Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

Liquid crystal devices for optical communication and information processing systems

Katsuhiko Hirabayashi[a]; Takashi Kurokawa[a]
[a] NTT Opto-electronics Laboratories, Kanagawa, Japan

To cite this Article Hirabayashi, Katsuhiko and Kurokawa, Takashi(1993) 'Liquid crystal devices for optical communication and information processing systems', Liquid Crystals, 14: 2, 307 — 317
To link to this Article: DOI: 10.1080/02678299308027645
URL: http://dx.doi.org/10.1080/02678299308027645

LIQUID CRYSTALS, 1993, VOL. 14, NO. 2, 307–317

Liquid crystal devices for optical communication and information processing systems

by KATSUHIKO HIRABAYASHI* and TAKASHI KUROKAWA
NTT Opto-electronics Laboratories, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa, 243-01, Japan

This paper reviews liquid crystal optical devices including tunable filters, photonic switches and spatial light modulators, and examines their application to optical communication and information processing systems. Optical processing has three major advantages: massive parallelism, high speed and broad wavebands. Compared with typical optical materials including silica, semiconductors and inorganic electrooptic crystals used in communication systems, a liquid crystal has a number of outstanding features including its large refractive index change and large polarization rotation power at a low voltage. These features make it possible to develop new optical components.

1. Introduction

Recently, optical fibre communication systems have advanced rapidly. However, switching and processing are both done electrically. The light is converted to an electrical signal at each end of the fibre, then switched and processed electrically, and re-converted to light. Electrical switching and processing limits both processing speed and transmission capacity.

To overcome these drawbacks, optical switching and processing are being actively studied; here light signals are switched and processed optically without being converted into electrical signals. Optical switching and processing systems fall into three categories: time division, space division and wavelength division. Space division can be sub-divided into waveguide and free space types.

Although liquid crystal (LC) optical devices are not suitable for time division optical processing, because of their slow response, they are suitable for wavelength and free space division processing, because of their large refractive index change at low voltages, large polarization rotation power and the ease with which two dimensional (2D) devices can be prepared.

NTT Laboratories are developing LC optical devices for optical communication and information processing systems, using these outstanding features.

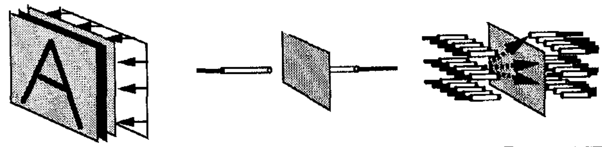
This paper reviews these devices: tunable wavelength selective filters [1, 2], photonic switches [3–5] for optical communication system and LC-spatial light modulators (LC-SLM) [6, 7] for optical information processing.

2. Differences between LC displays and optical devices

Today's LC technology has been developed mainly for displays. LCs for displays and optical devices have different requirements, as summarized in Table 1. LC displays operate at visible wavelengths over a wide range (0·4–0·7 μm), while LC optical devices operate in the infrared over a narrow range (0·85 μm, 1·3 μm, 1·55 μm). The characteristics of LCs have been studied well in the visible range, but not in the infrared

* Author for correspondence.

Table 1. Differences between LC displays and LC optical functional devices.



	Display	Optical Devices
Wavelength	Visible (0·4–0·7 μm) Wide range	Infrared (0·85 μm, 1·3 μm, 1·55 μm) (Narrow range)
Contrast	<100	>100
Size	Large (20 × 30 cm)	Small (1 × 1 cm)
Beam diameter	Large	Small (100 μm)

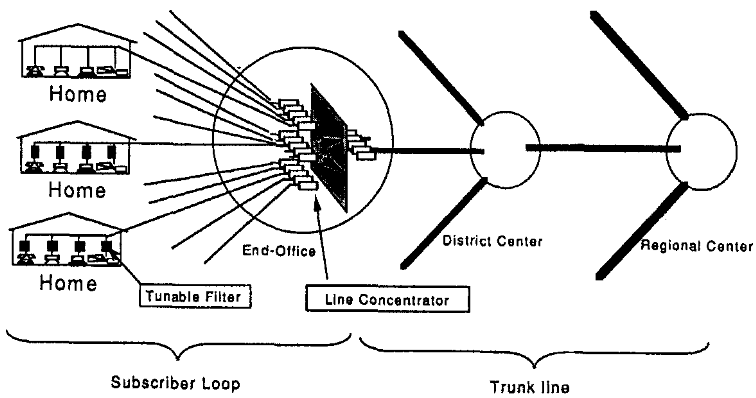


Figure 1. Optical communication network, which can be divided into trunk line and subscriber loop.

range. A contrast of around 100 is enough for displays, while higher contrast is required for optical devices. Displays are large, while optical devices are small (a few centimetres square), and uniformity is necessary. Beams passing through optical devices are very narrow (around 100 μm). Thus, the requirements for LC optical devices are more severe.

3. LC devices for optical communication systems

Optical fibre networks can be divided into subscriber loops and trunk lines as shown in figure 1. Today, trunk lines are optical fibres, while the subscriber loops are mainly still metal cables, which will be replaced by optical fibres in the near future. The trunk lines require high-speed (<1 ns) optical devices, while the subscriber loops require a large number of terminals, wide wavelength range, low cost and high reliability. GaAs and InP semiconductor devices and $LiNbO_3$ electro-optic devices are suitable for the trunk line system due to their fast response time. Although LC devices are too slow for the trunk line system, they are suitable for the subscriber loop systems, because of their low cost, their large change in refractive index at low voltages, their large polarization rotary power and the ease with which two dimensional (2D) devices can be prepared.

3.1. *Tunable wavelength-selective LC Fabry–Perot interferometer filter (LC-FPI)*

Wavelength division multiplexing (WDM) is a key technology for increasing transmission capacity. In the TV broadcast system, many channels are multiplexed by WDM and distributed to homes, where any channel can be selected by a tunable filter. Thus, a tunable wavelength selective filter is a key device in WDM systems. It must have a narrow bandwidth, a wide tuning range and a low loss. Conventional filters include a mechanically controlled grating monochromator and a piezoelectrically controlled Fabry–Perot interferometer [8], each of which has its own disadvantage such as bulky size, high operating voltage, high cost, poor reliability and excessive complexity.

To overcome these disadvantages, the authors developed a tunable LC filter [1], whose structure and mechanism are shown in figure 2. It has an LC layer sandwiched between two glass plates coated with indium tin oxide (ITO) transparent electrodes, dielectric mirrors, and thin alignment layers. Thus it is basically a Fabry–Perot interferometer with an LC intra-cavity. The resulting LC-FPI has a very simple structure, and is cheap and reliable. When a voltage is applied, LC molecules are realigned and the refractive index varies, as shown in figure 2(*b*). The resonance wavelength is shifted by the change in refractive index. The transmission spectrum of a typical LC-FPI with 99·5 per cent mirrors is shown in figure 3. The bandwidth (FWHM) is about 0·17 nm, the free spectral range is about 50 nm, the finesses is >400

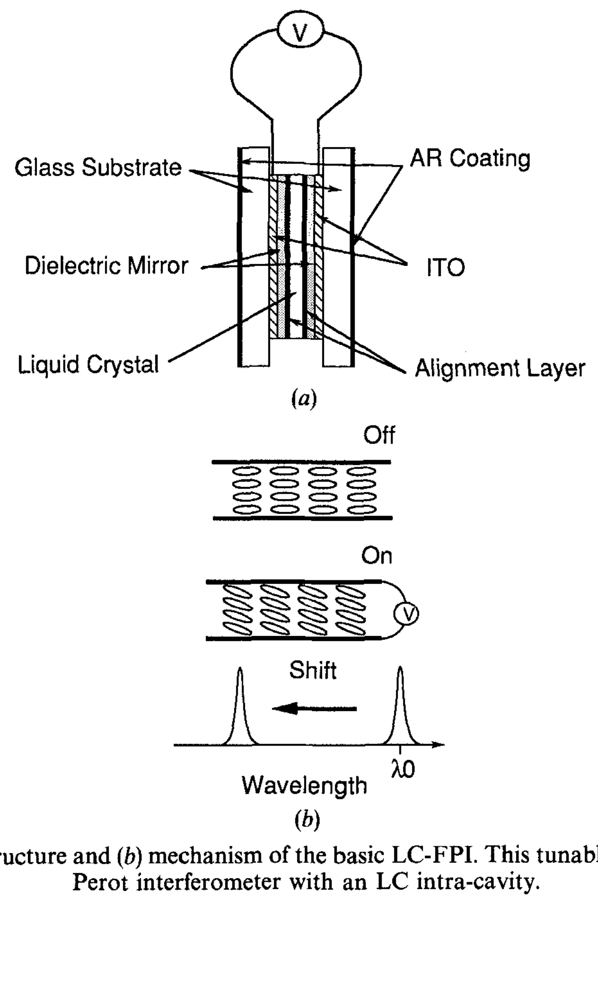


Figure 2. (*a*) Structure and (*b*) mechanism of the basic LC-FPI. This tunable filter is a Fabry–Perot interferometer with an LC intra-cavity.

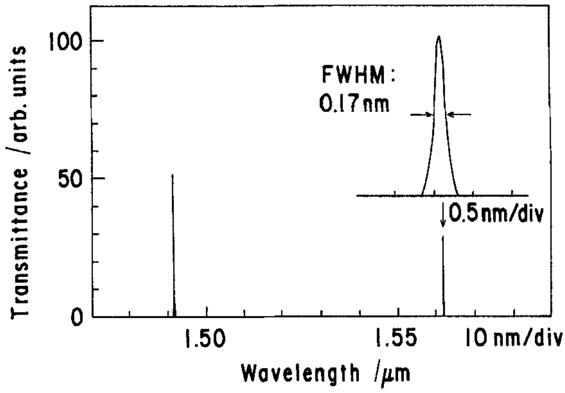


Figure 3. Transmission spectrum of a typical LC-FPI with 99·5 per cent mirrors.

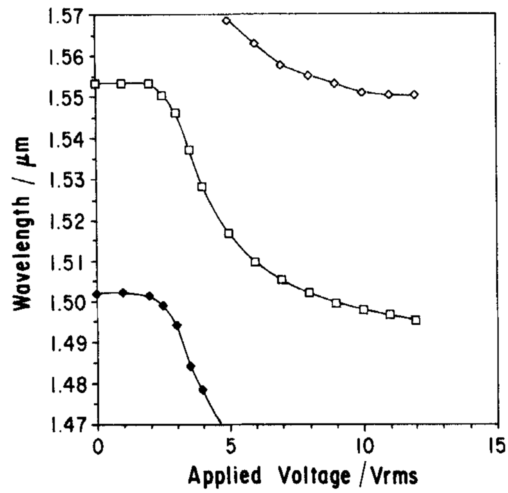


Figure 4. Tuning performance of an LC-FPI with a tuning range of about 50 nm.

and the loss is about 5 dB. The applied voltage dependence of the peak wavelength is shown in figure 4. The peak shifted 50 nm when only 12 V was applied. The tuning range is dependent on Δn of the LC. A typical tuning range is 50 nm–130 nm at 1·5 μm wavelength.

Frequency division multiplexing (FDM) requires a narrower bandwidth. Because a longer cavity gap narrows bandwidth, a double layer cavity LC-FPI was fabricated [2], where part of the LC layer was replaced by a 55 μm thin glass plate. The FWHM is 0·07 nm and the free spectral range is about 10 nm. We examined the ability of these two types of filter to select one of two light sources separated by 1 nm or 22 GHz. The non-selected channel was 15–20 dB below the selected channel which means that these filters are potentially capable of selecting over 50 channels.

The number of selectable channels can be increased by cascading two LC-FPIs. Each is operated by its own driver. The first LC-FPI has a tunable range of 130 nm. The double layer cavity LC-FPI has a very narrow bandwidth of 0·07 nm. The transmission peak of one LC-FPI was adjusted manually to that of the other so that only one transmission peak appeared in the wavelength range 1·47–1·60 nm. This peak has a narrow bandwidth of 0·067 nm and a wide tuning range of 130 nm. The transmittance was about 30 per cent. This filter is capable of selecting one channel from among over 600 [10]. The specifications of the above types of LC-FPIs are summarized in table 2.

Although these LC-FPI filters are basically polarization dependent, various polarization independent types of LC-FPIs have been proposed [9, 11]. The polarization independent LC-FPI module is shown in figure 5. This module is very compact with a bandwidth of 0·4–0·5 nm, tuning range of about 50 nm, loss of about 4 dB and polarization dependence below 0·5 dB.

Maeda and Patel in Bellcore have studied such tunable filters for application to WDM transmission systems [12, 13].

Table 2. Specifications of LC-FPIs.

Type	Bandwidth (nm)	Tunable range (nm)	Loss (dB)	Channels
Ordinary type	0·3	50	2–3	50
Wide tuning range type	3·4	130	0·3	10
Narrow bandwidth type	0·07	10	4	50
Cascaded type (Wide tuning + narrowband)	0·07	130	4–5	600

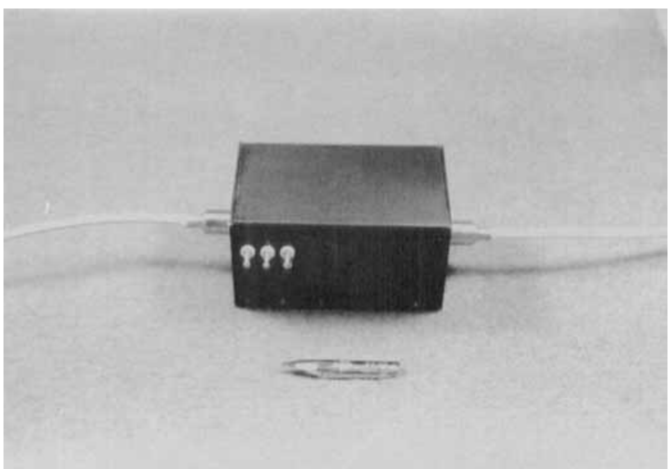


Figure 5. Polarization independent LC-FPI module.

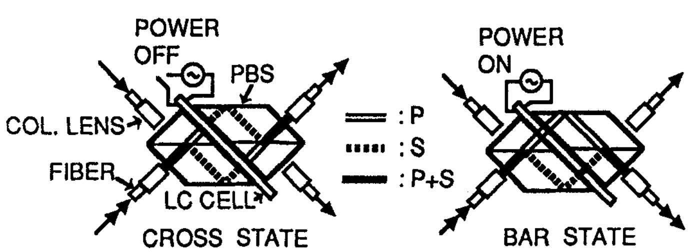


Figure 6. Structure of the LC 2 × 2 photonic switch.

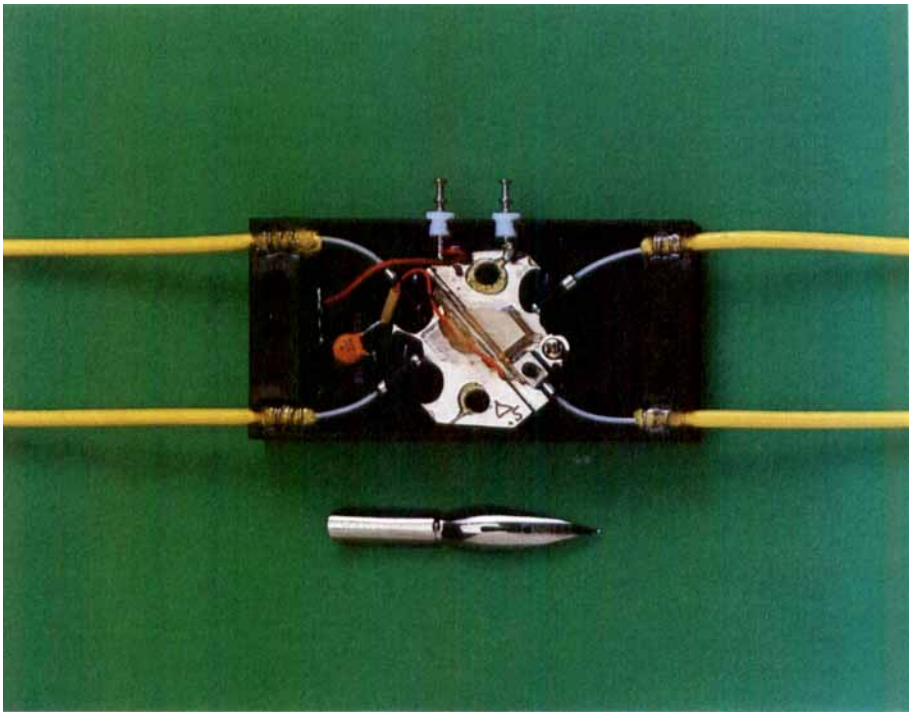


Figure 7. 2 × 2 LC photonic switch.

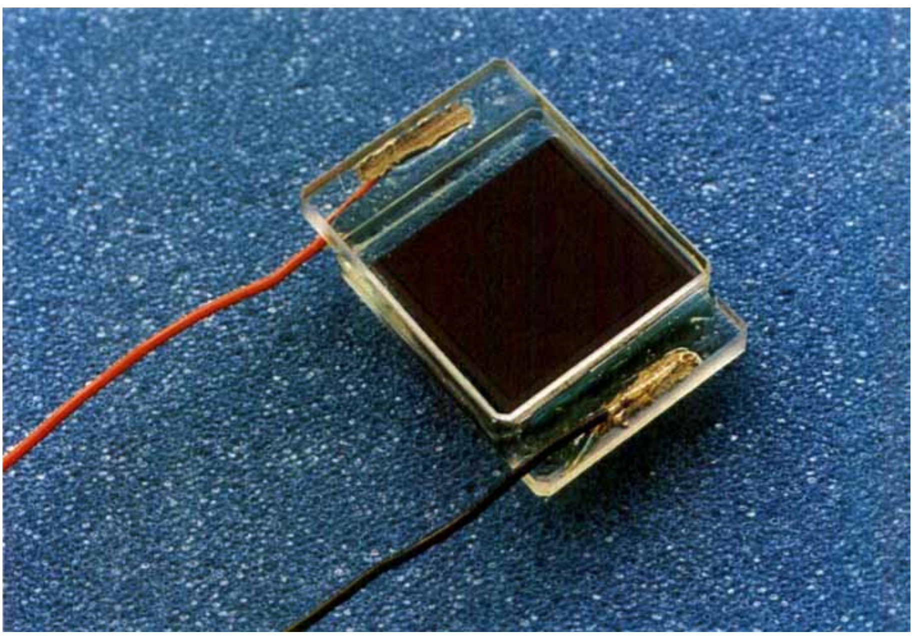


Figure 10. A typical LC-SLM.

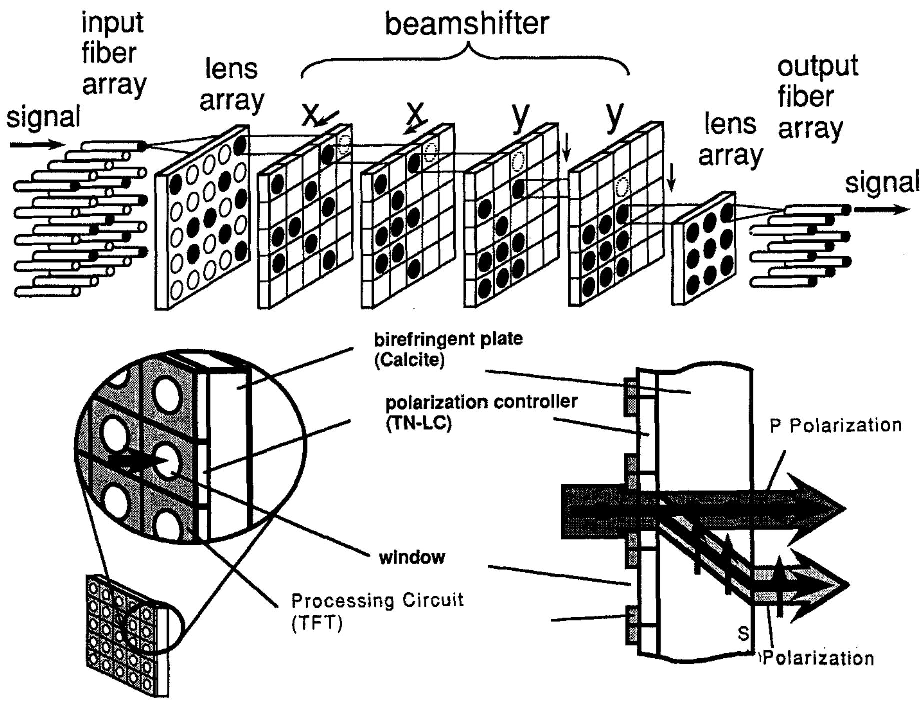


Figure 8. Structure of a 2-D photonic switch using array beam shifters.

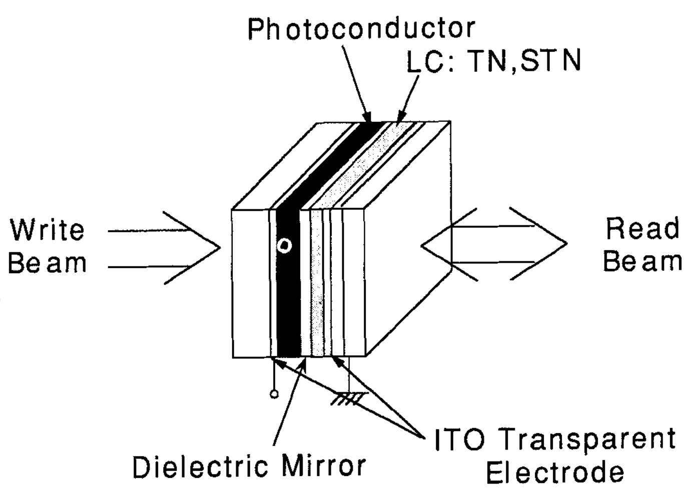


Figure 9. Structure of a typical LC-SLM.

3.2. *Optical switch*

A 2×2 optical switch is a basic device for the subscriber loop system. When a system suffers a failure, 2×2 switching to a backup system is necessary. Kurokawa and Yoshizawa [3] have developed a 2×2 optical switch using a TN-LC. The structure and a photograph of a 2×2 optical switch based on the polarization division configuration are shown in figures 6 and 7. The collimated beam from a single mode fibre is divided by a polarization beam splitter (PBS) into two beams with orthogonal linear polarizations. When no bias voltage is applied, the polarization of the light transmitted through the cell is rotated 90 degrees, and vice versa. The propagation direction of the polarization is switched by the PBS. The insertion loss and cross-talk were 1·4 dB and 26 dB, respectively. The polarization dependence was negligible at less than 0·1 dB and the back reflection loss was more than 23 dB. It was driven at a switching speed of 10 ms with 5 V because it had an LC oscillator inside.

The end office of the subscriber loop system needs switches between many input and output fibres. Thus, the line concentrator, which picks up all the live lines among the input lines and connects them to output lines is a key device (see figure 1). Although 8×8 matrix waveguide switches [14] have been reported, larger matrix waveguide optical switches are very difficult to make, because of the increase in switch volume and loss as the number of the terminals increases. LC free space division optical switches have been studied as the concentrators because of ease of preparing 2D devices like LC displays.

Two types of $N \times M$ free space switches, the 2-D photonic switch using array beam shifters [4] and the hologram-type optical switch [5] have been developed at NTT.

The structure of a 2-D photonic switch using array beam shifters is shown in figure 8. This switch consists of an input fibre array, lens array, array beam shifters and output fibre array. The array beam shifter shifts the beam in one direction, either the X or Y direction. These beam shifters are cascaded and consist of a photodetector, processing circuit, polarization controller, and birefringent plate. The TN-LC panels act as polarization controllers. The pixel size is $0{\cdot}33 \times 0{\cdot}33$ mm. The processing circuit is a thin film transistor (TFT). When the output beam from the polarization controller has P-polarization, it goes straight through the birefringent plate and exits from the same cell. When the output beam has S-polarization, the beam bends and shifts to the next cell. A $25(5 \times 5) \times 9(3 \times 3)$ switch whose effective size is $5\,\text{mm} \times 5\,\text{mm} \times 40\,\text{mm}$ has been successfully made. Recently, a 1024 input/256 output switch, which uses 8 stage array beam shifters has been successfully produced with an insertion loss of 6·8 dB [15].

These 2-D photonic switches using array beam shifters require a number of LC panels to be cascaded. On the other hand, a single hologram-type switch can distribute optical beams to any output port [5]. A commercial TFT-LC display panel can be used as a real time phase hologram-type switch. The input beams are diffracted in any direction by a grating pattern made on the TFT-LC panel. In the experiment, a TFT-LC panel with 640×400 pixels was used. The 4×4, 1×64 and 2×32 hologram-type free space photonic switches have been successfully made. The switching speed was about 100 ms, the loss was 13 dB and the on/off ratio was 12 dB.

3.3. *Other LC devices for optical communication and information processing*

Using the above outstanding features of LCs, various types of other optical devices have been developed. LC modulators were actively studied. However the slow modulation speed [16–18] has diminished interest in them. The bandwidth of a Ryot LC filter was too wide to be used for WDM systems [19]. In contrast, the tunable

LC-FPI filter described in this paper is suitable. For waveguide space division, the 2×2 switches [20, 21] had the serious disadvantage of polarization-dependence. Free space division devices [22–26] have attractive possibilities for optical communication systems.

4. LC devices for optical information processing

A light beam carries information with very high throughput because of the inherently massive parallelism of light in free space. Processing light beams is thus particularly effective for inherently two dimensional data, such as optical images and matrix data arrays. For instance, holographic filtering can obtain the spatial multiplication of Fourier transforms in parallel by utilizing the spatial coherence of light. Also introducting a parallel algorithm makes optical digital operation more effective, by using such unique pattern logics as symbolic substitution and optical array logic. SLMs are expected to evolve as key devices for optical information processing in free space because they can spatially, as well as temporally, modulate a two dimensional optical wavefront.

4.1. *LC-SLMs*

There are two types of SLMs: electrically addressable and optically addressable SLMs. The latter are more important for parallel information processing because 2-D optical data can be input without being converted to serial electrical data. A typical structure and a picture of an optically addressable LC-SLM are shown in figures 9 and 10. It has a sandwich structure consisting of an a-Si photoconductive layer (PC), a dielectric mirror layer, and LC layer and two ITO layers. Optically addressable SLMs must be sensitive, and offer a logic function and memory as well as faster switching and higher resolution. We have used super twisted nematic (STN) LC [6] and ferroelectric LC (FLC) for SLMs [7]. STN-LC has very steep threshold characteristics. An STNLC-SLM works well even if the a-Si layer is as thin as 1 μm, in contrast to a conventional TNLC-SLM, which needs a 10 μm a-Si layer. SLM sensitivity can be significantly increased to 2 μW cm^{-2} at 50 Hz operation by using the STN-LC, because the photoconductive layer is so thin. This is in contrast to the low sensitivity (about 10 μW cm^{-2}) of the conventional TN-SLMs. The STNLC-SLM has been applied to projection displays, where a CdTe blocking layer is inserted between the a-Si photoconductive layer and the dielectric mirror. The intensity of the input image can be amplified 10^3 times.

A FLC-SLM has excellent performance, including higher speed (60 μs), a memory function and high resolution (250 lp mm^{-1}). The FLC-SLM [7] can be applied to a range of parallel optical information processing.

By cascading two or three FLC-SLMs, optical image processing becomes possible [27]. When images A and B are input on the SLMs, both $A \cdot B$ and $\bar{A} \cdot B$ are obtained corresponding to two operation modes. These basic logic and memory functions make it possible to construct an optical image processor capable of performing all 16 boolean functions in parallel on the two optical binary images.

The FLC-SLMs ability to record interference patterns makes it a promising candidate for a real time hologram device, because of its high resolution (250 lp mm^{-1}) and high diffraction efficiency (40 per cent) [28]. Another application of the FLC-SLM is image encipherment [29].

S. Fukushima and T. Kurokawa [30] have recently proposed one-way direct image transmission over an optical fibre using an FLC-SLM as a phase conjugation mirror

(PCM) with an image input function. Although direct image transmission without image distortion had been proposed and demonstrated, based on an optical phase conjugation mirror [31], the reconstructed images end up in the same place as their original images. This problem can be overcome using FLC-SLM.

5. Conclusions

The usefulness in optical communication and information processing will lead to a growing market for LC optical devices, because optical fibres will be distributed to almost all homes in the near future.

Further improvements in LC technology are necessary, because today's technology was developed for displays, the requirements for which are less rigorous than for optical devices. LC switching speed is very slow for optical devices. Furthermore, although LC performance has been studied at visible wavelengths, studies are still needed at infrared wavelengths, especially 0·85 μm, 1·3 μm and 1·55 μm for communication and information processing. The LC contrast ratio may be enough for displays, but is too low to be applied to optical devices. These disadvantages must be overcome for optical devices.

Compared to semiconductor devices, however, LC optical devices are easy to make, inexpensive and reliable. As research on LC displays continues to mature, research on LC photonic devices for wavelength and free space-division will become active.

The authors wish to thank Dr T. Ikegami and Dr T. Sugeta for their encouragement, and Mr S. Fukushima and Mr T. Yoshizawa of NTT Opto-electronics Laboratories and H. Yamazaki and M. Yamaguchi of NTT Communication Switching Laboratories for supplying and discussing information.

References

[1] Hirabayashi, K., Tsuda, H., and Kurokawa, T., 1991, *I. E.E.E. Photon. Technol. Lett.*, **3**, 213.
[2] Hirabayashi, K., Tsuda, H., and Kurokawa, T., 1991, *I.E.E.E. Photon. Technol. Lett.*, **3**, 741.
[3] Kurokawa, T., and Yoshizawa, T., 1990, *Photonic Switching 2* (Springer Series in Electronics and Photon., Vol. 29), edited by K. Tada and H. S. Hinton (Springer-Verlag), p. 342.
[4] Yamaguchi, H., and Kobayashi, I., 1989, *Proceedings of ECOC'89*, Gothenburg, p. 272.
[5] Yamaguchi, H., and Yamaguchi, M., 1991, *Optics Lett.*, **16**, 1415.
[6] Hirabayashi, K., Fukushima, S., Kurokawa, T., and Ohno, M., 1991, *Optics Lett.*, **16**, 765.
[7] Fukushima, S., Kurokawa, T., Matsuo, S., and Kozawaguchi, H., 1990, *Optics Lett.*, **15**, 285.
[8] Mallison, S., 1987, *Appl. Optics*, **26**, 430.
[9] Hirabayashi, K., Ohiso, Y., and Kurokawa, T., 1991, *I. E.E.E. Photon. Technol. Lett.*, **3**, 1091.
[10] Hirabayashi, K., and Kurokawa, T., 1992, *I.E.E.E. Photon. Technol. Lett.*, **4**, 597.
[11] Hirabayashi, K., and Kurokawa, T., 1992, *I.E.E.E. Photon. Technol. Lett.*, **4**, 740.
[12] Patel, J. S., Saifi, M. A., Berreman, D. W., Lin Chinlon, Andreadakis, N., and Lee, S. D., 1990, *Appl. Phys. Lett.*, **57**, 1718.
[13] Maeda, M. W., Patel, J. S., Lin Chinlon, Horrobin, J., and Spicer, R., 1990, *I.E.E.E. Photon. Technol. Lett.*, **2**, 820.
[14] Kondo, M., Komatsu, K., Suzuki, S., Mitsuhasi, M., and Ohta, Y., 1986, *Record of National Convention of IECEJ*, p. 289 (in Japanese).
[15] Yamaguchi, M., Matsunaga, T., and Sirai, S., 1992, *Photonic Switching*, Minsk, July, 1A5.

[16] CHANNIN, D. J., 1973, *Appl. Phys. Lett.*, **22,** 365.
[17] VEILLEUX, C., LAPIERRE, J., and BURES, J., 1986, *Optics Lett.*, **11,** 733.
[18] LIU, K., SORIN, W. V., and SHAW, H. J., 1986, *Optics Lett.*, **11,** 180.
[19] WU SHIN-TSON, 1989, *Appl. Optics*, **28,** 48.
[20] KOBAYASHI, M., TERUI, H., KAWACHI, M., and NODA, J., 1982, *I.E.E.E. Jl quant. Electron.*, **18,** 1603.
[21] SHANKER, N. K., MORRIS, J. A., YAKYUMYSHYN, C. P., and POLLOCK, C. R., 1990, *I.E.E.E. Photon. Technol. Lett.*, **2,** 147.
[22] HIRABAYASHI, K., and KUROKAWA, T., 1992, *I.E.E.E. Photon. Technol. Lett.*, **4,** 737.
[23] SASAKI, A., and ISHIBASHI, T., 1979, *Electron. Lett.*, **15,** 293.
[24] SATO, S., 1983, *Kougaku*, **12,** 160 (in Japanese).
[25] SATO, S., 1979, *Jap. J. appl. Phys.*, **18,** 1679.
[26] ASCHAM, S. R., WILTSHIRE, M. C. K., MARSH, S. J., and GIBBONS, A. J., 1990, *ECOC'90*, p. 393.
[27] FUKUSHIMA, S., and KUROKAWA, T., 1991, *I.E.E.E. Photon. Technol. Lett.*, **3,** 682.
[28] FUKUSHIMA, S., and KUROKAWA, T., 1991, *Appl. Phys. Lett.*, **58,** 787.
[29] FUKUSHIMA, S., KUROKAWA, T., and SAKAI, S., 1991, *I.E.E.E. Photon. Technol. Lett.*, **3,** 1133.
[30] FUKUSHIMA, S., and KUROKAWA, T., 1992, *I.E.E.E. Jl quant. Electron.* (to be published).
[31] OLSSON, N. A., LOGAN, R. A., and JOHNSON, L. F., 1984, *Electron Lett.*, **20,** 673.