecting mirrors have also been constructed. Large sized channel waveguides and light switches were fabricated from transparent acrylic material by mechanical methods. The contact area between a light switch and a waveguides was as large as 12×12 mm^2. These large light switches were brought into a close proximity with the waveguide surface by vacuum suction. An efficient light extraction was demonstrated.

Discussions

Various configurations can be used to apply electromechanical light switches in waveguide panel displays. Figure 5 illustrates a multiple-channel waveguide panel display, which we are currently studying. A linear LED array is used as a side-lighting source. Light switches are in form of thin and long suspended beams. The crossing areas between light switches and channel waveguides form individual display pixels. The display operates in a line-scan mode with light-switches engaging sequentially one at a time and

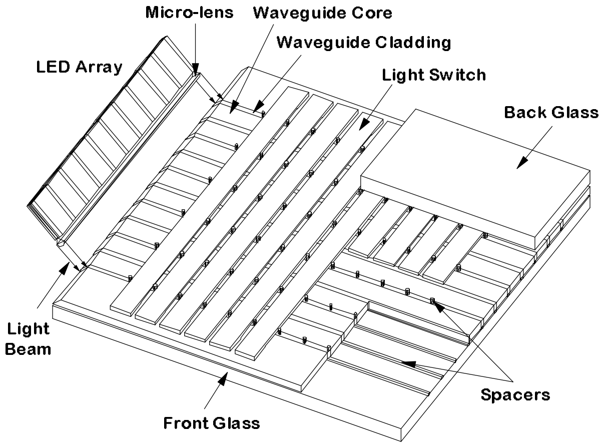

Figure 5. Schematic illustration of a waveguide panel display assembly. The diagram is not drawn in proportion to real dimensions.

the parallel driven LED array refreshing synchronically. In this configuration, line and column channels carry electrical and optical signals, respectively; therefore, they are completely decoupled. This significantly simplifies the design and construction of driving circuits.

The display configuration shown in Fig. 5 makes it possible to construct low-cost flat-panel displays based on the use of solid-state LEDs. Comparing to a matrix configuration, the number of LEDs in a waveguide panel display is significantly reduced. For example, to make an XGA 1024×764 full-color display, a matrix display requires 1024×764×3=2,347,008 LEDs while the waveguide display requires, at most, 1024×3=3,072 LEDs, which is almost a three orders of magnitude reduction. The full color display can be realized by injecting light beams of all three red-green-blue primary colors into each channel waveguide.

The advantages of using solid-state LEDs in flat panel displays are many. Solid-state LEDs are reliable, robust, and able to withstand extreme working temperatures. The commercially available (AlGaAs and InGaN) LEDs of all three primary colors are purer than the NTSC (National Television System Committee) television standard, therefore, the new display can provide a broader color gamut than that available on current television screens.[7] These LEDs have high energy-efficiencies. By calculating the optical loses for light coupling into and out of channel waveguides, we derived a very high luminous efficiency of 8.3 lm/W for a waveguide panel display using solid state LEDs as light sources. This efficiency is six times higher than that of active matrix liquid crystal flat panel displays. In our calculation, a spreading angle of 16° was assumed for collimated LED emitters, the refractive indices of 1.613 and 1.31 were assumed for waveguide core and cladding materials. The luminous efficiencies of 8.0, 31.3, and 10.2 lm/W were used for red (AlGaAs), green (InGaN) and blue (InGaN) LEDs. Our calculations also conclude that the solid state LEDs are suitable for making large-area high definition televisions (HDTV) of 1920×1820 resolution and 70 to 90 inch diagonal sizes. The power consumption of these LED HDTVs is potentially much lower than that offered by other technologies.

Conclusions

Waveguide panel displays using novel spatial electromechanical modulators have been demonstrated. The new display has the potential to operate with a high energy-efficiency and to be manufactured at low cost.

Acknowledgement

This work was supported in part by US Army Research Laboratory under a SBIR contract # DAAL01-97-C-0048 and the Michigan Center for Display Technology and Manufacturing at the University of Michigan.

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