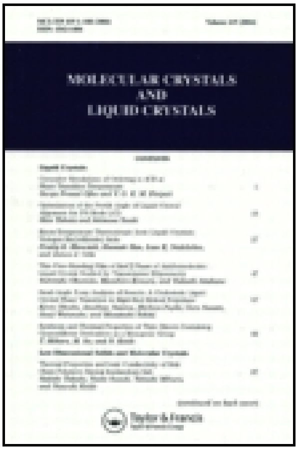

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

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Version of record first published: 24 Sep 2006

Mol. Cryst. and Liq. Cryst., 2000, Vol. 351, pp. 35-42
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Image Mode Projection using TN and PDLC Displays

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A laser video projection method that is based on the image mode laser has been developed. The image mode laser is a laser with a spatial light modulator placed inside an optically pumped high-gain laser cavity to provide area-selective Q-modulation. The transverse mode of this laser creates a desired image that can be projected onto a viewing screen. This method of creating a lasing projected image has the potential advantages of higher contrast and brightness at the faceplate over the traditional method of spatial light modulation of a uniform optical source. The elimination of scanning systems results in a simpler design without mechanical parts; also, this system can potentially be adapted to full color with a single laser providing optical pumping for image mode lasers of all three primary colors.

Keywords: laser; video projection; electronic cinema; PDLC

INTRODUCTION

Current video projection systems based on liquid crystal displays (LCD's) and cathode ray tubes (CRT's) have made significant advances recent years and currently dominate the projection market, but there are still many technical hurdles to overcome for large area projection applications, with regard to resolution, color gamut, and

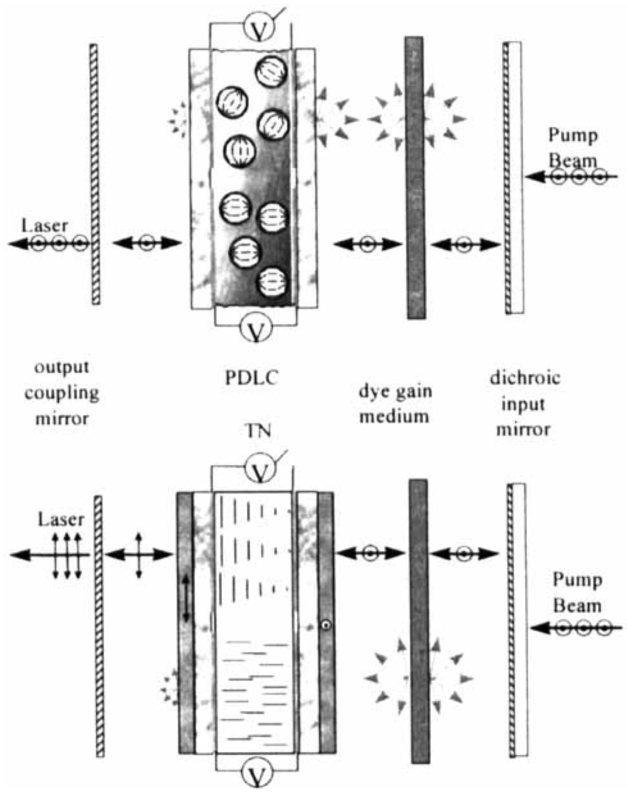

FIGURE 1 Operating principle of image mode lasers, which can employ either a scattering PDLC or an absorptive TN.

brightness. Many company and university researchers are aggressively pursuing research on laser projection for large-area applications because of the intense saturated colors made available from the inherent spectral purity of lasers [1], which results in not only a very large color gamut, but also a perceived brightness exceeding that of a such systems with an equivalent power output [2]. Current successful architectures for designing such systems have relied on raster scanning of laser beams with rotating polygonal mirrors, or a combination of one-dimension scanning with one dimension spatial light modulation [2], which are resolution limited because of timing issues.

The *image mode laser*, which we have developed, is a laser with a transverse mode that is a desired image, which can be projected onto a viewing screen. The advantage of this laser over the traditional method of spatial light modulation of a uniform optical source is that the image has higher contrast and brightness at the faceplate. The elimination of scanning systems results in a simpler design without mechanical parts; also, this system can potentially be adapted to full color with a single laser providing optical pumping for image mode lasers of all three primary colors [3].

CONCEPT

An image mode laser is a laser with a spatial light modulator (SLM) placed inside an optically pumped high-gain laser cavity, which provide area-selective modulation of the cavity-Q [4], as shown in Figure 1. An area of this cavity in which pixels are in an off-state have sufficient loss to maintain that local area laser below threshold, while an area with on-state pixels is above threshold and high optical power is locally emitted. The transverse mode profile of this laser is then the superposition of the transverse modes in the lasing areas, which is the desired image, which can be projected onto a screen. This response of the laser cavity to the loss element then results in a very high contrast system because the off-state output of a pixel is essentially zero (i.e., no lasing), while an on-state pixel extracts the full power available from the local region of the cavity. Also, higher intensity at the SLM can be achieved because the optical damage threshold of the SLM is increased. This is because the light interacting with the loss element in an off-state area is only the isotropic spontaneous emission passing through the solid angle of the pixel area in the cavity, as opposed to the case of placing the SLM outside the cavity, in which intense directional laser light that would always be incident upon it.

The polymer dispersed liquid crystal (PDLC) and the more conventional twisted-nematic (TN) were both investigated for use in an image mode laser. When a TN is used in the image mode laser, in the voltage off state the cell rotates the plane of polarization of the laser and is therefore transparent (low loss). It is this state that results in lasing, and any intermediate levels of gray above threshold. When the twist symmetry of the TN is broken by an electric field, the cavity is below lasing threshold, and only spontaneous emission results. PDLC's operate on the principal of voltage-controlled scattering which results from alignment of randomly oriented birefringent liquid crystals droplets in a polymer matrix, index matched to the normal optical axis of the liquid crystals [5]. PDLC's operate at low voltages comparable to TN's, they are robust and mechanically stable, have few steps of fabrication, and have nearly 100% on-state optical throughput. When a PDLC is used in the image mode laser, nearly all light scattered cannot contribute to lasing because of the flat-mirror Fabry-Perot cavity, so the output is modulated by the degree of scattering.

CAVITY GEOMETRY CONSTRAINTS

One limitation on the cavity geometry arises from the need to maintain an optical pumping fluence high enough to maintain the laser well above threshold for an on-state pixel. For example, with a high-power Nd:YAG laser providing 150-mJ in 10-ns pulses, the largest area which can be excited well above the typical lasing thresholds of ~10-mJ/cm^2 for the materials under investigation is approximately 4-cm^2. This is the size of LCD's used in current 800×600-pixel super video graphics array (SVGA) resolution projection systems.

In laser cavities which have a small aspect ratio (length/width) gain medium, amplified spontaneous emission (ASE) in the transverse direction can compete with lasing intensity, reducing and even quenching the output. We have developed and experimentally verified a model for this effect which predicts that ASE intensities behave in an exponential manner with respect to the inverse of the aspect ratio, placing a constraint on the minimum thickness for a given display area. For example, a 1-cm^2 pumping area requires at least a 1.5-mm thick gain region to significantly reduce ASE, depending on the losses in the cavity. Additionally, a system which employs a scattering PDLC rather than an absorbing TN can scatter back part of the forward travelling ASE, resulting in even higher levels of ASE in the cavity, which we have experimentally verified [6].

Inside the cavity, energy can be diffracted by the pixel apertures, which can result in energy coupling between neighboring pixels. By performing numerical stable-mode Fox and Li resonator simulations of an array [7] using the method of equivalent cavities for a cavity with internal limiting apertures [8], it was found that this energy coupling can be characterized by a parameter we have called the coupling Fresnel number N_c. This is defined as $N_c=ab/(\lambda L)$, where a is the pixel half-width, b is the half width between pixels, and L is the round-trip length between successive passes of the optical field through a pixel. In order to maintain pixel independence, it was found that $N_c>0.5$ [9]. For an SVGA resolution system with ~30×30-μm pixels, this results in a cavity length on the order of fractions of a millimeter, requiring unattainably high concentrations of dye and optical separation of pixels to avoid ASE quenching. However, simulations and experiments have shown that while pixel energy coupling does occur in lower coupling Fresnel number cavities, it is not severe, and may allow for relaxing of this constraint.

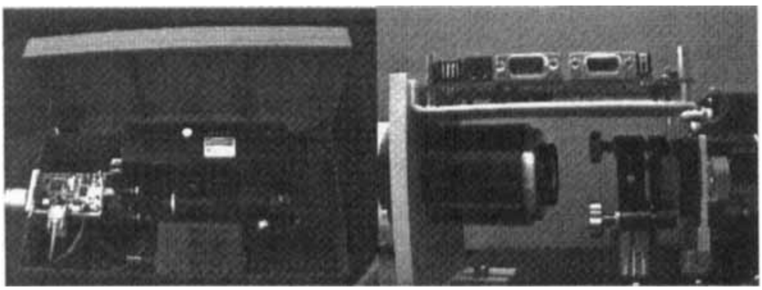

FIGURE 2 Photograph of the projection engine prototype, with a close-up of the image mode laser.

IMAGE MODE LASER PROTOTYPE EVALUATION

Figure 2 is a photograph of the monochrome projection engine prototype, which was built to evaluate the image quality. A 1.3" amorphous silicon TN light valve operating in the normally white mode was used as the SLM. Images were generated with 33×33 μm pitch pixels at 300×300 resolution, projected to a 1-m diagonal on-screen image. The gain medium was rhodamine B in an MMA:HEMA (methyl methacrylate, 2-hydroxyethyl methacrylate) copolymer host. It was optically excited by 532-nm, 10-ns pulses at 30-Hz from a frequency doubled Nd:YAG laser, at a fluence of was 80-mJ/cm^2.

Standard monochrome evaluation images are presented in Figure 3. Two standard contrast evaluation measurements were performed: 1) a totally black and totally bright screen comparison and 2) the contrast on the checkerboard between two adjacent squares in the black and bright state. The results are presented in the following Table 1, and are compared with both a full-color LCD projector and projection of laser radiation directly through the light valve, to determine if an image-mode laser can provide better contrast than such systems. The table indicates that a monochromatic image mode laser can provide far better contrast than a monochromatic element in the commercial LCD display system, and also provides better contrast than using a laser as a drop-in replacement for an illumination source.

Device	On/Off Contrast [Checkerboard]	Luminance (Cd/m^2)	Linecenter(nm) [Linewidth]
Image Mode TN	>500:1 [300:1]	32	594 [3-4 nm]
Laser through TN	180:1 [80:1]	49	594 [3-4 nm]
Commercial (white)	240:1 [140:1]	177	N/A
Commercial (R)	50:1 [35:1]	33	602 [~80]
Commercial (G)	75:1 [40:1]	52	546 [~50]
Commercial (B)	18:1 [12:1]	13	468 [~75]

TABLE 1 Comparison of image mode laser to direct laser projection and a commercial LCD system.

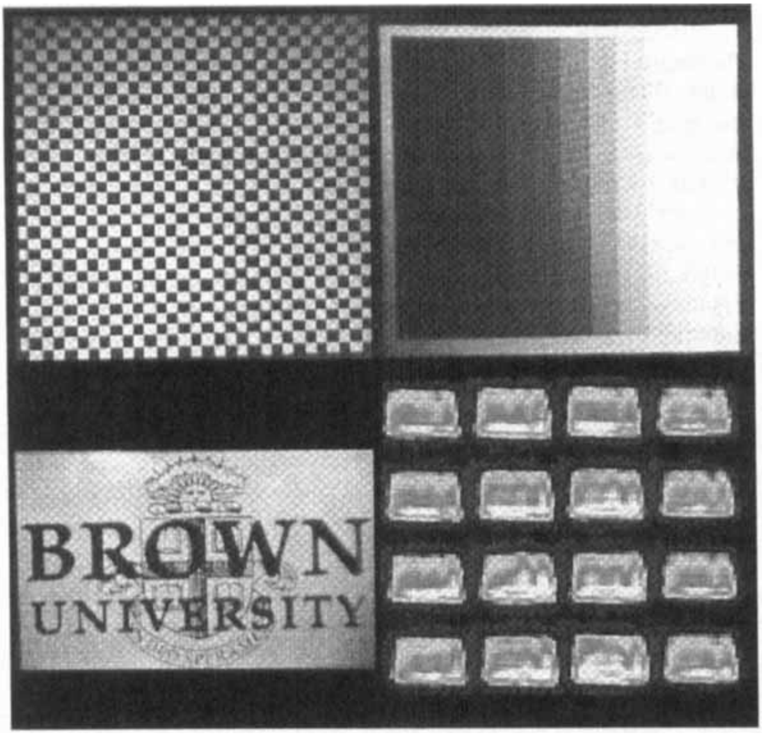

FIGURE 3 Photographs of 300×300-pixel image mode laser pictures, projected to a 1-m diagonal screen. The image in the lower right corner is a close up of a 4×4-pixel array projected onto a laser beam analyzer.

CONCLUDING REMARKS

The image mode concept is one of the most unique projection systems to date. There is still much research and development ahead to develop this into a commercially viable system. Because our investigations over the past few years have shown that both TN and PDLC liquid crystals are robust enough to sustain long periods of operation within the laser cavity, we do not anticipate any display materials issues to arise since. The gain medium, on the other hand, will need to greatly mature for this application. We are currently investigating a number of materials and schemes to improve the lifetime and efficiency of these materials.

Acknowledgements
This work is supported by Spectra Science Corporation, a State of Rhode Island Samuel Slater Grant, a phase II SBIR grant from the Ballistic Missile Defense Organization, and the Air Force Office of Scientific Research.

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