Twisting Light with Twisty Molecules

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1 Introduction

Spatial light modulators (SLMs) create a spatial variation of the amplitude and/or phase of a beam of light. SLMs can also be used to change a beam's polarization. They can be programmed to act as various diffractive optical elements using Fourier transforms, and are advantageous over traditional light modification devices because they are dynamic and have high resolution. The most common type of SLMs are based on liquid crystals and are widely available commercially. Other types are based on chemicals, mechanically deformable surfaces and acousto-optical or magneto-optical effects. They have applications in scientific research and commercial products. SLMs can be used to create dynamic optical vortices, which are of great interest to me.

2 Liquid Crystals

Liquid crystals (LCs) are state of matter between liquid and solid and therefore have unique properties.[1, 2, 3] The LC molecules are much longer than they are wide, which makes them dipoles and creates an intermolecular attractive force. They must also have a rigid central region so they can move together as a group. Molecules in a solid have *positional order* and *orientational order*; a liquid has neither; a LC has orientational order only. The molecules all point in almost the same direction, but are free to move or flow within a region. The preferred direction of orientation is described by the *director*. The order parameter of a LC describes the average deviation of molecules from the director direction and indicates how like a solid the LC is. Since LC molecules are dipoles, the director is very sensitive to electric fields and the properties of adjacent surfaces. There are many types of LCs, including *nematic*, which have orientational order only along their long axes; and *smectic* which are organized in more than one dimension. LCs are usually contained in a thin layer between plates and/or polarizers so that light can pass through them.

LCs are birefringent since light travels at different velocities depending on whether the light's electric field is perpendicular or parallel to the director. When a sample nematic LC is placed between crossed polarizers, a complex pattern of light, dark and grey regions is created which indicates the orientation of the director. In such an arrangement, the incident light enters the LC linearly polarized, passes through the LC and enters the analyzer elliptically polarized. Therefore, some light is transmitted through the crossed polarizers. When the director is parallel to the polarization axis of either polarizer, no light is transmitted and it will be

Figure 1: Nematic and smectic liquid crystal molecules, respectively, with orientational order. The director points upwards in both cases.

blocked by the analyzer.

Application of a voltage normal to the polarizers also changes the birefringence of the LC cell; a greater difference between the index of refraction of the extraordinary and ordinary axes creates a higher birefringence so LCs can be used as quarter, half, full, etc. wave plates. The pattern of light and dark regions created when a nematic LC is placed between two orthogonal polarizers contains regions where two bright and two dark places meet at right angles. This singularity is called a disclination, and the director always points away from it.

3 Spatial Light Modulators

LC-based SLMs can be transmissive, reflective, composed of nearly any type of crystal with any degree of twist, modulate phase alone, be controlled by light or electrical signals. Holoeye Photonics and Hamamatsu Photonics make two contrasting types of SLMs: the transmissive twisted nematic LC, and reflective parallel aligned nematic LC, respectively.[4, 5]

3.1 Transmissive Twisted Nematic LC SLMs

Twisted nematic LC SLMs operate by applying a voltage to a twisted nematic cell to modulate both intensity and phase up to 2π. Holoeye's LC-2002 model is electrically addressed and transmissive.

A transmissive twisted nematic LC cell consists of a nematic LC layer with a spiraling director between two transparent electrodes and two crossed polarizers. Because the orientation of the director affects the polarization of the light traveling through the LC, application of a voltage changes the director and also the amount of light transmitted through the LC; this is how regions are dark and light are created. The layer of NLC is separated by two orthogonal transparent electrodes that are treated so the director aligns parallel to the axis of the material. Electrodes are coated with a polyimide and mechanically rubbed so the LC molecules in contact with it align themselves to the direction of rubbing. This creates a $\pi/2$ rotation of the director in the LC between the two electrodes. When the cell is placed between crossed polarizers the electric field spirals with the director and emerges parallel to the analyzer, and the display is normally white. An applied voltage aligns the dipoles with the electric field direction, which is usually normal to the polarizers. The LC molecules closest to the rubbed polyimide are not altered by the field as much or at all; this limits the efficiency of the display. Since the axis of propagation of the light is collinear with the director, the polarization is unaffected by the LC, and the light is blocked by the analyzer. Greyscale is achieved by varying the amount of voltage applied after the threshold voltage is reached. A normally black display is created using parallel polarizers.

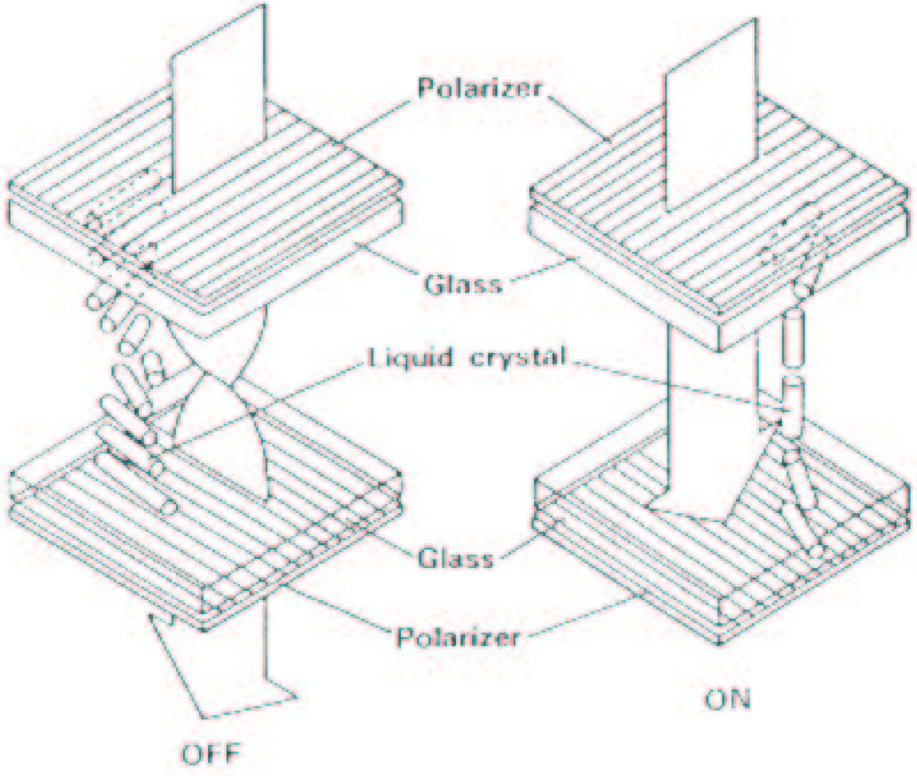

Figure 2: Twisted nematic liquid crystal normally white display.[6]

A twisted nematic LC SLM consists of a rectangular array of LC cells to control the properties of the incident light at each point. The phase is modulated by applying a voltage to each pixel and changing the orientation of the LC molecules, which changes the index of refraction of the cell. Light travels faster or slower in adjacent cells and there is a relative phase shift across the SLM. A disadvantage of twisted nematic LC SLM is that the phase and amplitude are adjusted in the same way, so unwanted modulation is inherent. The maximum phase shift per pixel equals the 2π phase rotation of the director in the TN LC cell, which limits the amount of phase shift per unit area that the SLM can induce.

The easiest way to wire a LCD to a voltage source is through multiplexing, where cells are arranged in a matrix and voltage is applied to the column and row of the desired cell. Electronically addressing the LC provides an easy interface between a computer and SLM. All of the cells in the row and column receive some voltage that must be below the threshold for sufficient straightening of the director. Matrix addressing is disadvantageous in that a voltage cannot be applied to every pixel at the same time. This limits the speed of dynamic modulation possible.

The resolution of a LC SLM is limited by the size of the pixels. Very small pixels are disadvantageous because fringe electric fields can unintentionally influence neighboring LC cells. Higher resolution displays also have more pixels in each dimension, which decreases the addressing time. The maximum rate of information that can be sent to a SLM is the channel capacity, which depends on the frame rate, number of greyscales and the space-bandwidth product. The space-bandwidth product is $\frac{XY}{2x2y} = \frac{N}{4}$ where XY is the area of the SLM, xy is the area of each pixel, and N is the total pixel number. The fill factor describes how much of the SLM is used to modify the phase. It is the ratio of liquid crystal to pitch, where the pitch is the total area of a pixel, including the space between adjacent pixels. Twisted nematic LC SLMs are often reflective, which allows for a greater fill factor and higher resolution. The LC layer is between a transmissive electrode and reflective silicon that contains most of the electronics; fewer wires are needed and the gaps are smaller.

3.2 Reflective Parallel Aligned Nematic LC SLMs

Parallel aligned nematic liquid crystal spatial light modulators affect only the phase of incident light. The Hamamatsu model is optically addressed, which allows for a shorter response time and greater resolution.

In a PAL SLM, the write beam (often a laser diode) creates a calculated hologram onto a photoconductive material such as amorphous silicon, whose resistivity decreases as the intensity of the write beam increases. Two transparent electrodes surround the LC cell and the photoconductive layer. This eliminates the need for pixels since any region of the LC can be addressed by the beam of light; a higher resolution is possible. At points where the resistivity of the silicon decreases, a voltage is allowed to pass through the LC cell. In the absence of a voltage, the nematic LC molecules are aligned parallel to the surface of the electrode. A voltage across a region of the cell aligns the LC director perpendicular to the electrode surface. Phase changes occur in the incident read light depending on the relative orientation between the director and electric field, and a hologram is created in the LC. The read beam enters the front of the PAL SLM linearly polarized and is reflected off a one-way dielectric mirror between the LC electrode and the photoconductive layer. Optically addressed SLMs must be reflective so the read beam does not unintentionally change the LC properties. While the resolution of PAL SLMs is higher than twisted nematic SLMs, they typically require additional hardware to interface to a computer.

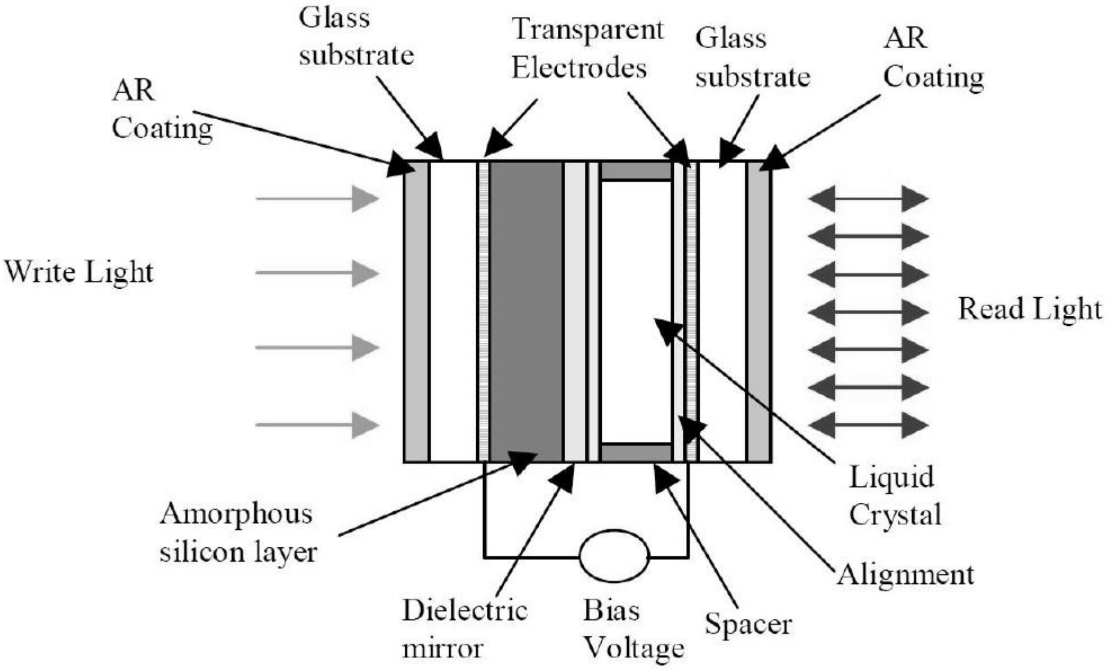

Figure 3: An optically addressed PAL SLM.[7]

4 Programming SLMs

Electric fields are described by a complex amplitude function whose real part is the amplitude and the imaginary part is the phase. Holograms modify an electric field in a specific way, described by the complex aperture function A. A wave P passing through the hologram is modified to Q. The Fourier transform of Q is the diffraction pattern R. The hologram written on the SLM is the inverse Fourier transform of the desired result R. There are a finite number of points in the diffraction pattern and the aperture function so the discrete Fourier transform is used. Various fast Fourier transform algorithms are used to make the computations practical.[8, 9, 10]

5 Applications

SLMs have applications in digital imaging, astronomy, security, medicine?

SLMs such as the Hamamatsu and Holoeye models are ideal for creating phase masks and holograms for scientific research and investigating properties of light. Optical vortices, for example, can be created using a SLM much more easily than they can be made using traditional diffraction amplitude gratings or laser mode conversion. Such beams can be used in optical tweezers, which is a way of manipulating small objects with light's momentum. Micron-sized glass spheres can even dance owing to the dynamic nature of SLMs.[11]

Deformable mirror SLMs are used in adaptive optics to correct lens aberrations and reduce atmospheric fluctuations that limit earth-based astronomical observation. An array of tiny mirrors mounted on hinges adjusts the phase of usually incoherent incoming light. The mirrors are fixed to hinges and electrostatic forces move the mirrors tiny amounts. Such adjustments require a continuous feedback system that reads and analyzes the incoming beam and calculates how to change the mirrors before the beam reaches it.

LC SLMs have many applications in digital imaging, including projectors and image recognition. Holograms utilize SLMs' dynamic properties to make moving 3D images possible. Because a phase modulation greater than $\pi/2$ is not required, ferroelectric LCs, which are a type of smectic LC that modulates amplitude only, are often used.[12] Ferroelectric molecules have a chiral shape whose direction of tilt varies from layer to layer. When a sample is placed between plates to maintain the molecular layers, the director spirals orthogonal to the plane of the layer. Each layer has a different polarization that is perpendicular to the director (there is no global polarization, however). The application of an electric field to a cell changes the director director, therefore blocking incident light when between crossed polarizers. There are only two ways the director can point, so this type of grating is amplitude modulating only.

Pulses can be reshaped by dispersing, filtering and recombining them using a SLM and a diffraction grating. A very short pulse contains very many frequencies that can be separated using a diffraction grating. The dispersed beam is modulated by an SLM programmed to change the phase and/or amplitude of certain frequencies. The resulting beam is recombined and precisely shaped since its frequency components have been altered. This is useful in studying chemical reactions since it can utilize an adaptive algorithm to reprogram to break specific bonds.

6 Conclusion

Spatial light modulators are ever becoming more important parts of many scientific research fields as well as in industry and commercial products. There are so many interesting ways to change the properties of light. The Hamamatsu PAL SLM has the advantages of phase-only modulation, higher speed, better resolution, and little relative loss of intensity, but is very expensive The Holoeye twisted nematic SLM has a less complicated computer interface and is much less expensive, thereby better suited for modest optics experiments.

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