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# Ferroelectric Liquid Crystal Optical Interconnect Switching Systems

## FINAL REPORT

Joseph W. Goodman, Principal Investigator

February, 1993

U. S. Army Research Army

Contract No. DAAL03-89-K-0102

Stanford University

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**Grant Number: DAAL03-89-K-0102**

### **Statement of the Problem Studied**

This grant explored the possible use of ferroelectric liquid crystals (FLC's) in the reamization of photonic switching fabrics. Problems addressed included device fabrication, switch architectures, and switch performance. Experimental versions of most architectures were constructed.

### **Scientific and Technical Accomplishments**

This contract began in August of 1989 and concluded at the end of December, 1992. The aim of the contract was to develop techniques for using ferroelectric liquid crystals (FLC's) for novel photonic switching architectures. In the beginning of the contract and through approximately its first two years, two Ph.D. students were supported by the grant, Robert McRuer and Lawrence McAdams. Both received their Ph.D. degrees in 1991.

Initial work was devoted to mastering the technology of making FLC polarization rotation shutters, which formed the basis for the switching architecture work to follow. Much of this work was performed using the facilities of Stanford's Center for Integrated Systems. We were able to build such shutters with respectable properties, including reasonable uniformity, an insertion losses of the order  $X$  dB and extinction ratios of the order of  $Y$  dB. Switching speeds observed were of the order of  $ZZZ$ . Having mastered the basic shutter technology, we moved on to employing such shutters in novel architectures.

Work on one architecture had begun before the initiation of the grant and was completed shortly after the grant began. A description of this switch was published in *Applied Optics* in late 1990 (Ref.[1]).

Many of the architectures of interest depended on a basic building block, namely a  $1 \times N$  switch. Such a device takes a single incoming optical signal and switches it to one of  $N$  possible output beams. Such switches were successfully built and were described in a paper published in *Optics Letters* in 1990 (Ref. [2])

Following the development of this building block, we focused attention on a method for constructing an  $N \times N$  network based on the use of  $2N$  of the  $1 \times N$  switching components. This network is strictly non-blocking.  $N$  of the  $1 \times N$  components are used to fan out the incoming signals, and  $N$  of the  $1 \times N$  devices are used to fan in the signals. This

architecture forms a crossbar switch with double crosstalk rejection, due to the use of active switches at both the input and the output. We built and evaluated a 4x4 version of this architecture. The network had an insertion loss of 1 to 7 dB, depending on the connection, and a crosstalk between -20 and -30 dB. The reconfiguration time was 40  $\mu$ sec. A description of this switch was published in a book on optical switching (Ref. [3]).

In the meantime we had conceived of some new ideas that we began to investigate. Mr. McRuer conceived of a new type of photonic switching architecture based not on the 1xN switches developed earlier, but rather on 1x2 digital deflecting elements made from liquid crystals. These switches used FLC switchable wave plates sandwiched between nematic liquid crystal prisms. The liquid crystal prisms serves as polarization sensitive deflectors. When one polarization is incident on the prism, no deflection occurs, but when the polarization has been rotated 90 degrees, deflection does occur. Such polarization sensitive prisms were found to be rather easy to make using nematic liquid crystals. A 1x64 scanner was demonstrated with an average loss of -5.3 dB. Crosstalk was reduced to -25 dB by use of an active filter. This work was published in *Optics Letters* in 1990 (Ref. [4]).

Mr. McAdams was the chief inventor of a new type of liquid crystal tunable Fabry-Perot etalon that could prove useful in dense WDM networks using tuning of optical filters to achieve configuration of the network. The unique aspect of this etalon, differentiating it from previous work done at Bellcore, was that it used oblique incidence, with several desirable properties resulting. The etalon was constructed from nematic liquid crystals. We demonstrated a prototype with an insertion loss of -1.7 dB, a finesse of 15.1, a free spectral range of 20.4 nm, and a continuous tuning range of over 40 nm with less than 5 volts applied. The tuning time was of the order of  $\mu$  msec. These results were reported in *Optics Letters* in 1991 (Ref. [5]).

In 1991 both Mr. McAdams and Mr. McRuer completed their doctorate dissertations and left Stanford (Refs. [6] and [7]).

Following the departures of Drs. McAdams and McRuer, a new student joined the project, Ms. Jane Lam. Following up on a suggestion by Dr. McAdams, Ms. Lam began investigating a new device concept aimed at realizing liquid crystal switches in integrated form rather than in the bulk form that had been pursued previously. The basic idea to be investigated is explained in what follows.

Ferroelectric liquid crystals are bistable, birefringent materials. The optical axis of a surface stabilized cell containing such material can have an optical axis that can be switched between two states.

As with any birefringent material, the refractive index experienced by a light wave passing through the material depends on polarization and the angle between an incident ray and the optical axis. If we align the optical axis of one state along the incident beam direction, only the ordinary index will be seen. In the other state, the refractive index experienced depends on the polarization of the incident wave and the angle between the incident direction and the optical axis. For SmC\* ferroelectric liquid crystal, this angle is about 45 degrees. The two states have different refractive indices and as a result beam walk-off will occur. Even when the wave vectors of the two states are in the same direction, the ordinary and extraordinary rays will be separated by walk-off. If beam walkoff can be introduced by application of a suitable voltage across the liquid crystal material, and if the two resulting beams can be physically separated, then we have achieved a method for photonic switching. The goal was therefore to try to exploit walk-off as a means for switching.

The FLC cell usually used is shown in Fig. 1, with the incidence direction perpendicular to the surface. There is beam walk-off inside the device, but unfortunately not enough to separate the two polarization states, since the cell is only a few microns thick. Although there is angular separation, the extraordinary ray needs to travel some distance before it can be spatially separated from the ordinary ray.

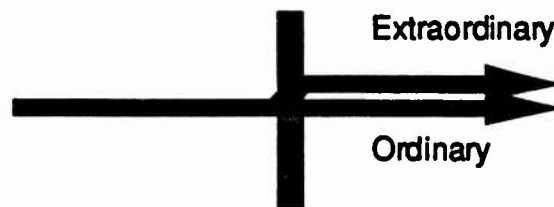


Figure 1. The extraordinary and ordinary rays can not be separated because the cell is too thin

The use of a planar waveguide made of FLC material provides a possible method for overcoming the limited spatial walkoff possible in a bulk device. The idea is illustrated in Fig. 2. Surface stabilized FLC has an optical axis that is parallel to the cell surface, so the walk-off direction is along the surface, while the guiding is in the orthogonal direction. The spatial separation can be controlled by choice of the electrode width along the cell surface.

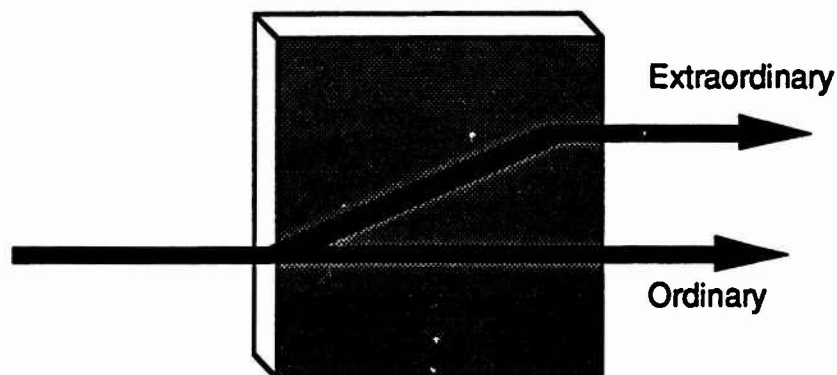


Figure 2. An FLC cell as a planar waveguide. Guiding is horizontal, spatial separation is vertical.

If a simply 1x2 switch could be made using this technique, then obviously several such devices could be cascaded, presumably within a single waveguide, to make a larger 1xN switch.

The device described above is an extremely complex one to understand from a full theoretical viewpoint. A proper understanding can only be developed on a modal basis. Conventional waveguide theory does not apply because of the birefringent nature of the material.

A long and detailed analysis of this structure was carried out by Ms. Lam. It was found that it is not possible to switch between pure ordinary and extraordinary modes, but rather than combinations of both are always present. Some help in this analysis was provided near the end by Ms. Irena Erteza, whose separate thesis had been devoted to new methods for analyzing wave propagation in waveguides. However, in the end we have concluded that the proposed device will probably not work, although we also have the feeling that further work on the device by someone might yield a breakthrough concept that would enable the difficulties to be overcome. No publications have resulted from this part of the effort.

Work was completed on the grant on December 31, 1992.

#### **Publications under the Grant**

[1]. L.R. McAdams, R.N. McRuer, J.W. Goodman, "Liquid crystal optical routing switch", *Applied Optics*, 29, 1304-1307 (1990).

[2]. L.R. McAdams, J.W. Goodman, "Liquid crystal 1 X N routing switch", *Optics Letters*, 15, 1150-1152 (1990)

[3]. L.R. McAdams and J.W. Goodman, "Ferroelectric liquid crystal 4x4 optical interconnect", in *Photonic Switching II*, K. Tada and H.S. Hinton, editors, Springer-Verlag, Berlin, 346-349 (1990)

[4]. R. McRuer, L. McAdams, J.W. Goodman, "Ferroelectric liquid crystal digital scanner", *Optics Letters*, **15**, 1415-1417 (1990).

[5]. L.R. McAdams, R.N. McRuer, J.W. Goodman, "Oblique-incidence liquid-crystal-tunable étalon", *Optics Letters*, **16**, 864-866 (1991).

[6].L.R. McAdams, *Photonic Switching with Liquid Crystals*, Ph.D. Dissertation, Department of Electrical Engineering, Stanford University, Stanford, California (1991).

[7]. R. McRuer, *Ferroelectric Liquid Crystal Switching Networks*, Ph. D. Dissertation, Department of Electrical Engineering, Stanford University, Stanford, California (1991).

### **Participating Scientific Personnel and Degrees Awarded**

Lawrence R. McAdams (Ph.D. degree 1991)

Robert McRuer (Ph.D. 1991)

Irena Erteza (Ph.D. 1993)

Karin Sperley (M.S. 1990)

Jane Lam (M.S. 1991)

### **Reportable Inventions**

One invention entitled "Oblique Incidence Liquid Crystal Tunable Etalon" was submitted. Patent application was made and assigned U.S. Patent Application Serial Number 07/800,558. A patent has not yet issued.