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Applications of Liquid Crystal Spatial Light Modulators in Optical Communications

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Abstract

Recent advances in liquid crystal (LC) materials and VLSI technology have enabled the development of multi-phase spatial light modulators (SLM) that can perform high-resolution, dynamic optical beam positioning as well as temporal and spatial beam shaping in the 1550 nm optical communication window. These attractive features can effectively be used to achieve optical switching, optical spectral equalization, tunable optical filtering and many other functions that are important for future reconfigurable optical telecommunication networks. In this paper, we review potential optical telecommunication applications based on LC-SLMs.

1 Introduction

Current optical networks are mainly point-to-point links with most of the intelligence performed by electronics on both sides of the optical link. Future service providers are required to offer more reliable and cost-effective network usage. These requirements have driven the market towards dynamically configurable all-optical telecommunication networks (AONs) and imposed the needs for all-optical components that control and manipulate light. Dynamic WDM optical components that perform spectral equalization, optical add/drop multiplexing, variable optical attenuation, optical cross-connecting and free-space switching will allow AONs to operate with fewer components, more speed and even larger cost savings [1,2]. Electronically switchable liquid crystal spatial light modulators (LC-SLMs) provide for a versatile all-optical fabric in which an incident light beam interacts with a holographic diffraction grating producing beam positioning and/or temporal and spatial beam shaping. By spatially distributing liquid crystal in a composite electro-optical pixilated matrix over a VLSI backplane, one can realize a reconfigurable SLM that can arbitrarily reshape an optical beam. This capability of SLMs to manipulate optical beams makes them competent candidates in future optical telecommunication applications as well as other photonics areas.

Several research organizations are currently working towards demonstrating prototypical LC-SLM based devices targeted for the telecommunications and WDM market. The fundamental figure of merit for such devices depends on how well the grating can be made by application of an electric field. Ideally, in its fully active state, the switchable SLM grating must display low loss (< 0.3 dB insertion loss), zero polarization dependence (< 0.2 dB polarization dependent loss) and other characteristics that approach those of high performance grating plates. In its totally inactive state, the grating will ideally act as a low loss mirror. Switching speed (< 10 ms desired) and voltage (< 5 V) are also important, which depend on future advances in LC materials to create configurations that are low size, polarization insensitive, and low loss.

The objective of this paper is to review the architectures of different dynamic optical components that use LC-SLMs to fulfill the requirements of future reconfigurable optical telecommunication networks. These components include optical switches, optical spectral equalizers, and tunable optical filters.

2 Liquid Crystal Spatial Light Modulators

Light modulation with liquid crystals is accomplished by applying an electric field across a liquid crystal layer. A light propagating through an anisotropic liquid crystal material experiences a refraction index that is a function of the applied voltage. Driving an LC material placed between two polarizers can lead to intensity and/or phase modulation for an incident light beam. A liquid crystal spatial light modulator (LC-SLM) is an array of LC cells whose crystallographic orientations are independently addressed to create a pixilated holographic diffraction grating plate. There are two types of LC-SLMs: transmissive and reflective. In transmissive LC-SLMs, the liquid crystal layer is sandwiched between two transparent electrodes. Application of voltage between the electrodes induces a phase shift in that layer. This is repeated periodically across pixel block with the intent to form a periodic phase profile characteristic of a grating. The operation of a reflective SLM is similar to that of a transmissive SLM, however, a reflective SLM has one of

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the electrodes is a high-reflectivity mirror. The advantage of a reflective SLM is that it can be easily integrated with silicon VLSI circuitry, for addressing and driving the LC cells [3,4]. Usually Indium-Tin Oxide (ITO) is used as the transparent electrode, and evaporated aluminum is used as reflective electrode. The ITO layer is generally grounded and a voltage is applied at the reflective electrode by the VLSI circuit below the LC layer. A typical cell of a reflective SLM is shown in Figure 1.

Note that, future optical networks will require optical components that are polarization insensitive. Therefore, the LC-SLM, being a key element in dynamic optical component architectures, is required to be polarization insensitive. This stringent requirement has recently been solved. Recent advances in LC materials and Layer thickness control have allowed the incorporation of a thin quarter-wave-plate (QWP) layer between the LC and the aluminum mirror to accomplish polarization-insensitive multi-phase-level LC-SLMs [5].

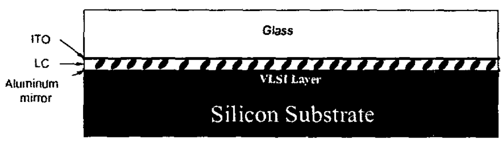

Figure 1. A typical LC cell of a reflective SLM

Addressing the array of LC cells (i.e. applying an electric field across the cell) may be achieved optically or electrically. Electrical addressing is by far the most typical addressing mechanism used in SLMs. In a matrix-addressing scheme, the SLM is organized into linked set of rows and columns, with each row sequentially selected and the data written via the column address line [6,7]. Another addressing mechanism that has been proposed is a controlled electron beam in a cathode ray tube applying charge to a surface where a layer of LC is sandwiched. Yet another addressing mechanism is the "traveling wave", where a radio frequency signals are applied at the edges of the SLM to couple charge into a specific row/column of the cell array. In optical addressing, the control signal that determines the cell's electrical field is determined by the optical field arriving at that pixel. Such schemes are generally referred to as "smart pixels", and have great potential in applications where the input and control signals are directly related, as is the case in certain control and signal processing applications [8,9].

3 LC-SLM-based beam steering for optical switching

An LC-SLM can steer a collimated beam with very high efficiency by applying an appropriate virtual blazed phase grating on the top of the VLSI chip. Figure 2 shows the principle of beam steering for a reflective pixilated SLM, where only a stepped blazed phase grating can be realized. This slightly reduces the first-order diffraction efficiency and induces additional higher diffraction orders. The relationship between the incidence and diffraction angles of a blazed grating on an M- phase SLM in is given by

$$\lambda = M \cdot d[\sin(\alpha) + \sin(\beta)] \tag{1}$$

where, λ is the wavelength of the light and d is the pixel size. For example, a 4-phase SLM having a pixel size of 10.8 mm can steer a 1550 nm laser beam by a maximum angle of 2°. The maximum diffraction efficiency of an SLM depends on the number of discrete phase levels that the VLSI can accommodate. The theoretical maximum diffraction efficiency is given by [10]

$$\eta = \mathrm{sinc}^2\left(\frac{\pi n}{M}\right) \tag{2}$$

where M is the number of phase levels, $n = gM + 1$ is the diffraction order ($n = 1$ is the desired order), and g is an integer. Thus an SLM with binary phase levels can have a maximum diffraction efficiency of 40.5%, while a four phase levels allow for efficiency up to 81%. In an LC-based optical switch, the higher diffraction orders (which correspond to the cases $g \neq 0$) are usually unwanted crosstalk, which must be attenuated or properly routed outside the output ports to maintain a high signal-to-crosstalk performance.

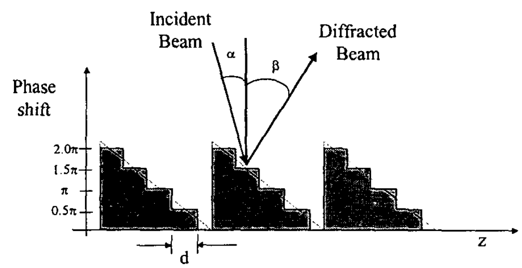

Figure 2. 4-phase stepped blazed grating structure.

A typical structure for a 1xN LC-SLM optical switch is shown in Figure 3. In this structure, a Fourier lens is used to convert the light emerging form an input optical fiber into a collimated beam with an appropriate beam diameter. Then an appropriate holographic diffraction grating is uploaded on the SLM. By changing the pitch of the blazed grating the collimated beam is steered to a desired direction. Another Fourier lens is then used to focus the steered collimated beam and couple it into a fiber port of an output fiber array. An important consideration in this switching structure is the output fiber coupling efficiency, which can be described by an overlap integral between the propagating modes in the fiber and the optical field pattern arriving at the fiber end:

$$\eta = \frac{\left|\int\int_{-\infty}^{\infty} U(x,y)G(x,y)\,dxdy\right|^2}{\int\int_{-\infty}^{\infty} |U(x,y)|^2\,dxdy \int\int_{-\infty}^{\infty} |G(x,y)|^2\,dxdy} \tag{3}$$

where U is the optical field incident on the fiber end, and G is the field distribution of the propagating mode (approximately Gaussian for a single mode fiber). The coupling efficiency therefore is very sensitive to the incident angle (phase profile) as well as position of the incident beam [11]. This places a limit on the maximum number of output ports of the switch. A 1×16 LC-based optical switch with 8 dB insertion loss and less than –20 dB crosstalk has been reported [12], and 1×32 switches are practically achievable. To realize N×N optical switching two SLMs can be used in a Z- or W-configuration, where each SLM is partitioned into N pixel blocks, each acts as a switchable holographic diffraction grating.

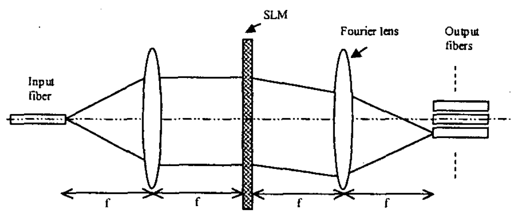

Figure 3 A typical 1xN LC-SLM optical switch.

4 LC-SLM-based dynamic spectral equalization

As data and Internet traffic continue to drive the need for higher bandwidth and longer connection distances, network designs must enable dynamic channel equalization with minimum insertion loss to provide complete wavelength flexibility at the network nodes. Figure 4 shows the principle of operation of an LC-based optical dynamic spectral equalizer. A holographic diffraction grating separates the incoming WDM channels, then a liquid-crystal SLM selectively blocks or attenuates the various channels. At the output, another holographic diffraction grating is used to recombine the optical channels into a single fiber. Dynamic spectral equalizers have low polarization-dependent loss and can achieve channel-blocking isolation as high as 35 dB and up to 15 dB of pass-through channel attenuation.

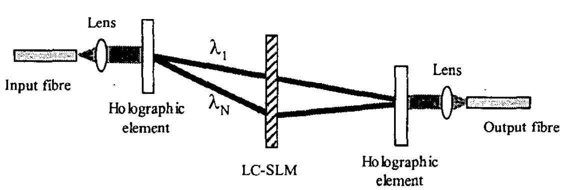

Figure 4. Dynamic spectral equalizer using liquid crystal spatial light modulation.

The principle of dynamic spectral equalizer can also be used to dynamically flatten the gain spectrum of an erbium-doped fiber amplifier (EDFA). Gain flattening is critical in long WDM optical links, where cascading several EDFAs leads to more amplification for some WDM channels than others. Currently, most EDFA gain-spectrum flattening techniques use a passive optical notch filter (e.g. Bragg grating) whose center wavelength and bandwidth are optimized to flatten the EDFA gain spectrum [13,14]. However, since the EDFA gain depends on the input WDM signal power, the optimization of the optical notch filter can only lead to gain-flattening for a limited range of input power levels. Therefore, in order to maintain a high-quality service, dynamic EDFA spectral equalization is vital. EDFA gain spectrum equalization is based on cascading several optical equalizers whose center wavelengths and weights are dynamically optimized to minimize the gain ripples over a wide bandwidth. Figure 5(a) shows the EDFA response to a uniform WDM input signal. It can be seen that, without a spectral equalizer, the gain around 1530 nm is more than 10 dB higher than that around 1550 nm. Figure 5(b) shows the EDFA output spectrum when a spectral equalizer has been used. Excellent gain equalization is seen over more than 30 nm bandwidth.

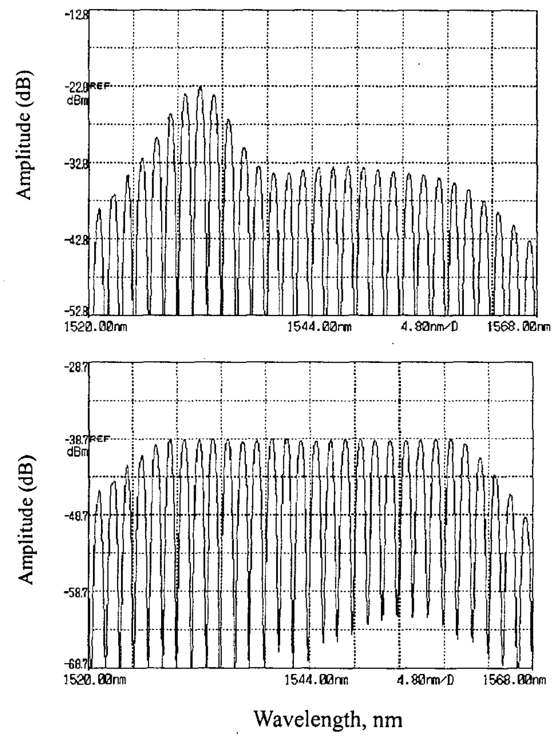

Figure 5. Gain spectrum of an erbium-doped fiber amplifier: (a) without equalisation, (b) with spectral equalization [15].

5 LC-SLM-based tunable optical filter

A tunable optical filter is a key component in optical telecommunication network. Most tunable optical filters are based on mechanically adjustable Fabry-Perot cavity. However, LC SLM can realize optical filtering without the need of moving parts. Figure 6 shows an LC-SLM-based tunable optical filter structure that was reported by Parker et al. [16].

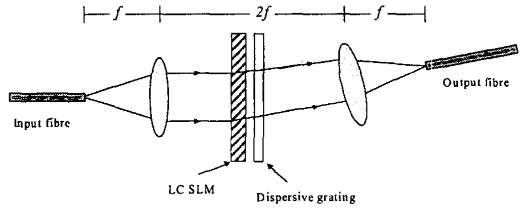

Figure 6. SLM-based tunable optical filter.

A transmissive SLM and a passive high-dispersion grating plate are placed after a lens that collimates the light from an input fiber. The collimated polychromatic light is spatially dispersed by the SLM. Since the SLM has a relatively low dispersion, the grating plate was added to amplify its dispersion, thereby diffracting the various wavelengths through higher-angle directions. A second lens couples a narrow band of the diffracted wavelengths that is aligned to its axis into an output fiber, leading to a bandpass optical filter response. Figure 7 shows a typical response of the optical filter shown in Figure 6. A 3-dB bandwidth of 2.5 nm can easily be achieved. By changing the period of the SLM diffraction grating, one can change diffraction angle, and hence the center wavelength of the optical filter.

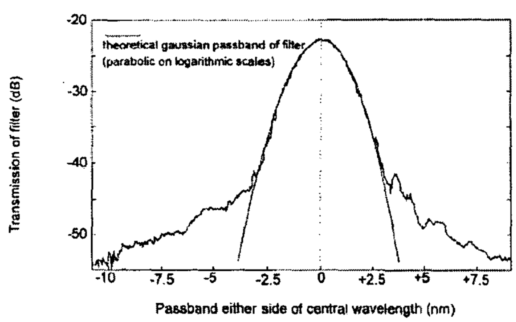

Figure 7. Typical filter response of SLM based optical filter [16].

6 Conclusion

We have shown that the combination of liquid crystal and VLSI technologies can produce high performance liquid crystal spatial light modulators (LC-SLMs), which enable the realisation of key dynamic optical components for future reconfigurable optical telecommunication systems. The ability of LC-SLMs to realise optical beam positioning as well as temporal and spatial beam shaping has been discussed, and topologies of LC-SLM-based dynamic optical components, such as optical switch, dynamic spectral equalizer and tunable optical filter, have been described.

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