

# PHOTONIC SWITCHING TECHNOLOGY APPLICATIONS

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This paper will review some of the possible photonics technologies that could become important components of future telecommunications systems. It will begin by dividing photonic devices and systems into two classes according to the function they perform. The first class, relational, is associated with devices that, under external control, map the input channels to the output channels. The second class, logic, requires that the devices perform some type of Boolean logic function. After the classes are defined, some of the strengths and weaknesses of the photonic domain will be presented. Relational devices and their applications will then be discussed with a special focus on the spatial light modulator and the directional coupler. This will be followed by a description of two of the optical logic devices, the self-electro-optic device and the nonlinear Fabry-Perot etalon. Finally, there will be a brief discussion of optical logic systems and their potential applications.

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## Introduction

Within recent years there has been a significant amount of interest in applying the new and developing photonics technology to telecommunications switching. As the transmission plant has converted its facilities to fiber, there is an economic interest in completing the optical path through the switching system to the terminal facilities without requiring optical-to-electrical conversions. There are several devices that have emerged within the past few years which have the capability of meeting this goal. These devices can be arranged into two major classes according to the function they perform.

The first of these classes, called *relational* devices, performs the function of establishing a relation or a mapping between the inputs and the outputs. This relation is a function of the control signals to the device

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and is independent of the signal or data inputs. As an example, if the control signal is not enabled, the relation between the inputs and the outputs of a  $2 \times 2$  device might be upper input  $\rightarrow$  upper output and lower input  $\rightarrow$  lower output. When the control is enabled, the relationship might be upper input  $\rightarrow$  lower output and lower input  $\rightarrow$  upper output. This change in the relation between the inputs and outputs corresponds to a change in the state of the device. Another property of this class is that the information entering and flowing through the devices cannot change or influence the current relation between the inputs and outputs. An example of this type of device is the directional coupler as it is used in switching applications. The major weakness of relational devices is that they cannot sense the presence of individual bits that are passing through them, a characteristic which limits their flexibility.

The second class of devices will be referred to as *logic* devices. In these devices, the data or information-carrying signal that is incident on the device controls the state of the device in such a way that some Boolean function is performed on the inputs. For this class of devices, some of the devices within a total system must be able to change states or *switch* as fast or faster than the signal bit rate. This high speed requirement for logic devices will limit the bit rates of signals that can eventually flow through their systems to less than those that can pass through relational systems.

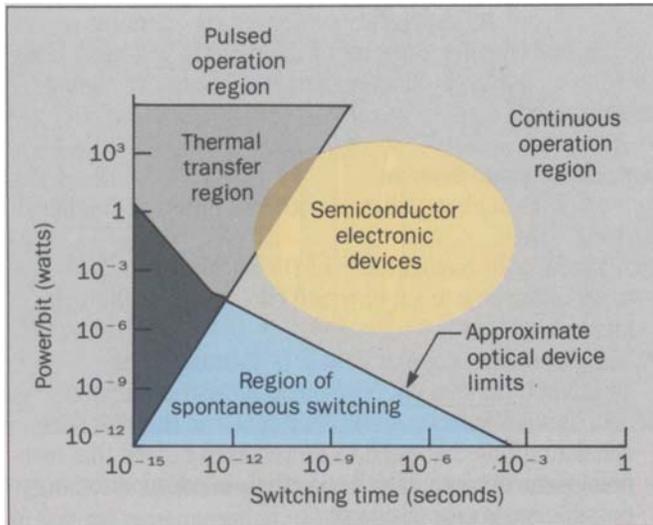
This paper will begin by discussing both the strengths and limitations of the photonic technology. Some of the items to be discussed include power, speed, bandwidth, and parallelism. The paper will then discuss optical relational systems with a focus on the directional coupler. The reason for this focus is that directional couplers will most likely be the initial photonic switching component that enters the marketplace. Finally, there will be a discussion of optical logic systems. These systems are still primarily in the research labs and not ready for development.

### Strengths and Limitations of Photonic Technology

This section begins by discussing the power, speed, and bandwidth limitations of photonic devices. It then examines parallelism and how it can be used in photonic systems. Finally, it briefly considers the minimum size of future devices.

**Power, Speed, and Bandwidth.** There are two speed limitations that must be considered in the design of photonic switching systems. The first of these limitations is the time required to switch or change the state of a device. "Switching," in this case, refers to the changing of the current state of a device to an alternate state, as opposed to the "switching" that is analogous to an interconnection network reconfiguration. In the normal operating regions of most devices a fixed amount of energy, the switching energy, is required to make them change states. This switching energy can be used to establish a relationship between both the switching speed and the power required to change the state of the device. Since the power required to switch the device is equal to the switching energy divided by the switching time, a shorter switching time will require more power. As an example, for a photonic device with an area of  $100 \mu\text{m}^2$  and a switching energy of  $1 \text{ fJ}/\mu\text{m}^2$  to change states in 1 ps requires 100 mW of power instead of the  $100 \mu\text{W}$  that would be required if the device were to switch at 1 ns. Thus, for high-power signals the device will change states rapidly, while low-power signals yield a slow switching response.

Some approximate limits on the possible switching time of a given device, whether optical or electrical, are illustrated in Figure 1. In this figure the time required to switch the state of a device is on the abscissa while the power/bit required to switch the state of a device is on the ordinate. The region of spontaneous switching is the result of the background thermal energy that is present in a device. If the switching energy for the device is too low, the background thermal energy will cause the device to change states spontaneously. To prevent these random



**Figure 1. Fundamental switching limits at  $\lambda = 850$  nm.**

transitions in the state of a device, the switching energy required by the device must be much larger than the background thermal energy. To be able to differentiate statistically between two states, Smith assumed in Reference 1 that each bit should be composed of at least 1000 photons. Thus, the total energy of 1000 photons sets the approximate boundary for this region of spontaneous switching. For a wavelength of 850 nm this implies a minimum switching energy on the order of 0.2 fJ.

The thermal transfer region has the property that, for continuous operation, the thermal energy present in the device cannot be removed any faster than  $100 \text{ W/cm}^2$  ( $1 \mu\text{W}/\mu\text{m}^2$ ). It is also assumed in this region that there will be no more than an increase of  $20^\circ$  in the temperature of the device. Devices can be operated in this region using a pulsed rather than continuous mode of operation. Thus, high-energy pulses can be used if sufficient time is allowed between pulses for the absorbed energy to be removed from the devices.

The oval area in Figure 1 represents the performance capabilities of current electronic devices. The figure illustrates that optical devices will not be able to switch states orders of magnitude faster than electronic devices when the system is in the continuous rather than the pulsed mode of operation. There is, however, more to both optical computing and photonic switching than how fast a single device can change states.

Assume that several physically small devices need to be interconnected so that the state information of one device can be used to control the state of another device. To communicate this information, there needs to be some type of interconnection with a large bandwidth that will allow short pulses to travel between the separated devices. Fortunately, the optical domain can support the bandwidth necessary to allow bit rates in excess of 100 Gb/s, which will allow high-speed communication between these individual switching devices. In the electrical domain the communications bandwidth between two or more devices is limited by the resistance, capacitance, and inductance of the path between the different devices. Therefore, even though photonic devices cannot switch orders of magnitude faster than their electronic counterparts, the communications capability or transmission bandwidth present in the optical domain should allow higher-speed systems than are possible in the electrical domain.

The second speed limitation, which applies only to relational devices, will be referred to as the transmission bandwidth. After relational devices have been put into a particular state, they act as transmission lines to any data entering their inputs. This input data cannot change the state of the device, thus the signal bit rates passing through a relational device are not limited by the constraints outlined in Figure 1. For most relational devices this bandwidth should be able to support bit rates in excess of 100 Gb/s.

In summary, networks composed of relational devices will have their signal bit rates limited by the transmission bandwidth and their reconfiguration rates limited

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by the switching time of the devices, while switching networks based on optical logic will have both their signal bit rates and reconfiguration rates limited by the switching time of their devices.

**Parallelism.** Another method of increasing the capacity of a system, in addition to operating at higher speeds, is to operate on information in parallel instead of serially. Because of the communications capability in the optical domain, it has been assumed that parallel architectures will exploit the potential high connectivity possible between individual devices and offer a second strength for the optical domain, parallelism. To pursue parallelism, attention has recently been placed on free-space optics. These types of systems normally are composed of multiple two-dimensional (2-D) arrays of optical devices that are interconnected through either bulk optics or holography.

To take advantage of the parallelism inherent in free-space optics, a device must have the capability of driving many other devices (fan-out) in addition to being controlled by more than one device (fan-in). Since fan-out corresponds to a division of the energy emitted from a device output to the inputs of other devices, the output energy must be significantly larger than the energy required by the input to the subsequent device. Another factor that affects the fan-in is the contrast ratio, which is the ratio of the transmitted intensity of both states of a device. For low contrast ratios, unwanted noise is present in the system and reduces the ability of a device to sample the input correctly.

By pipelining several 2-D arrays, a parallel system operating in the pulsed mode is possible. Such a pulsed system can be realized if each array of devices is pulsed with information followed by a cooling period to allow the heat to be removed from the material.

**Device Size.** The minimum size of an optical switching device cannot be reduced below a volume of  $\lambda^3$  (Reference 1). For the case of a 2-D array of devices, and assuming that the devices are fabricated so that there is a separation of  $\lambda$  between the devices, then approximately 25 million devices per square centimeter could be possible

at  $\lambda = 1 \mu\text{m}$ . As the device switching speed increases, the thermal transfer capacity of the devices will most likely prevent such a large number of devices from ever being realized.

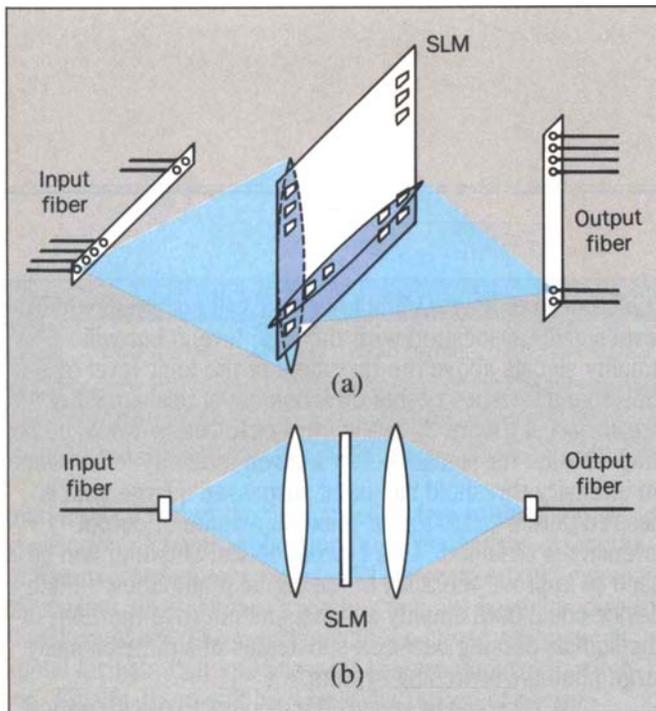
### Optical Relational Systems

This section will deal with two different relational devices:

- A spatial light modulator (SLM) consisting of a 2-D array of devices, each of which can modulate the light incident on it.
- The directional coupler as it is fabricated in the Ti:LiNbO<sub>3</sub> technology. The discussion of directional couplers will include some comments on the practical considerations that need to be resolved before this technology can achieve its full potential, in addition to some possible system applications.

**Spatial Light Modulators.** Each of the modulators in an SLM (Figure 2) is independent of the others.<sup>2</sup> For the applications described in this paper, the modulators are assumed to be digital, in that they possess two states: transparent to the incoming light (on) and opaque to the incoming light (off). A SLM currently available in the marketplace is based on the magneto-optic effect.<sup>3</sup> These arrays are electrically controlled such that an electrically enabled pixel will be transparent while a disabled pixel will block the incident light.

Figure 2 gives an example of how a SLM can be used as a photonic switch.<sup>4</sup> In the figure the fiber inputs are horizontally aligned as a row of inputs. The inputs are aligned to associate each fiber with a unique column of the SLM. A lens system spreads these inputs vertically so that the light emitted from each input is spread over all the elements of the SLM's associated column. The appropriate pixels of the SLM are enabled before data passes through the system so that one or more of the pixels in that column are allowed to pass the incident light through while the remaining pixels block the incident light. The output column of fibers accepts the light that is passed through the SLM. An important restriction for this type of structure is



**Figure 2. An SLM-based crossbar interconnection network. (a) Logical representation. (b) Required lens system.**

that only one pixel on each row can be enabled at any time. The relational nature of this structure is that each row of the SLM acts like an  $N \times 1$  switch, where  $N$  is the number of pixels per row. The total structure is topologically equivalent to a nonblocking crossbar interconnection network.

As with all relational structures, high signal bit rates pass through the switch. The speed limitation is the system reconfiguration time.

**Directional Couplers.** A directional coupler is a device that has two optical inputs, two optical outputs, and one control input. The control input is electrical and has the capability of putting the device in the *bar* state, in which the upper (lower) optical inputs are directed to the upper (lower) optical outputs, or the *cross* state, in which the upper (lower) optical inputs are directed to the lower (upper) optical outputs. The most advanced implementations of these devices are those using Ti:LiNbO<sub>3</sub> technology.<sup>5</sup>

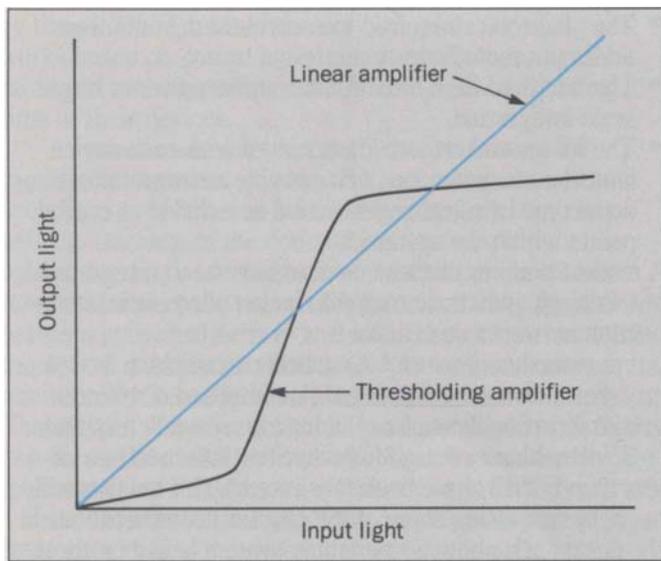
The strength of directional couplers is their ability to control extremely high-bit-rate information. They are limited by several factors:

- The electronics required to control them limits their maximum reconfiguration rate.
- The length of each directional coupler prevents large-scale integration.
- The losses and crosstalk associated with each device limit the maximum size of a possible network unless some type of signal regeneration is included at critical points within the system.<sup>6</sup>

A modest number of these devices have been integrated onto a single substrate to create larger photonic interconnection networks such as an  $8 \times 8$  crossbar interconnection network.<sup>7</sup> As another example, a  $4 \times 4$  crossbar interconnection network composed of 16 integrated directional couplers, all having crosstalk less than  $-35$  dB with an average fiber-to-fiber insertion loss of less than 5.2 dB, have been fabricated.<sup>8</sup> This section will begin by discussing some of the practical considerations in the design of a photonic switching system based on these directional couplers. Several potential applications will then be discussed.

**Practical considerations.** There are several practical issues that need to be considered when designing a system based on Ti:LiNbO<sub>3</sub> directional couplers. These issues include the required parallel development of polarization-maintaining (PM) fiber, optical amplifiers, and the packaging to make the devices reliable and easy to use.

To minimize the required drive voltages, directional couplers have been optimized to operate on a single linear polarization. This requirement reduces the required voltage from approximately 50 volts to the 10- to 15-volt range. These lower voltages are desired to allow high-speed switching of the directional couplers. One problem with using single-polarization devices is that, as light propagates through standard single-mode fiber, the state of polarization can be changed from a linearly polarized wave to a wave having an elliptical polarization. Another complicating factor is that this change in the state of polarization does not remain constant over time. To solve this problem PM fiber is required for the interconnection from all the laser sources to the Ti:LiNbO<sub>3</sub> substrates and for any sub-



**Figure 3. Characteristics of two types of optical amplifiers. Most optical amplifiers are linear. Thresholding amplifiers act on signals above the logic level 1.**

strate-to-substrate interconnection. In addition to PM fiber, there must also be PM fiber connectors. These connectors become important when networks involving the interconnection of multiple Ti:LiNbO<sub>3</sub> substrates is required.

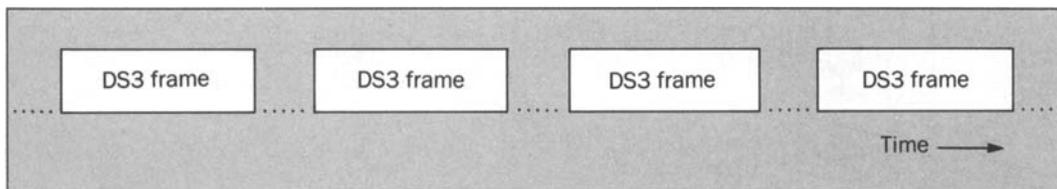
The eventual size of a switching fabric composed of directional couplers is limited by either the losses through the system or the individual crosstalk terms which degrade the system signal-to-noise ratio (SNR) below an acceptable value. To avoid this problem, thresholding optical amplifiers can be inserted at critical points in the network to both boost the strength of the signal and remove accumulated noise. Most of the optical amplifiers under investigation are linear amplifiers.<sup>9</sup> These amplifiers have the disadvantage of amplifying the low-level noise signals as well as the desired signals. With this type of optical amplifiers, the SNR of a system will limit its eventual size.

It is desired to have an amplifier that will not amplify low-level signals associated with the logic level 0 but will amplify signals above the threshold of the logic level of a 1. The characteristics of this thresholding optical amplifier<sup>10</sup> are shown in Figure 3. In the ideal case, there would be no amplification for signals below a given intensity level. Once an intensity threshold has been surpassed a large gain is desired until a saturated or maximum value of output intensity is obtained. This type of optical amplifier can be used to improve the SNR of the signal it amplifies.<sup>11</sup> Such a device could both amplify a signal and improve the SNR of the signals passing between substrates of a dimensionally large photonic switching system.

A component required in conjunction with optical amplifiers is an all-optical isolator. In addition to isolating lasers from reflections that can occur at connectors, splices, and other interfaces, all-optical isolators are required to prevent optical amplifiers from lasing. Lasing action can occur, since the two requirements for a laser are met: optical gain and positive feedback. The optical amplifier provides the gain and the connectors, splices, and other reflecting interfaces on both sides of the optical amplifier provide the positive feedback required. For high-gain optical amplifiers this unwanted lasing can occur with small interface reflectivities. Placing an isolator between the unwanted reflections and the optical amplifier reduces the feedback, thus preventing the unwanted lasing.

**Packaging.** To develop a system that is both marketable and reliable, devices have to be packaged in a useful and reliable manner. This is one of the most overlooked aspects in the development of this technology. At the current time, most of the devices are housed in their own separate package. For large systems this could involve an enormous amount of physical space just to house all the individual components. High-speed packaging is another unresolved issue. This subject will require a large amount of attention before this technology can successfully enter the marketplace.

**Applications of directional couplers.** Perhaps the key event required to drive Ti:LiNbO<sub>3</sub> technology into the



**Figure 4. Proposed photonic DS3 signal format.**

marketplace within the next three to five years is a *good* application. A good application requires that the strengths of this new technology be used. This section will begin by discussing several space switches that are based on directional couplers. The section will then cover variations in signal formats that will allow for time-multiplexed switching. Finally, there will be a brief discussion of packet switching systems of the future that could be based on directional couplers.

Space switching will most likely be the first application of Ti:LiNbO<sub>3</sub> directional couplers. It requires long hold times with moderate reconfiguration rates. Once a path has been set up, high-speed data, multiplexed speech, or video can be transferred through the fabric. When the transfer is complete the path is broken and the bill sent.

The implementation of a large space switch requires the interconnection of many smaller photonic switches that are used as building blocks. These building blocks will most likely have dimensions less than  $16 \times 16$  because of the large size of directional couplers and the large bending radii required in the integrated waveguides. Two examples of topologies for these building blocks are the crossbar interconnection network<sup>6</sup> and the broadcast network proposed by Spanke.<sup>12</sup> For point-to-point networks the interconnection of these building blocks to construct a larger switching system can be done with Clos, Benes, banyan, omega, or shuffle networks. If video information is to be a main component of the system traffic, then a broadcast environment becomes important. A good topology for a broadcast network is a Richards network.<sup>13</sup>

A good application of a directional coupler is a protection switch. In this environment the only time the switch will need to be reconfigured is when a failure

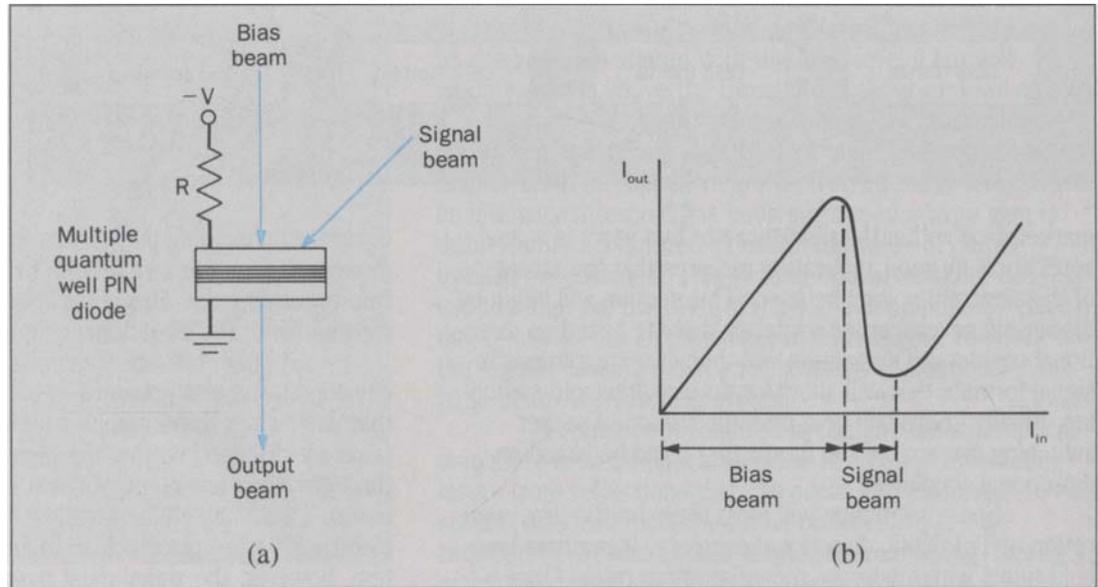
occurs in an existing path. Thus, high bit rates can be passed through the switch with moderate reconfiguration rate requirements. This application perfectly matches the capabilities of the directional coupler.

As high-bit-rate transmission systems are being developed, there is pressure to build switching systems that will switch these complex signals. Transmission systems are designed so that the high-bit-rate signal passes through only a few elements as it is generated or processed. These few elements allow all the controlling electronics to be placed close together. In a switching system, however, the signal must pass through a large number of switching elements which are normally spread over a large physical space, and this makes switching difficult at high bit rates.

As bit rates continue to increase, there will have to be a compromise between the complexity of transmission and switching systems. One potential solution to this problem is to change the signal format from a bit-multiplexed to a block-multiplexed format. By changing the format, transmission systems will become more complex because buffers will be required at all the inputs to the multiplexers. Such a new format will simplify switching systems by allowing them to operate directly on the information rather than having to demultiplex the information and then switch the lower-bit-rate signals.

An example of such a proposed format is SYNTRAN.<sup>14</sup> The concept of this block-multiplexed format is good for future photonic applications, but the relatively slow DS3 bit rate it proposes does not make sense for the photonic domain. The concept can be extended to higher bit rates by using individual 125- $\mu$ s frames of the 45-Mb/s DS3 information as the basic quanta of the system. As an

**Figure 5. The self-electro-optic effect device.**



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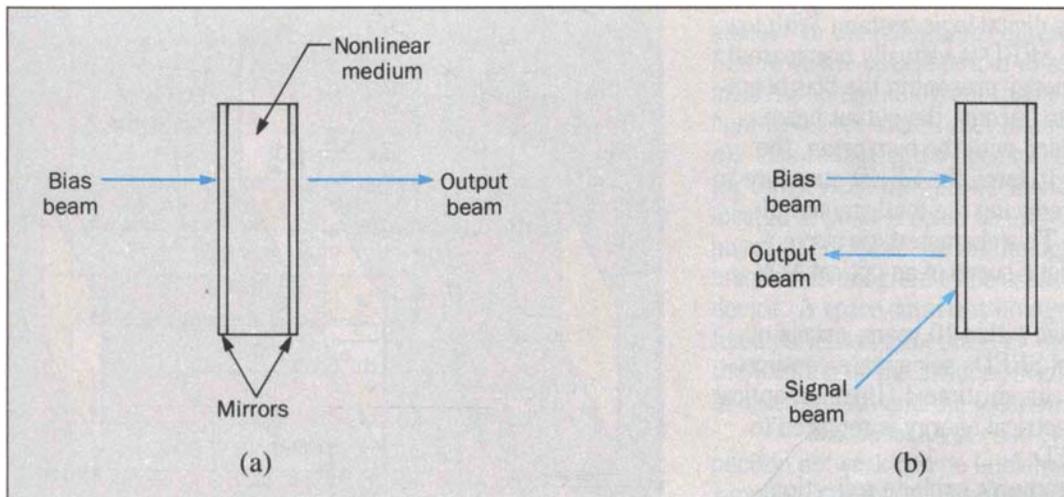
example, in the FT series G transmission system a single 125- $\mu$ s frame of the 1.7-Gb/s data stream contains 36 frames of DS3 information. The bits in these frames, plus overhead bits, are interleaved and mixed so that individual DS3 frames can not be extracted from the stream unless that stream is at least partially demultiplexed down to DS3 channels. By requiring that the DS3 frames be block-multiplexed onto the high-speed channel with a small gap between them, individual extraction and insertion of DS3 frames should be possible. A simplification of this signal format is shown in Figure 4. The characteristics of a directional coupler (slow reconfiguration rates, but high signal bit rates) make it an ideal device to be used with a block-multiplexed format.

As the bit rate passing through these photonic switches increases, there approaches a point where no single information source can occupy all the bandwidth without some type of time-division multiplexing. As an example, uncompressed digital NTSC television signals require approximately 100 Mb/s while digital high-

definition television will be about 600 Mb/s. Thus, if the transmission system operates at 1.7 Gb/s then at least 16 NTSC channels or two high-definition channels can be time-multiplexed together.

To build such a system will require a time-slot interchanger and an elastic store if the system is to cover a large geographical area. The elastic store will also be required to remove both frequency and phase jitter from the system inputs. Proposed elastic stores and time-slot interchangers have been demonstrated using fiber delay lines as the memory<sup>15</sup> or bistable laser diodes as bit memories.<sup>10</sup>

In implementing a packet switching system based on directional couplers, a header has to be read to determine the final location of the packet. This can be done by stripping off a portion of the optical energy and monitoring the header (trailer) electronically. If necessary the header (trailer) could be at a lower bit rate than the packet data, allowing the slower electronics to respond to the controlling information. If the header bit rate is at the same bit



**Figure 6. The nonlinear Fabry-Perot interferometer optical gate.**

rate as the data, then the eventual bit rate upper limit would be governed by the speed of the electronics. It would be possible to have headers operate at slower bit rates than the data at the cost of reducing the total throughput of the switching system.

Such a system requires a large amount of electronics surrounding a small number of photonic devices. Thus, to be economically justifiable, large packet lengths are required.

### Optical Logic Systems

There are certain applications that are not well suited for relational devices. One such application requires the ability to both sense and respond to individual bits of information. A packet switch is a good example of this requirement. A packet entering a network requires a system of devices that can read and understand the header and then reconfigure the network to allow the packet to pass to its desired destination. The ability to interact and sense the individual bits in a stream of information is one of the strengths of optical logic devices.<sup>16</sup>

To make a useful system, these devices need to be interconnected, as in current electronic switching sys-

tems, to create a large interconnection network. The purpose of this section is to discuss several of the optical logic devices that have been fabricated and to describe two methods of optically interconnecting these devices.

**Digital Optical Logic Devices.** There are two optical logic devices that have received a considerable amount of attention the past few years. The first of these devices, the self-electro-optic-effect device (SEED),<sup>17</sup> is an electro-optical device that requires both optical and electrical energy. The second device, referred to as a nonlinear Fabry-Perot (NLFP) etalon, is an all-optical device<sup>16</sup> in that it needs only optical energy. Both devices can be fabricated into 2-D arrays that are both enabled and controlled optically. The 2-D arrays provide the opportunity to exploit the parallelism present in the optical domain.

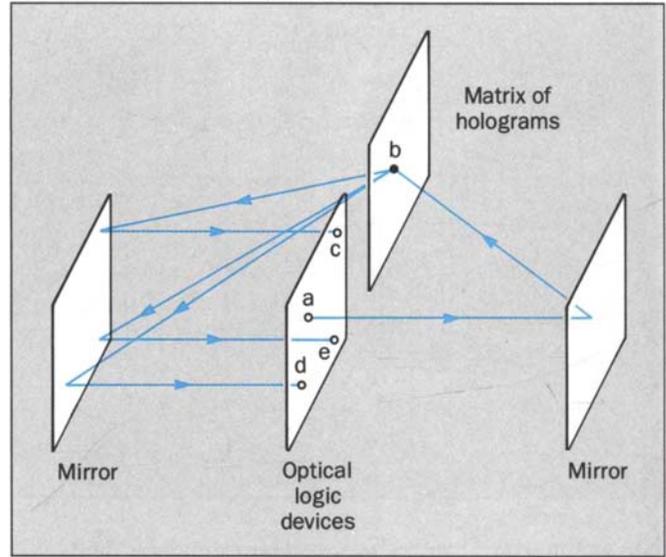
A functional diagram of the SEED is shown in Figure 5a. A PIN diode with a multiple quantum well material in the intrinsic region is connected in series with a resistor to form the SEED structure. The characteristic curve for the device is shown in Figure 5b.

A bias beam is required to provide the energy that will be modulated by the signal beam. This modulation of the energy source by the signal beam provides the differen-

tial gain that is required in a digital logic system. With low signal beam intensities, the SEED is virtually transparent. This allows nearly all the energy present in the bias beam to pass through the device to become the output beam. When the signal beam is added with the bias beam, the combined energy is enough to force the SEED structure to become an absorber, thus reducing the total amount of energy in the output beam. This characteristic curve is equivalent to the characteristic curve of an optical NOR gate.

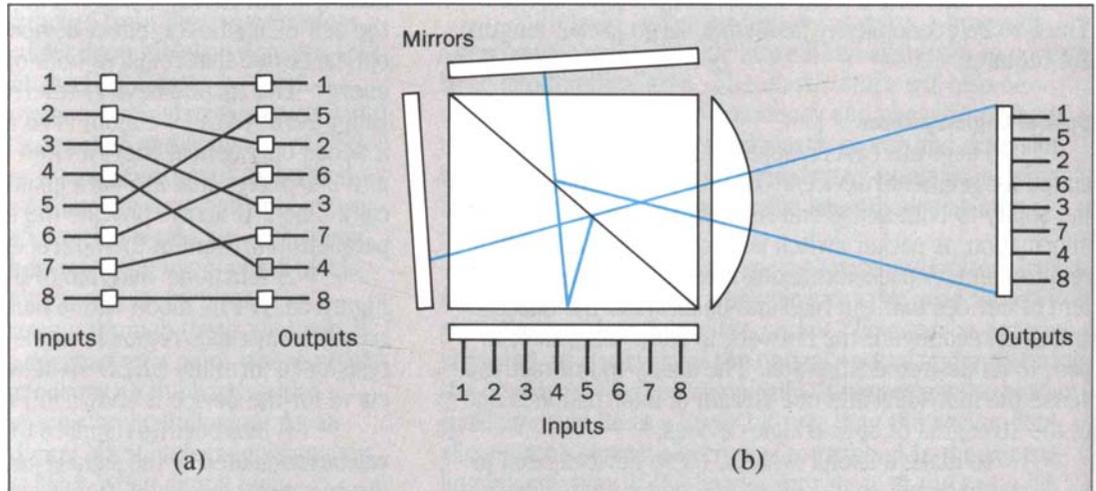
It is conceivable that within 10 years, arrays of 10,000 to 100,000 individual SEEDs per square centimeter will be possible. At the current time  $4 \text{ fJ}/\mu\text{m}^2$  of optical energy and  $16 \text{ fJ}/\mu\text{m}^2$  of electrical energy is required to change the state of the SEED.

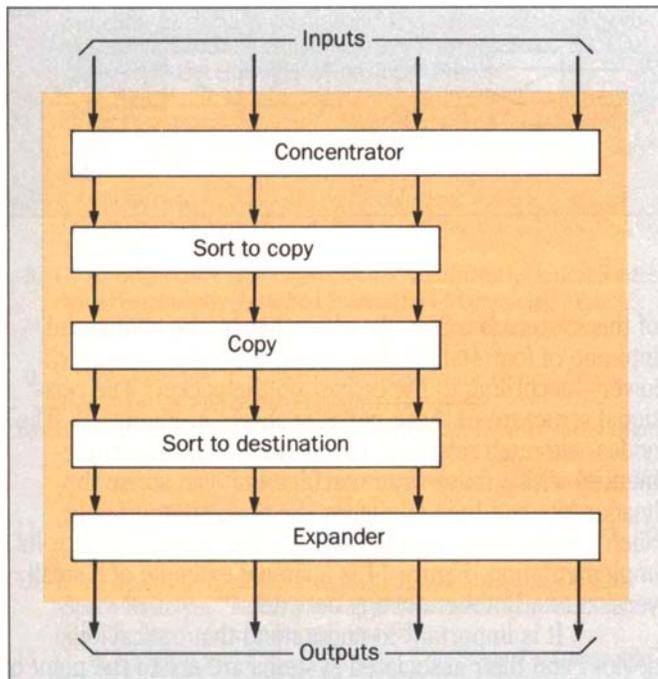
The NLFP interferometer exploits reflection instead of absorption to control or modulate a bias beam. Figure 6a illustrates that, without a signal beam, the bias beam passes through the NLFP. With an incident signal beam, Figure 6b, the NLFP changes state, forcing the bias beam to be reflected instead of transmitted. This device, like the previously described SEED, is operating as a NOR



**Figure 7. Holographic interconnection network. Hologram at b redirects light from a to one or more points (c, d, e). The redirected light becomes the input at the points of incidence.**

**Figure 8. Perfect shuffle interconnection network.**





**Figure 9. Starlite wideband digital switch.**

gate. The NLFP can also be designed so that it can operate as an AND, OR, NAND, or XOR gate.<sup>16</sup> The optical switching energy for NLFPs has been measured to be less than  $40 \text{ fJ}/\mu\text{m}^2$  (Reference 18) with switching times less than 100 ps (Reference 19).

**Device-to-Device Interconnection.** Once two-dimensional arrays of optical logic gates are available it will become necessary to interconnect the individual devices on the arrays. This section will discuss two methods of free-space interconnection: holography and bulk optics.

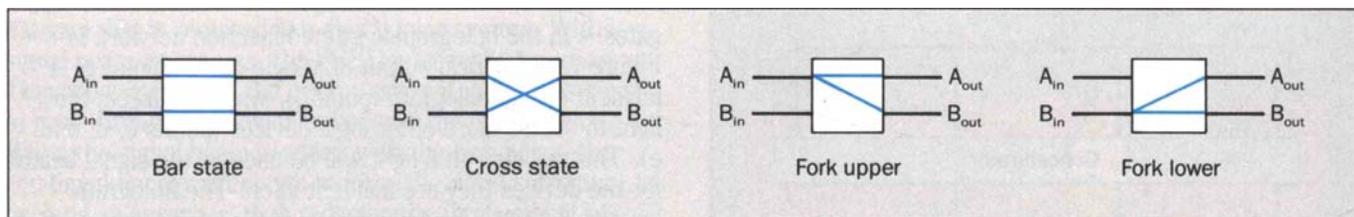
**Holography.** A hologram is a mechanism that can be used to modify and redirect a light wave that is incident upon it.<sup>18</sup> Thus, a hologram or collection of holograms can be used as the *photonic wires* interconnecting optical logic

gates.<sup>21</sup> In the holographic interconnection network in Figure 7, the optical output of a logic device (point a) is incident on the hologram (point b), which redirects the light to one or more other logic devices (points c, d, and e). This redistributed light will be used as the signal beams for the devices they are incident upon. The hologram located at point b could be either space-variant or space-invariant. A space-variant hologram is created to allow a unique subhologram to be associated with each logic device. A space-invariant hologram has the property that a fixed pattern is generated by the hologram regardless of the location of the incident beam. This fixed pattern will be centered around the location of the incident beam.<sup>21</sup>

**Bulk Optics.** A second type of free-space interconnection network can be implemented with bulk optics. The simplest example of this type of an interconnection network is a standard optical imaging system composed of conventional lenses. Such a system can be used to transfer the information on the outputs of one array to the inputs of a second (or the same) array. Another example of a free-space optical interconnection network based on bulk optics is an optical perfect shuffle.<sup>22</sup> Figure 8a illustrates the rearrangement performed by a perfect shuffle network. Figure 8b shows how an optical perfect shuffle can be implemented with a beamsplitter, a lens, and two mirrors. The perfect shuffle can also be used as photonic wiring to interconnect 2-D arrays of optical devices.

**Applications of Optical Logic Devices.** There are many functions performed by telecommunications switching systems that require high-performance general-purpose computing. An example is the processing for billing and maintenance. Another is the processing required in each node of a packet switching system; nodes must be able to read a packet header, in some cases modify it, and reconfigure the node so that the entering packet is directed to the proper output channel.

A packet switching system that could eventually be implemented by optical logic and optical interconnection between the logic devices is the Starlite wideband digital



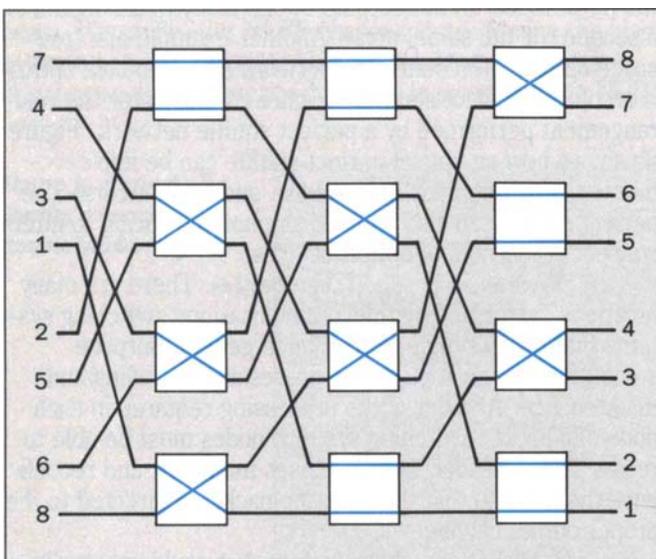
**Figure 10. Configurations of a  $2 \times 2$  switch.**

switch.<sup>23</sup> The Starlite switch (Figure 9) is a self-routing, nonblocking, constant-latency packet switch that can handle gigabit data rates.<sup>24</sup> Each of the basic functions (concentrator, sort to copy, copy, and so forth) can be decomposed into some type of shuffle network that interconnects  $2 \times 2$  switching nodes.

As an example, the sort function is performed by a Batcher bitonic sorting network.<sup>23</sup> The basic active node

of this system is a  $2 \times 2$  switch that can be configured into one of four states—bar, cross, fork upper, and fork lower—according to the header on the packet. The relational structure of these nodes is shown in Figure 10. The nodes, although relational in function, should be implemented with a finite state machine that can sense the header bits and then configure the node appropriately. Such a finite state machine will require optical logic for its implementation. Figure 11 is a simple example of a small version of a Batcher sorting network.<sup>23</sup>

It is important to understand that optical logic devices and their associated systems are not to the point of development at this time. The devices that have been discussed are research prototypes that are not ready to be manufactured.



**Figure 11. Simple example of Starlite sorting network.**

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