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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Lithium Niobate Devices in Switching and Multiplexing [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1989 **329**, 83-92
doi: 10.1098/rsta.1989.0060

Phil. Trans. R. Soc. Lond. A **329**, 83–92 (1989) [83]
Printed in Great Britain

Lithium niobate devices in switching and multiplexing

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Integrated-optics devices in lithium niobate have reached a significant maturity in recent years, and several complex devices have been demonstrated. In addition to performing modulation of light in fibre-optic transmission systems, lithium niobate devices currently offer the only components for photonic switching. Thus lithium niobate devices can be used as spatial, temporal and wavelength switches in high-speed and low-speed systems. In these systems electronic signals control the lithium niobate switches, which process the optical information and which are optically interfaced to optical fibres. Hence I am not concerned with all-optical switching. Examples of applications are multiplexing and demultiplexing of high-speed data streams, bit-by-bit or word-by-word switching in, for example, time–space–time stages or in access couplers in high-speed bus systems. Switch arrays, generally operating at lower speeds (below 1 GHz), can be used for network rearrangement, digital crossconnect, protection switching and generally in situations where the frequency and code transparency of the devices can be used to advantage.

The status of lithium niobate devices for switching is reviewed, and performance limitations (including those imposed by polarization properties) and trade-offs are discussed, emphasizing time- and space-switching devices and applications.

1. Introduction

The past decade has seen a dramatic development in the area of optical-fibre communications. The optical fibre is today an unrivalled transmission medium and can, in fact, be regarded as superior to free space, because spreading due to diffraction does not occur. The unique properties of the guided optical wave channel are in this respect the high bandwidth and the low attenuation, the small optical–optical interaction, as well as freedom from electromagnetic interference. The emergence of this new transmission medium and the introduction of a carrier wave at *ca.* 300 THz frequency, replacing electric currents or radio-frequency electromagnetic fields, do, however, raise questions relating to the architecture of future communications and switching systems. The growing amount of information being carried optically and the unique features of optics suggest, in a simplistic way, that advantages could be gained by increasing the optical domain of the total system (in the extreme case an entirely optical system would result). However, development in the area of optical signal processing and related areas has until now lagged behind that within the transmission area.

This paper treats the role and current status of $LiNbO_3$ devices in the area of optical switching in the time and space domains. I am thus concerned with switching of optical informating, the controlling signals being of electronic origin.

2. INTEGRATED-OPTICS SWITCHING DEVICES

The most common integrated-optics switch is the coupled waveguide structure of figure 1, the electro-optic directional coupler (Tamir 1979). Here two optical waveguides are arranged at such a small separation that light is periodically coupled back and fourth between the waveguides in the direction of light propagation. By arranging electrodes at the waveguides, the refractive index can be changed by means of an applied electric field, using the electro-optic effect. Hence, the original phase-matching between the waveguides is destroyed and switching of light between the output ports can be accomplished.

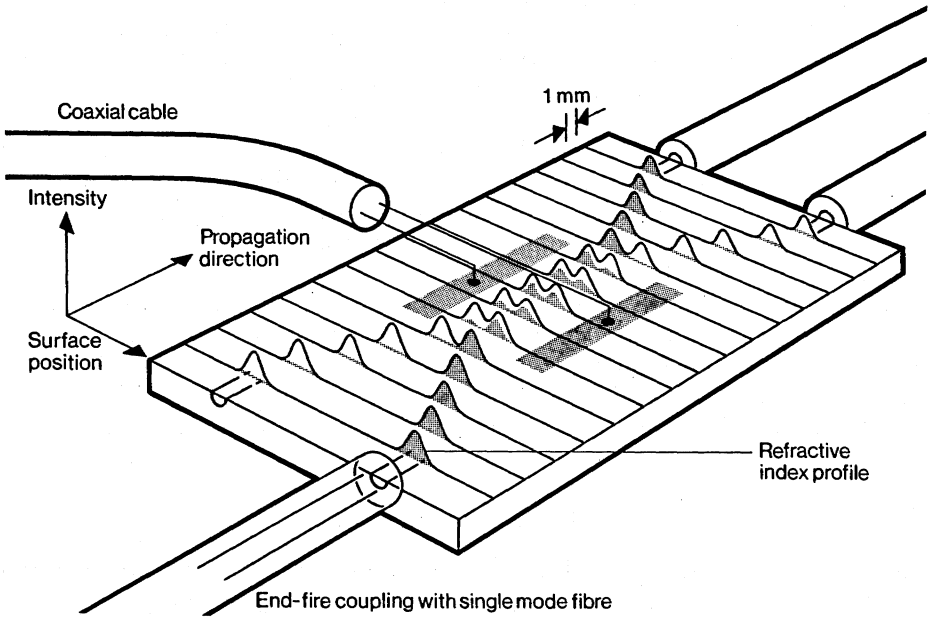

FIGURE 1. Electro-optic directional coupler switch. The incident light (lower left) is switched between the output ports by applying a voltage over the electrodes.

To ease fabrication tolerances (the coupler otherwise has to be an exact multiple of coupling or cross-over lengths) the stepped configuration (Schmidt & Kogelnik 1975) was devised and has been extensively used. However, other four-port switching devices exist, and figure 2 shows in addition to the directional coupler two other types of switches: the crossing waveguide switch (Tsai *et al.* 1978; Neyer 1983) ('X-Switch') and the elongated crossing waveguide switch (Papuchon & Roy 1977) ('BOA-switch'). The electro-optically induced index change has different effects in the latter two. In the 'BOA' and 'X-switch', the refractive index change alters the relative dephasing of the eigenmodes of the composite two-channel coupler ('supermodes') without coupling between the modes, leading to a change in modal interference and hence switching state at the coupler output. In the directional coupler, the 'supermodes' are instead coupled to one another without phase changes, again changing the modal interference. (Coupling and dephasing are interchanged when changing from the supermode to the 'coupled-mode' picture of the interaction.) The exact arrangement of electrodes determines if a structure is operated as a BOA or a directional coupler (Neyer *et al.* 1985).

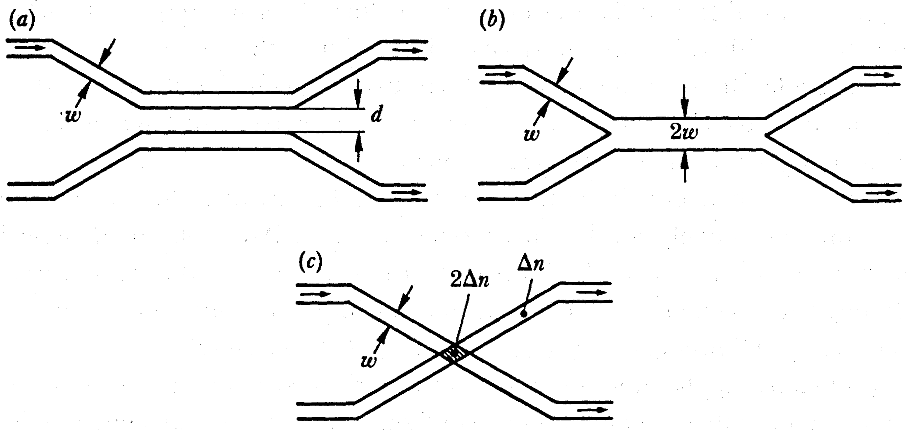

FIGURE 2. Different types of optical switching devices, based on induced (e.g. by an electric field) refractive index changes. (*a*) Directional coupler, (*b*) BOA coupler, (*c*) X-switch.

These switches form the basic building blocks for time and space switches and are used to generate more complex devices as described below.

3. $LiNbO_3$ SWITCHING DEVICES

3.1. *Device types*

$LiNbO_3$ today represents the most mature technology for integrated optics (Thylén 1988). Since the first demonstration of Ti indiffused waveguides in $LiNbO_3$ (Schmidt & Kaminow 1977) the fabrication process has been developed, the material improved and tools for modelling the device fabrication developed (Thylén *et al.* 1983). The relatively simple fabrication of devices of lower insertion loss and drive voltage than is the case for semiconductors has made $LiNbO_3$-devices prevalent and led to the fabrication of increasingly complex structures, which today cover an impressive functional spectrum of which a non-exhaustive listing follows:

high-speed modulators and switches (Alferness *et al.* 1984; Becker 1984; Thylén *et al.* 1984);
polarization converters (Alferness & Buhl 1981; Hedrich *et al.* 1986);
frequency shifters (Wong *et al.* 1984; Kingston *et al.* 1982; Thylén *et al.* 1985);
switch matrices (Granestrand *et al.* 1986; Neyer *et al.* 1986; Bogert 1987);
integrated high-speed devices (Thylén *et al.* 1985*b*; Lagerström *et al.* 1987);
time multiplexers and demultiplexers (Sawano *et al.* 1987);
wavelength filters (Alferness & Schmidt 1978);
polarization-independent devices (Alferness 1979; McCaughan 1984; Granestrand *et al.* 1988*a*; Watson *et al.* 1986).

Some of these devices are highlighted below.

3.2. *Devices for high-speed switching, multiplexing and demultiplexing*

High-speed $LiNbO_3$ devices are generally of the travelling wave type (Izutsu *et al.* 1977; Alferness *et al.* 1984; Becker 1984; Thylén *et al.* 1984), where the modulating electrical signal propagates on a microwave transmission line. In general, integrated-optics high-speed devices are characterized by different figures-of-merit: voltage-length product, bandwidth-length product and bandwidth over voltage derived by dividing the former two. These numbers reflect the basic trade-off between voltage and bandwidth on one hand and length on the other hand. In general, travelling wave (TW) devices are preferred for high-speed applications because of their higher bandwidth/voltage figures.

Representative numbers of voltage times length and bandwidth times length are 80 V mm and 90 GHz mm respectively for TW directional couplers. Attempts to increase bandwidth (such as thicker buffer layers, complex electrode structures, etc.) tend to also increase the drive voltage, although in the small signal régime certain improvements can be made (Thylén & Djupsjöbacka 1985; Djupsjöbacka 1985; Nazarathy & Dolfi 1987).

The most obvious application of high-speed optical switches is for multiplexing and demultiplexing of a number of channels in a configuration such as that shown in figure 3. This is only one possibility of several configurations. Other applications are user interconnect and drop/insert on high-speed data buses. Whereas the application of figure 3 in general concerns switching on a bit-by-bit basis, the latter two could involve bit-by-bit or word-by-word switching. The reason for turning to optical switching is in general the possibility of avoiding high-speed, wideband electronics. Thus, in figure 3, two $\frac{1}{2}N$ b s^{-1} channels, requiring $\frac{1}{4}N$ Hz drive electronics bandwidth, are optically multiplexed by a $\frac{1}{2}N$ Hz narrowband signal to yield a N b s^{-1} output signal. This multiplexing is, however, not trivial and the bandwidth requirements on the multiplexers are higher than superficially expected due to mutual coherence of the source channels (Djupsjöbacka 1988). As a result of dispersion, a single laser source, would be preferred. In all applications, however, the rise time requirements on the switches are of the order of the bit rate, any significant deviation from this can only be achieved by using techniques such as 'guard time slots' between words in word-by-word multiplexing.

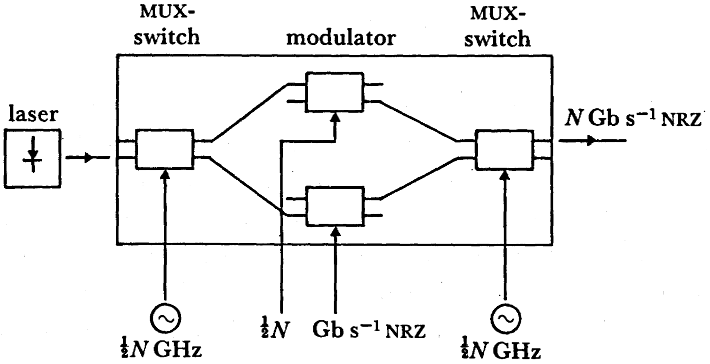

FIGURE 3. Optical multiplexing of two $\frac{1}{2}N$ Gb s^{-1} signals. The requirements on electronic bandwidth are reduced by multiplexing in the optical domain.

A cascade of TW $LiNbO_3$-switches which performs demultiplexing has been demonstrated (Sawano *et al.* 1987). In this case a 1.6 Gb s^{-1} RZ data stream was demultiplexed into four 400 Mb s^{-1} channels, utilizing three cascaded TW switches.

Another application of $LiNbO_3$-switches in high-speed networks is described below.

Integrated-optic devices can be used as, for example, switchable taps and access couplers. In the case of point-to-point link network in the shape of a ring, the failure of one terminal causes the entire system to go down. If an optical bypass function is provided in such a network, system flexibility as well as reliability increases.

An integrated-optic device in Ti:LiNbO$_3$ that implements such an optical bypass function as well as high-frequency modulation in a 2.4 Gb s^{-1} system has been developed (Thylén *et al.* 1985*a*).

A schematic of the device and its systems environment is depicted in figure 4. In normal operation, the incident data on the fibre bus are coupled to the detector through switch S$_1$, detected and processed. Data to be transmitted (whether repeated or terminal-generated) modulate the directional coupler TW modulator XM, the output of which is coupled to the output fibre through switch S$_2$. The two bypass switches, S$_1$ and S$_2$, are designed so that the chip becomes optically transparent to the bus fibre if the corresponding terminal goes down. Use of the two bypass switches is necessary to prevent direct transmitter–receiver crosstalk, and also normally improves the crosstalk performance. In general, the loss L allowed for one device is related to the maximum allowable transmission loss M by $M = (2+p)L$, where p is the number of successive terminals which are allowed to go down. With a conservative value of 20 dB for M and $L = 4$ dB, $p = 3$.

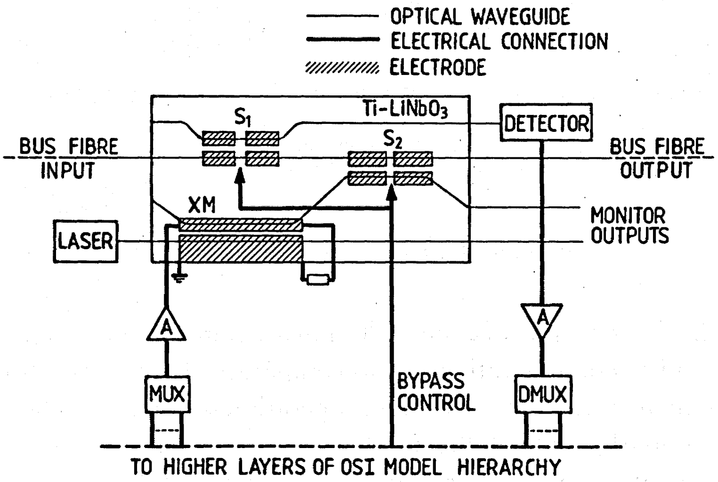

FIGURE 4. Integrated-optics device for a high-speed communications structure. The device includes a high-speed (above 3 Gb s^{-1}) modulator (XM) and two switches S$_1$, S$_2$. In the application shown, the device is located in a terminal in a ring network to make the network tolerant to terminal failures.

Typical insertion losses (fibre to fibre) are 3–4 dB. If the low-speed switches, S$_1$ and S$_2$, are also made into high-speed TW switches the device could be used for bit-by-bit processing of the data on the fibre. This would allow it to work as a multiplexer/demultiplexer, for example, or as an interface between high-speed data (on the fibre) and low-speed data (in the terminal), if the pertinent protocols are implemented. The device is large enough to permit such an upgrading of the low-speed switches to high-speed (TW) switches.

3.3. *Space switches*

By cascading a number of the basic building blocks of figure 1, different types of blocking or non-blocking 'switch matrices' can be built (cross-bar, lattice structures, etc.). Figure 5 shows some basic switch matrix structures. For strictly non-blocking switch arrays optical signals in any of the inputs can be routed to any of the outputs without rearranging existing connections by switching the appropriate crosspoints electrically. Fabrication complexity is greatly decreased by integrating all the matrix on one 'chip'. An intergration of 64 switch elements on one $LiNbO_3$ chip to form an 8×8 cross-bar matrix of the type shown in figure 5

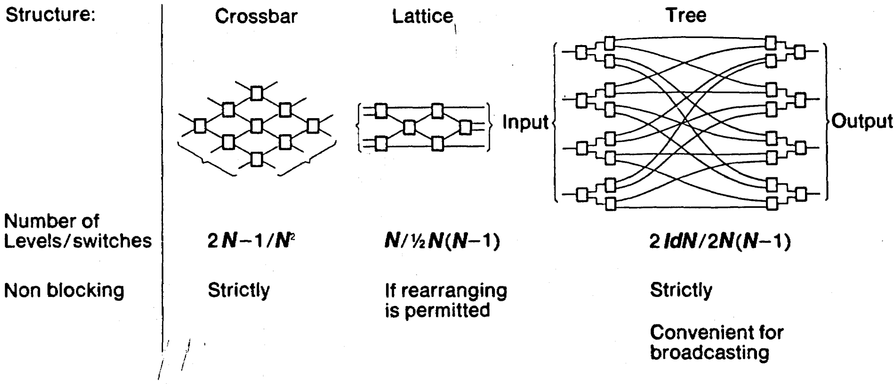

FIGURE 5. Different switch matrix structures.

(the chip is shown in figure 6 and is 12 mm × 60 mm × 1 mm) has been reported (Granestrand *et al.* 1986). The high level of integration entails comparatively high switch voltages (*ca.* 25 V) so that only low-frequency (less than 100 MHz) operation is practical. The (average) crosstalk of each switch is −30 dB, making the total matrix crosstalk −21 dB (−42 dB electrical crosstalk) as the crosstalk in a crossbar structure according to figure 5 will be increased by 10 log N dB over that of the individual switch element (worst case). The fibre-to-fibre insertion loss is 4–6 dB, and is uniform across the matrix. In other configurations, crosstalk can be

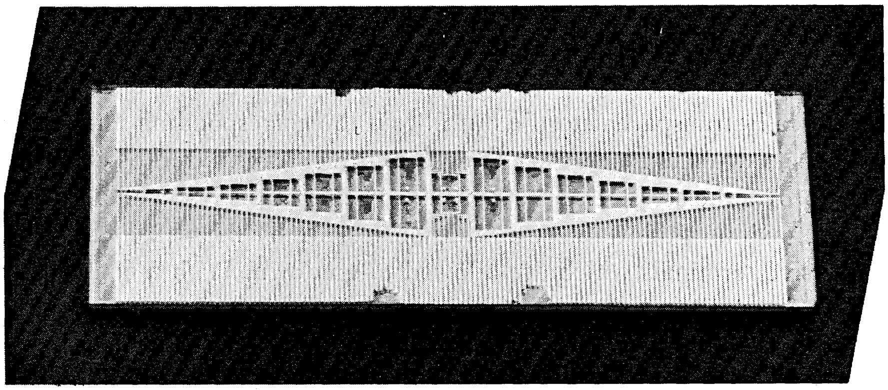

FIGURE 6. 8×8 strictly non-blocking $LiNbO_3$ switch matrix. The 64 switches are located under the line in the middle of the chip.

improved at the expense of complexity (Spanke 1986) and recently, a 4×4 tree-structure (figure 5) polarization independent matrix (Granestrand *et al.* 1988*b*) (figure 7) as well as a 4×4 polarization independent duobanyan structure (Nishimoto *et al.* 1988) have been reported. The former matrix architecture allows communicative as well as distributive switching, gives excellent crosstalk performance (*ca.* 50–60 dB could be inferred from single switch measurements, below −35 dB, instrument limited, was measured). The matrix of

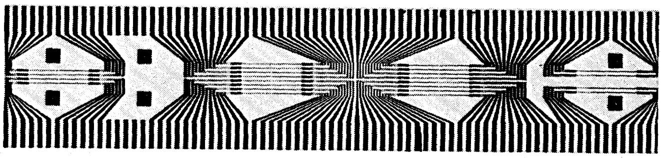

FIGURE 7. Polarization independent 4 × 4 switch matrix chip. Dimensions: 40 × 12 mm.

Granestrand *et al.* (1988*b*) is based on the novel switch design of Granestrand *et al.* (1988*a*) tolerant to fabrication errors to increase yield. The duobanyan array (Nishimoto *et al.* 1988) only utilizes three cascaded levels, making lower switch voltages possible, at the expense of intrinsically worse crosstalk properties.

The reason for the interest in space switches is their 'frequency and code transparency': low-frequency electrical signals can route optical signals, practically irrespective of their frequency contents and code format. As an example, dispersion will limit the achievable bandwidth to above 1 THz for a 10 cm propagation length in $LiNbO_3$ for a polarization dependent device, and to 10 GHz in a polarization independent device as in Granestrand *et al.* (1988*b*) and Nishimoto *et al.* (1988). In both cases, however, the total bandwidth is of the order of 40 nm.

To construct still larger matrices one can cascade a number of chips (e.g. interconnect chips with fibres) in Clos nets. Table 1 gives a summary of the number of chips required for different matrix sizes. The values are based on the assumption that several switches are hosted on one chip by arranging the switches in parallel.

TABLE 1

(Number of $LiNbO_3$ chips required for different matrix sizes ($N \times N$) arranged in Clos nets. Several matrices are assumed to be hosted on a $LiNbO_3$ chip to decrease the number of chips.)

number of inputs/outputs (N)	number of chips	number of stages in Clos-nets
32	3	3
64	10	3 or 5
128	25	5
256	65	5

4. SYSTEMS EXPERIMENTS INVOLVING LITHIUM NIOBATE DEVICES

Two examples of systems experiments with lithium niobate devices are described below.

The ability to perform switching functions that do not solely rely on a 'memory-less' operation, i.e. functions like time slot interchange, synchronization, etc., requires optically triggered optical memories. A number of such elements in the shape of bistable devices have been presented (Gibbs 1985), here we only describe a configuration which is based on an optically or electrically controlled bistable laser, using saturable absorption (Tomita *et al.* 1987; Öhlander *et al.* 1989). This device is, in contrast to most other bistable devices, quite tolerant to deviations of the input signal's wavelength, of the order of ±5 nm wavelength deviation can be accommodated, restores output power levels and can be optically triggered at reasonable power levels and speeds (e.g. 100 μW and 1 ns). An experiment involving time slot interchange is shown in figure 8, involving $LiNbO_3$ multiplexer/demultiplexer devices as well as optical bistable elements (Suzuki *et al.* 1986).

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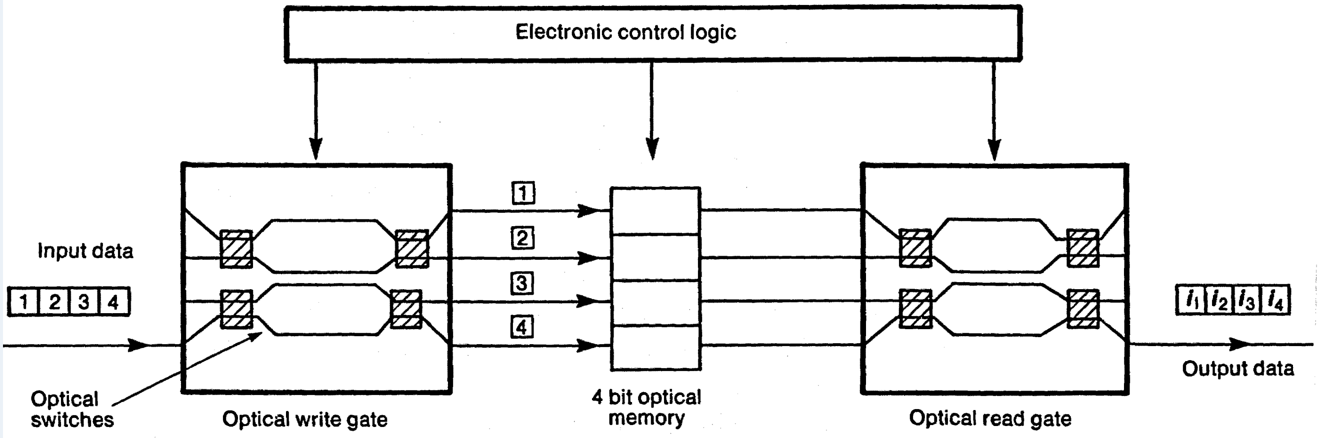

FIGURE 8. Optical time slot interchange demonstration (Suzuki *et al.* 1986). Two 4 × 4 $LiNbO_3$ optical switches as well as four bistable optical elements (Tomita *et al.* 1987) to permute the data sequence. A blocking-free arrangement would require 8 bits of memory.

Figure 9 shows a systems experiment involving self-routing of data in the 8 × 8 switch matrix of Granestrand *et al.* (1986) (Blumenthal *et al.* 1987, 1988).

Self-routing switching devices are of great interest in packet-switched networks; by optically deriving the routing information, as in figure 9, the role of electronics can be greatly reduced (Blumenthal & Thylén 1988). In the experiment of Blumenthal *et al.* (1988), a 12.5 Gb s^{-1} data rate was routed at a crosspoint switching rate of 100 MHz.

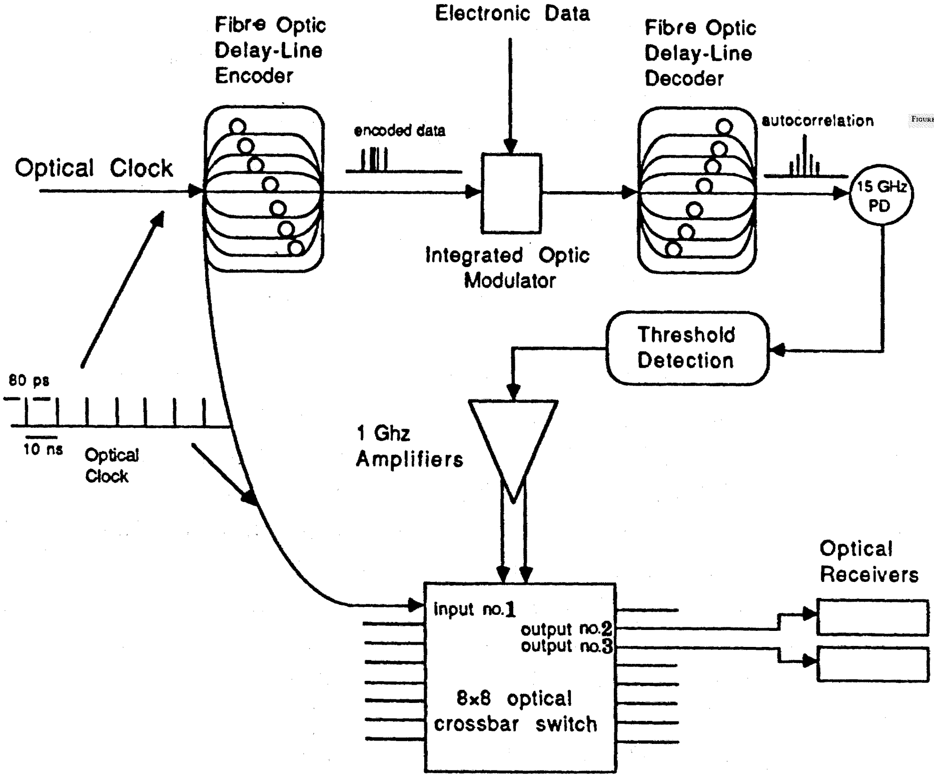

FIGURE 22. Neotectonic evidence discernible in the Kosi Valley (Valdiya 1987*b*).

FIGURE 9. Self-routing switch network, comprising optical processing to control switching in an 8 × 8 switch matrix. (After Blumenthal *et al.* 1988.)

5. SUMMARY

State-of-the-art photonic switching devices based on lithium niobate technology, currently the most mature one, were reviewed, emphasizing time and space switching. New families of devices of increasing complexity are emerging and the combination of these devices with optical amplifiers and bistable elements widens the scope of applications of optical switching with $LiNbO_3$ devices. Progress has been made in understanding the temporal drift phenomena of $LiNbO_3$ devices, and further research is expected to give devices compatible with the telecom environment requirements. Further research in the areas of polarization independence is also required. Continued progress in lithium niobate as well as semiconductor-based integrated optics and optoelectronics is envisaged to have a strong impact on future communications and information handling systems.

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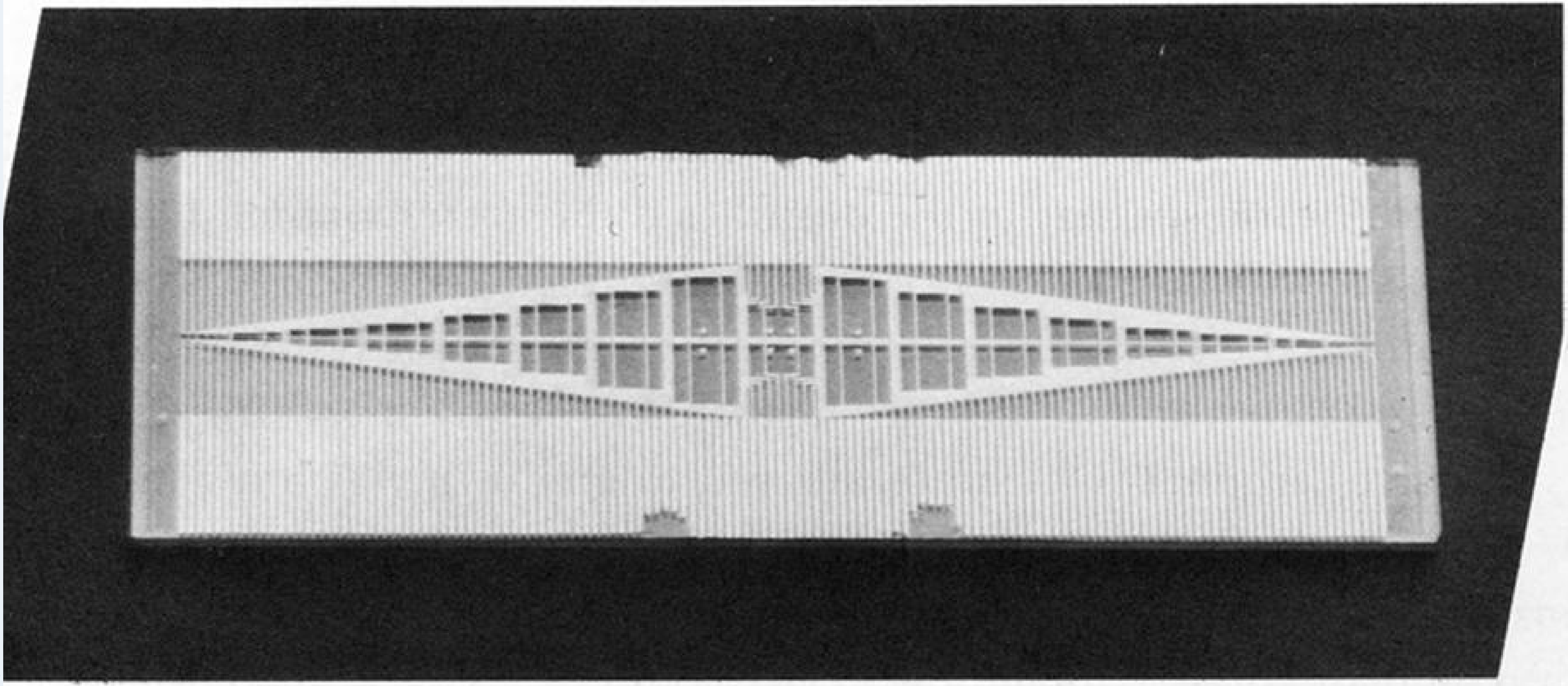
Discussion

J. E. MIDWINTER, F.ENG., F.R.S. (*UCL, London, U.K.*). Could Dr Thylén please speculate on the applications for lithium niobate components in real networks?

L. THYLÉN. If lithium niobate components are considered, modulators would increase the performance of very high speed (much greater than 1 GHz) *transmission* systems. As for the *switching* components, it seems likely that the first applications would be of the 'slow-switching' type, such as protection switching, digital crossconnect, etc., where the rearrangement is done for high-bit-rate data streams without the necessity of accessing or controlling the information. Other possibilities are overlay-type video switching in LANS, etc. Finally, time multiplexed switches (like the space stage in a time–space–time switch) offer interesting possibilities, especially when combined with the wavelength division multiplexing capability of the lithium niobate switches.



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