Electrically Addressable Lasing Pixel for Large Screen Display

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Abstract

A novel lasing projection system based on the concept of an image mode is presented. Such a laser uses a polymer dispersed liquid crystal (PDLC) light valve as a voltage driven spatially patterned loss element placed within a laser cavity. In the regions where the cavity loss is sufficiently high, the local transverse area of the laser is below threshold, whereas in the transparent regions, the area is above threshold. By addressing certain parts of the loss medium, the laser can be forced to have a transverse mode profile which exists in those transparent parts of the light valve, which can then be projected onto the display screen.

Introduction

Laser based projection displays were developed in the seventies and have experienced a resurgence in interest over the last few years. The large available optical power and spectral purity of lasers address the primary problems of current projection displays, which suffer from chromatic aberration through imaging optics, reduced available color pallette, and lack of brightness. Current lasing projection technology makes use of laser scanned front and back illumination systems. The laser scanning approach, although it produces large, bright and sharp images, suffers from the associated maintenance needs of all of the subsystems involved. In addition, because of low optical power throughput and beam clean-up requirements, these display systems require several large lasers with significant electrical power consumption and space requirements.

In an attempt to bridge the gap between the laser based and the more conventional projection-TV systems, Spectra Science Corporation has begun the development of a novel projection system based on the concept of an image mode. The generation of a full color image using this hybrid technology is accomplished by mixing three image sources which each individually emit laser light. Furthermore, the approach builds on mature projection-TV liquid crystal technology to produce the image while using stationary solid state lasers to provide the pump energy for the lasing process. This approach eliminates scanning of individual lasers but still results in laser bright and chromatically pure images.

The image mode concept is based on the use of a low voltage spatially patterned loss element placed within a laser cavity.[1,2] This loss is achieved by using a medium with a variable scattering state such that when the loss in the cavity is sufficiently high, the laser is below threshold. When voltage is applied the medium becomes transparent, bringing the laser above threshold. By electrically addressing certain parts of the loss medium, properly designed lasers can be forced to have transverse mode profiles which exist in the transparent part of the loss element forming the image modes. In the weak coupling limit, the loss element excites a superposition state of a large number of transverse modes of the unperturbed cavity to create the image.

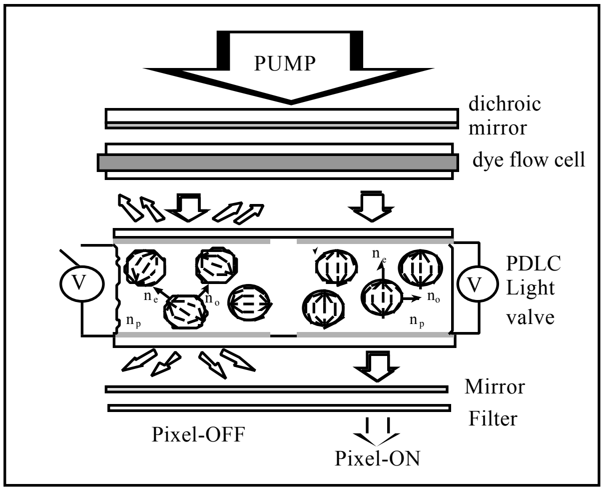

Figure 1. Optical layout of the image mode laser projection device. Optical pumping with an apodized beam is used to create a spatially uniform gain. A patterned PDLC device within the laser creates the desired image mode.

Device Operation

The addressable loss element used to produce the image mode effect in our experiments is a polymer dispersed liquid crystal (PDLC) light valve device.[3] Active matrix PDLC's are currently being introduced into the projection display market as pixellated amplitude masks for incoherent light sources. The benefits of these materials over other liquid crystals are low turn-on voltages (~7 volts) which are consistent with TTL standards, simple device fabrication, and the elimination of optical losses associated with polarizers.

A PDLC light valve is made from a mixture of optically anisotropic liquid crystals and a polymer solution placed in a thin layer between two glass plates coated with the transparent conductor indium tin oxide (ITO). The components are chosen so the index of refraction perpendicular to the long axes of the liquid crystal is equal to that of the polymer. When this mixture is cured, the liquid crystals disperse into micro-droplets (~1 μm), with the orientation of the liquid crystal molecules being determined by the interface forces. With no voltage applied, the sym-metry axes of the droplets are randomly oriented and light normally incident to the device is scattered by the effective differences in index of refraction between the droplets and the host polymer. With an applied voltage, the liquid crystal molecules within these regions align normal to the device and parallel to the applied field, producing a spatially uniform index of refraction and a highly transparent state.

Figure 1 shows a schematic of our optically pumped experimental image mode device which uses a flowing laser dye as the gain medium. By adjusting the pump absorption length of the gain medium, essentially all of the pump energy is absorbed before it reaches the PDLC. Optical damage is eliminated in the off-state because the only light incident on the liquid crystal material is the spontaneous emission of the dye which is distributed over 4π steradians. In this mode of use, only when a part of the PDLC is rendered transmissive does a significant internal optical field interact within the liquid crystal material. This is in contrast to placing the PDLC in front of an intense coherent or incoherent light source, resulting in the situation in which the maximum brightness of the display is limited by the amount of incident light that the PDLC can withstand before damage will occur.

Mode Simulations

In order to determine how a PDLC light valve shapes the resonator mode, numerical stable-mode resonator simulations were performed using the methods established by Fox and Li.[4] The two mirrors in figure 1 were assumed to be perfectly reflecting and infinite in extent as compared to the pixel width. The pixels were modeled as rectangular apertures, separable in the horizontal and vertical directions, and placed in the resonator in accordance with our experimental geometry. We could then model the resonator as an infinite progression of slit apertures, with a length between apertures alternating between twice the distance from the PDLC to the dichroic mirror, and twice the distance to the output coupling mirror. The complete integral of the Fresnel diffraction kernel was used in the simulations to allow for the flat high Fresnel number geometry of the cavity.

A variety of simulations were performed for an eight pixel array. The numerical experiments varied the resonator lengths, pixel widths, and pixel separation in order to find the regime of resonator conditions where the system would resonate in a stable mode which was confined within the transparent regions of the internal loss pattern. Defining a pixellation Fresnel number,

$$N_F = ab/2\lambda L,$$

where a is the pixel width, b the pixel separation, and L is the distance from the PDLC to the most distant mirror, we were able to show that this quantity had to be of the order of $N_F \geq 2$ to produce image modes. Figure 2 shows how the mode confinement in an 8-pixel array breaks down as N_F decreases. Confining the mode is an important requirement for producing the desired image as well as preventing the off-state area from damage due to a high optical field.

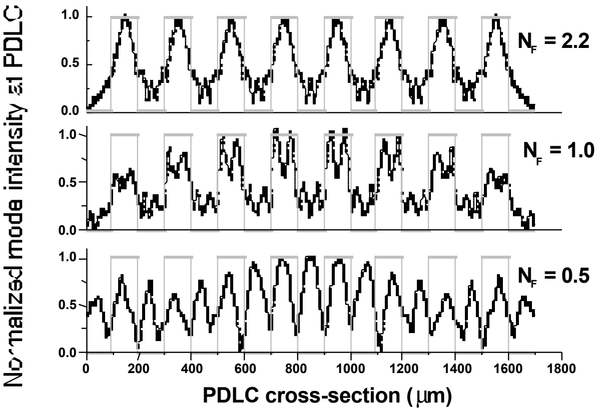

Figure 2. Numerical simulations of stable mode profiles for a device with 8 pixels in the "on" state. A lasing transverse mode which faithfully reproduces the pixellation pattern is possible for resonators with sufficiently high pixel Fresnel number, N_F.

Results

In the actual experiments an image mode device was built using rhodamine 6G in ethylene glycol solution at a 2.5 × 10^{-4} M concentration flowing through a 500 μm thick flow cell as a gain medium. The liquid crystal in the PDLC device used in our experiments was TL205, and the polymer host was PN393 (E.Merck). A 5 micron layer allowed for low voltage turn-on and desired scattering properties. They were combined in a ratio of 4:1 by weight, and cured using UV light from a mercury lamp. The system was pumped by a Q-switched frequency doubled Nd:YAG laser with 7 ns pulses at a video rate of 30 Hz. A 7 × 7 passively driven PLDC, with pixel widths of 100 μm, was created by photolithographically patterning the ITO plates used to make the PDLC.

In one series of experiments we measured the output intensity emitted from a 100 μm pixel line of the dye based device with respect to the driving voltage. The results in figure 3 demonstrate how the voltage which drives a pixel can control the output lasing intensity such that gray-scale control and high contrast can be achieved. The insets in figure 4 also show the spectral purity of the emitted light in the “off” state and in the “on” state.

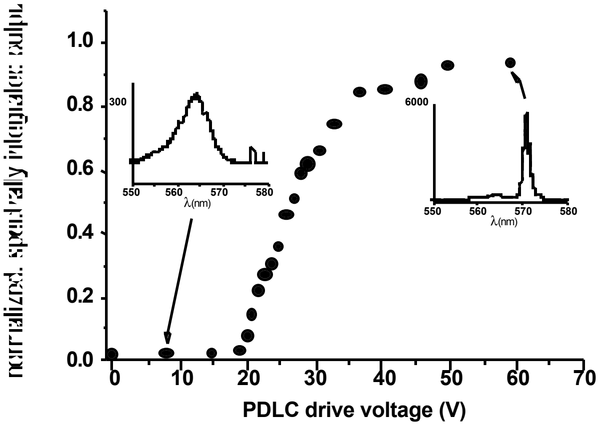

Figure 3. Voltage control of the image mode laser device using Rhodamine 6G as a gain medium. The data represents the total spatially integrated output energy of a 100 μm wide lasing pixel line. The inset graphs show the output spectra at low and high voltage, corresponding to fluorescence and lasing well above threshold.

Figure 4 shows the output of a 7 × 7 passively-driven image mode laser. The far field image is created by focusing the output beam so that the plane of the PDLC light valve is imaged onto the viewing screen. Lasing efficiencies of ~40% were observed when a 100% reflective dichroic mirror and the glass-air interface were used as the laser cavity mirrors. This corresponds to an output of over 600 lm/cm^2 at a wavelength of 570 nm. This result is to be compared with record outputs of 5 lm/cm^2 achieved with extremely high voltage, watercooled projection system CRT devices.[5]

Future Development

The successful implementation of this technology for projection displays will require a full RGB system. Based on our demonstration of this concept, with 355 nm pumping of other blue and green emitting laser dyes such as the coumarins and stilbenes, we believe that a single pump laser system based on a long life diode pumped Nd:YAG laser is quite feasible. Figure 5 shows a schematic of how such a system might be configured. In order to achieve the greatest possible image color palette, the RGB components must be chosen near the three corners of the chromaticity diagram by a proper choice of the organic dyes and dichroic mirrors in the individual systems.

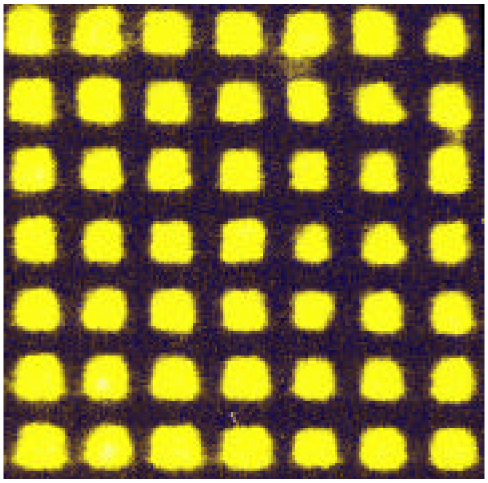

Figure 4: Imaged output of an optically pumped 7 ¥ 7 passively driven image mode laser device.

Future directions for the development include the use of an active matrix PDLC to increase the pixellation density of the devices and to eliminate the fringe field effects which can smear the individual pixels. On a parallel track work is also underway to use solid state gain media to replace the flowing dyes used in this prototype. Materials that have shown exceptional promise for this application are polymeric semiconductors such as PPV, MEH-PPV, and BDOO-PF and HEH-PF.[6] These materials also eliminate the solubility limits of dyes allowing for very high gains in very thin geometries. In addition they can be directly spin coated onto the PDLC cells allowing for the required resonator length decreases which must accompany the smaller pixel sizes necessary for high resolution.

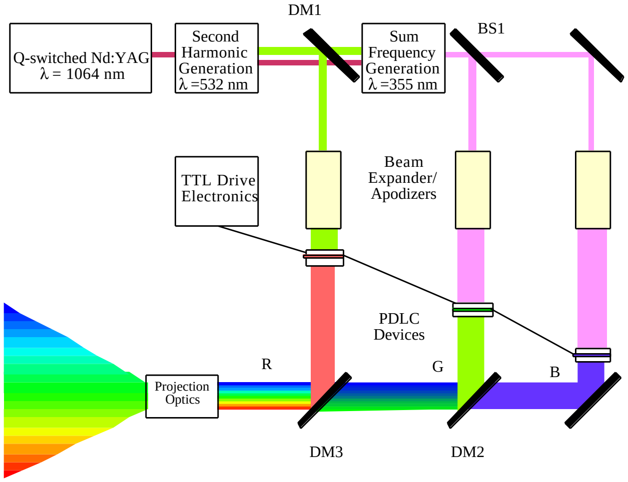

Figure 5. Schematic of a lasing projection system using the image mode laser devices. A red emitting gain medium is pumped by the second harmonic of the Nd:YAG laser, while the green and blue gain media are pumped by the third harmonic.

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