

# Free-Space Photonics in Switching

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Free-space digital optics is a new technology that exploits the ability of optics to handle thousands of light beams, or information channels, at once. This and other features of optics complement the strengths and weaknesses of purely electronic systems. Especially when combined with electronics, free-space optics allows the development of new architectures in digital systems. In particular, it offers large numbers of closely spaced interconnections inside digital processors that can be used to make large digital switching fabrics. In this paper, we outline some of the strengths and weaknesses of this emerging technology, and we briefly describe some of its experimental systems.

## Introduction

The use of optics in telecommunications is now routine, with lasers and optical fibers carrying much of our long distance traffic. Optics can also help *inside* digital machines, such as telephone exchanges and computers, although for different reasons and with different technology. In this paper, we examine why and how optics can be used in digital machines.

Much of the technology needed for using optics in digital machines is still being developed, and the applications are just emerging. Nevertheless, the underlying reasons are compelling, and its increasing use is inevitable.

The need for optics inside digital switching machines is due, in part, to optical fibers. It would be technically feasible to install fiber in every home or office today. We could conceivably provide every subscriber with a 150-megabit-per-second (Mb/s) line, instead of the current 64-kilobit-per-second (kb/s) line, which would increase the information rate to and from the customer by a factor greater than 1000. The inherent technical problem lies not in the transmission, but in the switching. By substituting fiber for copper, we have massively increased our ability to send information, but where is the matching technological leap that will enable us to switch or route that information?

**Large System Limitations.** Today, digital electronics performs most of our switching. Obviously, electronic technology is improving at an impressive rate. Silicon technology produces more and smaller devices on chips, and both gallium arsenide and silicon electronics are operating at ever-increasing rates. As a natural consequence, shouldn't we expect electronics to advance rapidly enough to solve this switching problem? It is by no means clear that it will. Advances in electronic devices do not solve all the problems associated with developing large systems, such as switching machines. In many ways, these advances make system design harder, not easier.

As the number and speed of electronic devices increase, sending information between electronic chips becomes more difficult. At high speeds, wires experience higher transmission losses. They emit more "crosstalk" (mixing of information from adjacent wires), and they distort the shape of the information pulses. Pulses of information intended to go in one direction, say from A to B, may, in fact, reflect from B, confusing the information transfer. Sending electrical information between chips requires significant energy, and the power must be dissipated on the chip. Much of the chip area can be taken up by the circuits that drive information over the electrical lines. Because the lines from

**Panel 1. Abbreviations, Acronyms, and Terms**

2-module	— a simple switching node
2D-OEIC	— two-dimensional optoelectronic integrated circuit
EGS	— extended generalized shuffle
F-SEED	— field-effect transistor self-electro-optic effect device
MCM	— multi-chip module
MQW	— multiple quantum well
SEED	— self-electro-optic effect device
S-SEED	— symmetric-SEED

one set of logic gates to another can vary in length and follow different paths, synchronizing all the inputs to a given gate can be difficult. This communication problem, known as "clock-skew," becomes progressively worse at higher speeds or longer distances, preventing us from fully exploiting fast electronic devices in large systems. Typically, communications problems, not device switching time, dictate most of the cycle time in large, fast machines.

To avoid these problems, some computing systems put as much of the computer as possible on one chip. If many computations must be performed on a small amount of information, this approach can work; a few external "pins" on the chip operating at moderate bit rates might be enough. But switching is not a problem of this kind. Switching chips require a large number of inputs and outputs that operate at moderate bit rates, or faster. Although switching requires only a few simple computations to route information along one path rather than another, the amount of information that must be processed is massive. Machines designed around the communication throughput limitations of electronics are not necessarily good at solving these problems.

It will be difficult to use electronics alone for high-capacity switching systems. Because the problems are fundamental and cannot all be solved simply by making more and better electronic devices, we must turn to other technologies for a solution. Fortunately, the capabilities of optics almost exactly complement those of electronics, even though the technology is still less mature.

**Features of Optics.** Sending information on light beams immediately avoids several of the key problems of sending it over wires. Given the distances that informa-

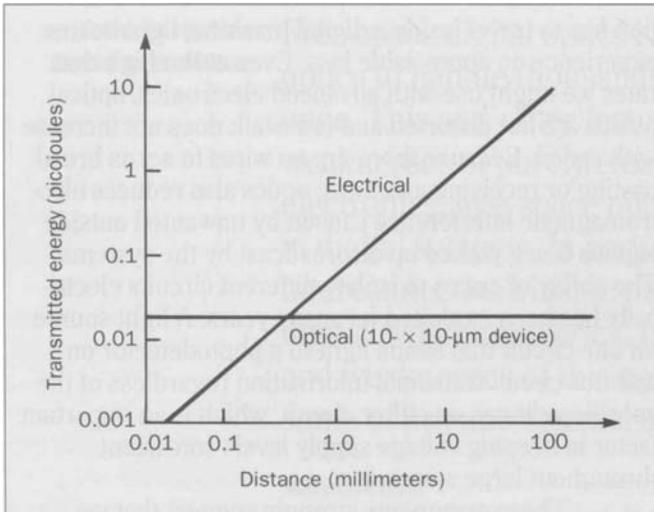
tion has to travel inside a digital machine, light beams experience no appreciable loss. Even at the high data rates we might use with advanced electronics, optical pulses are not distorted and crosstalk does not increase with speed. Because there are no wires to act as broadcasting or receiving antennas, optics also reduces electromagnetic interference caused by unwanted outside signals being picked up or broadcast by the systems. The ability of optics to isolate different circuits electrically has been exploited for many years. A light source on one circuit that sends light to a photodetector on another circuit transmits information regardless of the specific voltages on either circuit, which is an important factor in keeping voltage supply levels consistent throughout large systems.

These arguments strongly suggest that we should substitute optical interconnections for wires in large, high-speed systems. Even with existing laser, optical fiber, and photodetector technology, this makes good sense and is being implemented now.

Other features of optics are being explored for use in switching systems. Directional couplers,<sup>1</sup> which switch light beams from one path to another, are well suited for rerouting information from one fiber to another. They can also be used for complicated switching functions and high-speed multiplexing and demultiplexing of optical signals. Although there are advantages to rerouting optical signals directly, many switching functions require that information be read (converted to digital format) and repackaged on its way through the switch. Devices such as directional couplers, which do not read the information, cannot independently convert information to digital format and, therefore, cannot form a complete digital switching system.

Today, we cannot make a general switching system that does not convert information to electrical form somewhere; electronic technology is the only means currently available to perform some of the complex logic functions required in certain parts of the machine. The applications of optics described in this paper are complementary to devices like directional couplers and other analog switching approaches, such as wavelength-division switching. Optics can be useful in digital technology, whether or not the information starts out in optical form.

Optics has many more features, most of which require new technologies, but offer long-term benefits. Some of the attractive features of optics are simple and



**Figure 1. Required communication energy as a function of distance, assuming 1V signals. Beyond a certain break-even distance, optical interconnections require less energy than electrical connections.**

obvious, such as its ability to handle entire images of information in digital systems at one time. For example, the lens in a human eye can make many thousands of "connections" simultaneously, enabling us to see many points in a picture at the same time, even though the waves from these points are emitted in all directions at once and cross over and through one another. The same feature could allow us to connect the points on one chip to those on another chip (perhaps several thousand with existing lenses), numbers greatly exceeding those possible with wires or fibers. These interconnections would be two-dimensional (surface-to-surface), rather than the one-dimensional (edge-to-edge) connections usual in electronics. Although this seems like a radical idea, we will discuss simple digital switching systems<sup>2</sup> and optical processors<sup>3-5</sup> that are entirely connected in this way.

An imaging, or "free-space," interconnection has other advantages. Because all the information from one plane of devices flows through a similar optical path, the clock skew is minimal. Free-space interconnections allow us to create patterns that are difficult to form with wires. Many useful patterns, especially in switching systems, require numerous wires, or paths, that cross in a regular pattern. These patterns can be produced simply in optics.

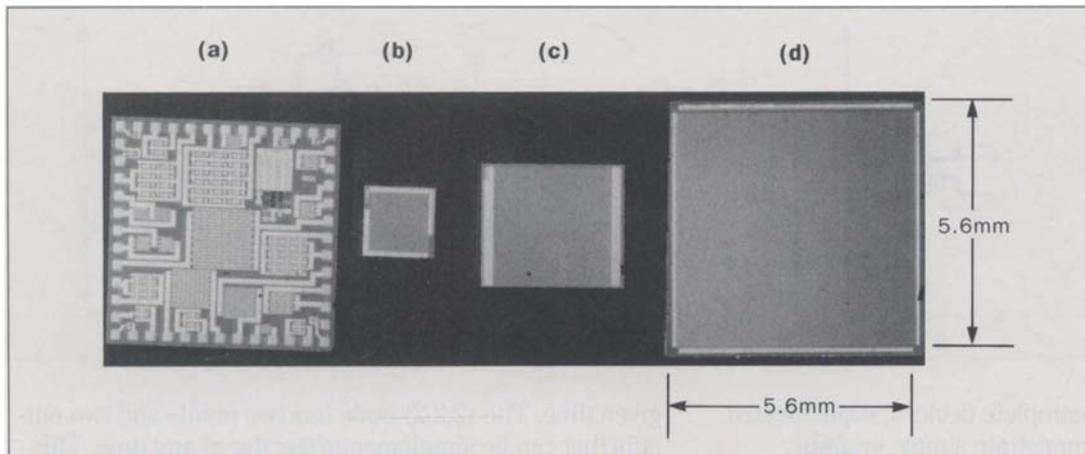
Optics can lower the energy needed to communi-

cate logical signals from one chip to another. For fundamental reasons, all wires require large energies per unit length to charge them up to the voltage levels used in electronic logic. About 20 picojoules (pJ) of energy are needed to charge a 30-centimeter-long line to 1 volt (V). Although this may not seem large, it is nearly 1000 times greater than the energy needed to make a good electronic logic-circuit switch. Optics can solve this problem in principle because signals are sent as bunches of photons, not as voltages, thereby eliminating the need to charge lines. Technically, this feature is called "quantum impedance conversion."<sup>6</sup> Beyond a certain "break-even" distance, optics requires less energy than electrical connections (see Figure 1). The break-even length depends on the quality of the optical technology.

To take full advantage of quantum impedance conversion, we must be able to make large quantities of small optoelectronic devices that are efficient at low power levels. The photodetectors must be small (e.g.,  $10 \times 10$  micrometers [ $\mu\text{m}$ ]) and integrated with electronic circuits. Unless photodetectors are close to the electronics, they require either too much energy to run or too sophisticated an electronic amplifier. Therefore, we need to develop an optoelectronic integration technology. Although this is feasible, the laser, modulator, and photodetector technology needed to support it is just being developed.

Developing light sources that can transmit efficiently at low powers is a challenge that can be met with very-low-threshold laser diodes. This technology is advancing steadily, although significant work remains to be done and integration with electronics is still difficult. Another solution involves using many modulators, along with a single external source to generate the necessary set of light beams. Quantum-well optical modulators,<sup>7</sup> new devices based on multiple quantum wells, work efficiently at low levels of powers. Researchers are now integrating them with electronic logic technologies. The use of small, integrated modulators and detectors could reduce the "break-even" length to a few hundred micrometers (see Figure 1). A technology that could optically connect many electronic "islands," sometimes called smart pixels,<sup>8</sup> each a fraction of a millimeter in diameter, could be physically and functionally attractive.

In the future, optics will make extremely fast devices possible. Even optoelectronic quantum-well self-electro-optic effect devices (SEEDs),<sup>9</sup> which were not



**Figure 2. Generations of S-SEED arrays, including (a)  $16 \times 8$ , (b)  $64 \times 32$ , (c)  $64 \times 128$ , and (d)  $128 \times 256$ .**

intended to run fast, can operate individually in 35 picoseconds (ps) because they do not need high-speed electrical connections.<sup>10</sup> Ultrafast optical logic devices operating in 1 ps or less have been successfully demonstrated using optical fiber and short optical pulses.<sup>11</sup> Researchers conducting systems experiments are just beginning to uncover the potential difficulties and benefits of such fast devices. Currently, the high energy levels required by these devices make large systems difficult to contemplate. However, we can expect advances in short pulse lasers, nonlinear optical materials, and new device concepts to remove the restriction so that large systems are possible.

### Free-Space Switching Devices

Free-space technology takes advantage of some of the features of optics that we discussed, especially the novel ones of two-dimensional parallelism and quantum impedance conversion. Researchers can use these features in switching fabrics to make many "pin-outs," or connections (spatial bandwidth), rather than being forced to put more data at a higher bit rate (temporal bandwidth) on a small number of pins.

To explore such free-space systems, researchers need two-dimensional arrays of devices with optical inputs and outputs, some of which have been proposed and even demonstrated. There have been several attempts to make arrays of all-optical devices without internal electronics; however, these arrays have seldom been used in systems experiments because of power consumption and critical biasing requirements. Although optoelectronics can be incorporated in many devices, the

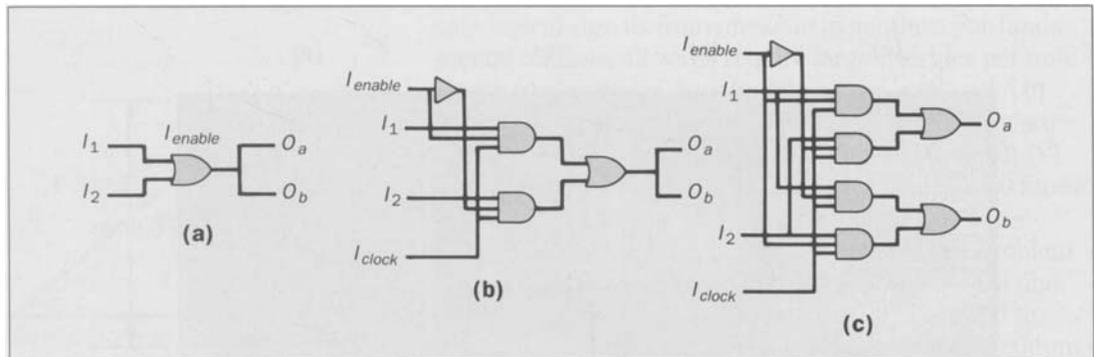
devices needed for two-dimensional arrays are very different from those used for long distance communication. We can make long distance systems from a small number of expensive, low-yield, high-power-consumption devices that need not be integrated with electronics. On the other hand, to develop free-space systems, we need to integrate thousands of low-cost, high-yield, low-power-consumption devices.

Because working arrays for optoelectronic devices are difficult to make, they usually start out as logically simple devices. Some use light emitters for the optical output, such as photo-thyristor devices (double heterostructure optoelectronic switch [DOES<sup>12</sup>] and vertical-to-surface transmission electrophotonic [V-STEP<sup>13</sup>]) that emit light after being switched on by another light pulse. Researchers are investigating these and other approaches to incorporate surface-emitting vertical cavity lasers<sup>14</sup> into two-dimensional arrays with acceptable optical efficiency.

The array device most often used in systems experiments is the quantum-well SEED.<sup>9</sup> Figure 2 shows a picture of the four generations of this device, whose optical output is based on quantum-well absorption modulators. Quantum-well structures consist of many thin layers of two different semiconductor materials. Individual layers are typically 10 nanometers (nm) (about 40 atoms) thick. One device would contain 100 layers and measure about 1 micrometer thick. When a voltage is applied across the layers, the optical transmission of the quantum wells changes significantly, creating an optical modulator.

SEEDS take advantage of quantum impedance conversion; can be made in high-yield, two-dimensional

**Figure 3. Switching nodes using the (a) 2-module, (b) (2,2,1) node, and (c) (2,2,2) node logic gates.**



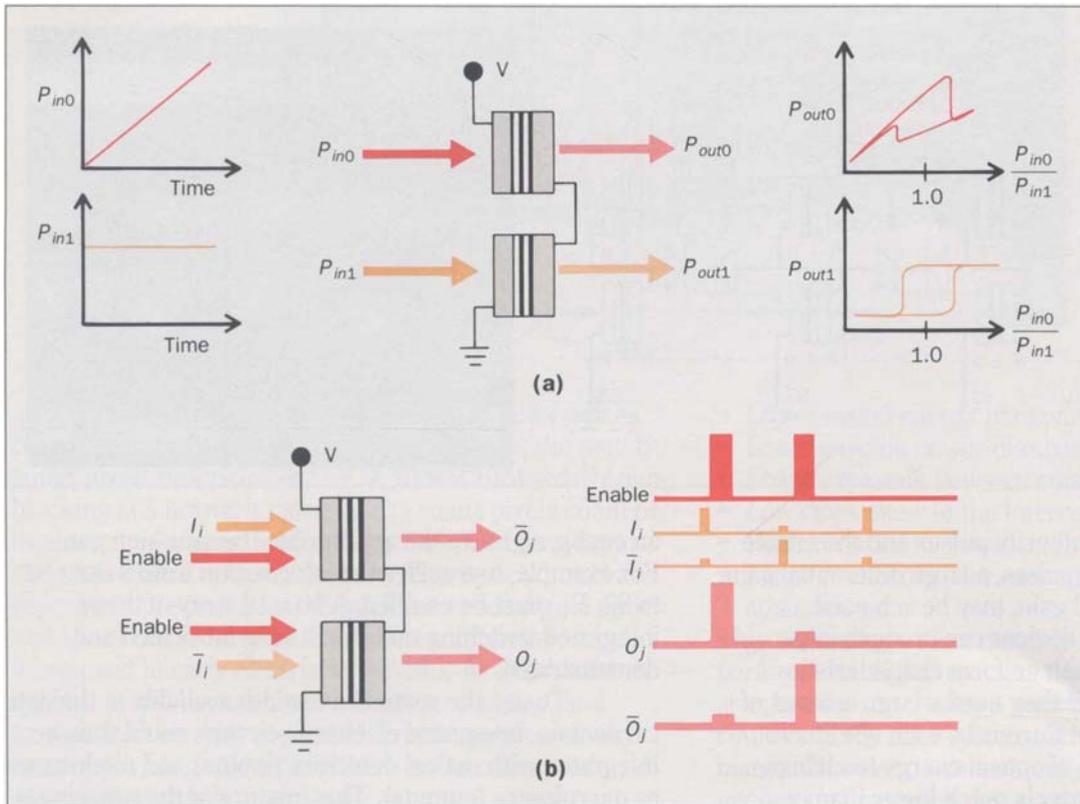
arrays; and are logically complete devices, sophisticated enough to be used to demonstrate simple systems. Because of the array fabrication used, the cost of individual devices is much lower, for example, than the cost of lasers for compact disc players. The so-called symmetric-SEED (S-SEED<sup>15</sup>) has been a particularly useful device in these systems experiments. The S-SEED has provided a platform to investigate the systems and optics associated with free-space optical switching. Experience gained with the first-generation S-SEED technology will also improve future devices. Logically smarter extensions of the S-SEED already exist. In the future, we can expect to have arrays of smart pixels, two-dimensional optoelectronic integrated circuits (2D-OEICs) with transistors that supply both electronic logic (“smartness”) and power gain (to reduce optical energies). Research on these integrations is being conducted now. For example, the field-effect transistor SEED (F-SEED)<sup>16</sup> has been successfully demonstrated. Modulators could be put on silicon to get optical outputs from integrated circuits.<sup>17</sup> Such free-space smart pixels would use electronics for logic, whenever appropriate, and optics for interconnection. The optics that interconnect free-space devices could contain either holographic elements<sup>18</sup> or bulk optical elements, such as lenses and mirrors.<sup>2</sup>

**Switching Nodes.** We can build a large-dimensional digital network by interconnecting many smaller switches or networks; each of these smaller switches can be referred to as a switching node. Figure 3 illustrates several digital switching nodes.<sup>19</sup> The triplet notation shown in this figure represents: number of inputs, number of outputs, capacity of the node. The first two parameters of the triplet represent the number of inputs and outputs, and the third parameter shows the number of channels that can pass through the node at a

given time. The (2,2,2) node has two inputs and two outputs that can be simultaneously active at any time. This node is topologically equivalent to a directional coupler, but because it consists of digital gates, it does not have the optical transparency of its analog counterpart. The (2,2,1) node in the center of the figure has two inputs and two outputs, although both outputs contain the same information; therefore, the node has a capacity of one. In this node, the input AND gates select the input channel that will be allowed to pass its contents to the outputs. These nodes work well in networks where only one input to a given node can be active at any time. These include dilated Benes,<sup>20</sup> Ofman,<sup>21</sup> and extended generalized shuffle (EGS)<sup>22</sup> networks. The 2-module is a simpler version of a (2,2,1) node. This node also requires the network to guarantee that only one node input will be active at any time, but since this node cannot block signals entering on the inputs, no signal can be present on the unused input line.

**S-SEED Based Switching Nodes.** An S-SEED based device, which has two inputs and two outputs, can be used to implement the switching nodes described earlier, as shown in Figure 4a. This device contains two multiple-quantum-well (MQW) pin diodes that become complementary when electrically interconnected in series. When one diode is “on,” the other will be “off;” thus, one diode will be in the absorbing state, while the other is in the transmissive state. Figure 4 shows these characteristic curves.

The device is bistable. For certain input powers, there are two possible output powers. Increasing voltage on a given diode decreases absorption and photocurrent (the same diode works simultaneously as a modulator and a photodetector), which causes bistability. Such “negative resistance” is known to create bistability in



**Figure 4. (a) Operating characteristics and (b) S-SEED based 2-module in an S-SEED operation.**

simple electrical circuits. Perhaps the greatest strength of the S-SEEDs is that changing states is a function of the ratio of the two input powers and not of the absolute intensity of the input beams.

The optically bistable loop is centered around the point at which the two inputs,  $P_{in0}$  and  $P_{in1}$ , are equal. These figures show that the device will remain in its current state until that ratio either exceeds 1.3 or is less than 0.7. Ratio switching enables the allowable noise on the signal inputs to be much greater than that of common mode "single-beam" devices (the S-SEED does not have to be biased close to a switching point to obtain signal gain).

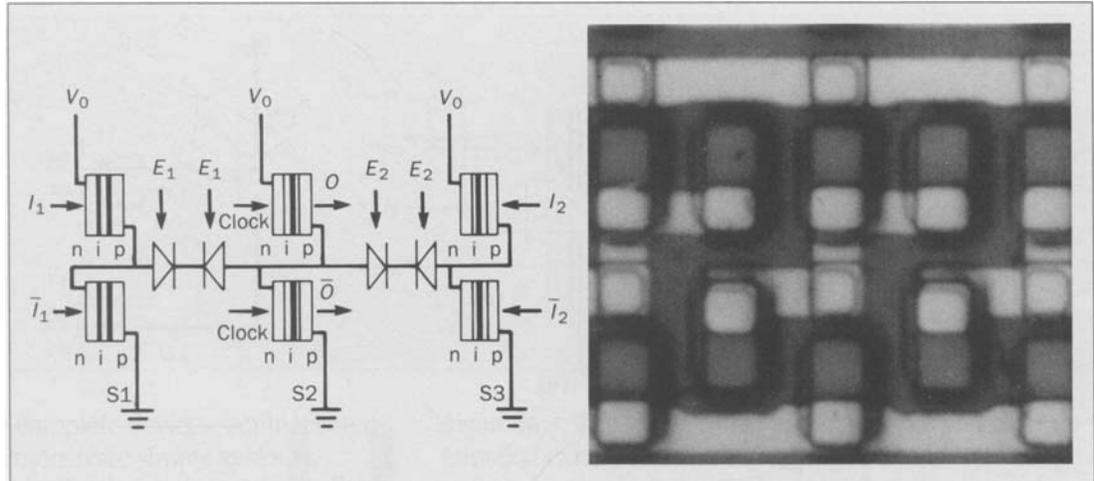
An S-SEED can be used as a 2-module because it stores information from the previous stage in the network during the read cycle and then passes that information to the next stage when the clock signal is applied to it. To block a signal from passing through the S-SEED 2-module, the clock signal is withheld from the previous device, effectively preventing the stored information from being transferred to the next stage in the network.

A spatial light modulator controls which devices receive clock signals, and, therefore, could block or inhibit selected S-SEEDs.

To operate the S-SEED as a 2-module, the differential inputs,  $I_i$  and  $\bar{I}_i$ , are also separated in time from the enable input, as shown in Figure 4b. The  $I_i$  and  $\bar{I}_i$  inputs, which represent the incoming data and its complement, set the state of the device. When  $I_i > \bar{I}_i$ , the S-SEED will enter a state in which the upper MQW pin diode will be transmissive, forcing the lower diode to be absorptive. When  $\bar{I}_i > I_i$ , the opposite condition will occur. Low switching intensities can change the device's state when the clock signals are not present.

After the device has reached its proper state, "enable" beams, which enable the inputs to be passed to the outputs, turn on the device. Since the two enable beams should be equal in intensity, the ratio between the power of the two incident beams should be nearly one, which will prevent the device from changing states. These higher-energy enable pulses will transmit the state of the device to the next stage of the system. Because the

**Figure 5. Schematic diagram and photograph of an S-SEED based, integrated (2,2,1) node.**



inputs  $I_i$  and  $\bar{I}_i$  are low-intensity pulses and the enable beams are high-intensity pulses, a large differential gain, known as time-sequential gain, may be achieved.

Although S-SEED devices can produce large arrays of small devices with uniform characteristics ( $128 \times 256$  [32K] arrays),<sup>23</sup> they need a large amount of optical energy to operate. Currently, each S-SEED element requires about 1 pJ of optical energy to change states. Although this energy is much lower than communication energies needed in electronics, it must emanate from an external light source that distributes the optical energy equally among the S-SEEDs used. The limited power available from current practical laser sources also limits system speed. In future work on S-SEEDs and other devices, such as F-SEEDs, developers will attempt to reduce the energy needed.

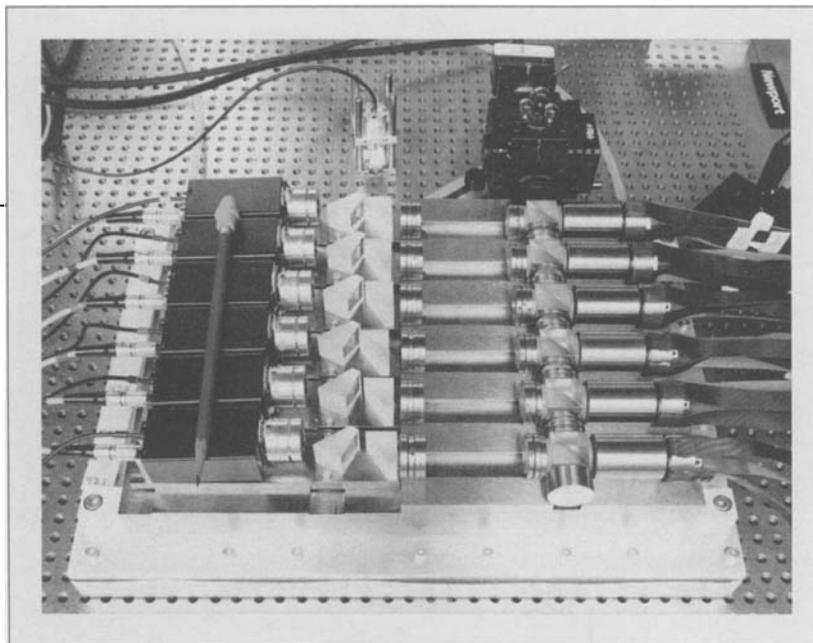
Adding more functionality or intelligence to each switching node in a two-dimensional array can both reduce the control complexity and the number of stages required in multistage interconnection networks, which in turn reduces the cost. These smarter nodes, fabricated into two-dimensional arrays, are referred to as smart pixels. Figure 5 shows a schematic diagram and photograph of an S-SEED-based, (2,2,1) node smart pixel.<sup>24</sup> Optoelectronic transmission gates,  $E_1$  and  $E_2$ , consisting of pairs of back-to-back quantum-well photodiodes, connect neighboring S-SEEDs (S1, S2, and S3). These photodiodes transfer the voltage from one S-SEED to another. Input signals,  $I_i$  and  $\bar{I}_i$ , set the states of S-SEEDs S1 and S3. The information is transferred from these S-SEEDs to the output S-SEED S2 by applying

an enable signal to the appropriate transmission gate. For example, to transfer the information from S-SEED S1 to S2,  $E_1$  must be enabled. A  $10 \times 16$  array of these integrated switching nodes has been fabricated and demonstrated.

To use the spatial bandwidth available in the optical domain, integrated electronic circuits could then be integrated with optical detectors (inputs) and modulators or microlasers (outputs). This mixture of the processing capabilities of electronics and the communications capabilities of optics would encourage connection-intensive architectures with more complex nodes to be implemented. In addition, the gain provided by the electronic devices should allow the nodes to operate at high speeds. In the simplest case, 2D-OEICs could be arranged into a large 2-D array of smart pixels such as (2,2,1), (2,2,2), or even (4,4,4) nodes. Each node in the 2-D array is electrically independent, except for a common ground and power supply. These smart pixels also could include the more complex circuitry necessary for self-routing nodes.

#### **Free-Space Interconnection Networks**

We can build large-dimensional interconnection networks by interconnecting the 2-D arrays of switching nodes using free-space interconnections. Figure 6 shows the optics that demonstrated the first six stages of a  $16 \times 32$  network.<sup>2</sup> In this system, each of the channels was 32 bits wide. Someday, each of these fine-grained switching fabrics could produce large dimensional fabrics. For example, we could show a  $1024 \times 1024$  nonblocking EGS fabric using 19 S-SEED ( $64 \times 128$ )



**Figure 6. A  $32 \times 32$  free-space switching fabric, each of whose channels is 32 bits wide.**

arrays and their associated optical hardware, as well as two stages of a  $64 \times 64$  EGS network based on the S-SEED smart pixels described earlier. A  $1024 \times 1024$  strictly non-blocking EGS network using (2,2,1) smart pixels could be implemented using 18 ( $32 \times 64$ ) smart pixel arrays and their associated optical hardware. This optical hardware represents the first generation of free-space digital optics and should be likened to the discrete components and wires used in early electronic systems. As this hardware evolves, it will become more complex, compact, and manufacturable, just as printed circuit boards and very-large-scale integration (VLSI) have led to mass-produced electronic systems.

**Networks Using Electronic Nodes.** In general, 2D-OEICs are not restricted to systems based on chip-to-chip interconnection. These structures could also be used to provide optical interconnection between multi-chip modules (MCMs) or printed circuit boards. For example, 2D-OEIC chips (arrays that contain modulators, micro-lasers, and detectors) could be flip-chip mounted (that is, mounted face to face) on MCMs to provide the required MCM-to-MCM interconnections, or connectivity. These optical interconnections are small, and have a high-performance input/output footprint and a lower on-chip power dissipation than their electrical counterparts when the distance between MCMs is greater than 1 millimeter and the bit rates exceed 100 Mb/s.<sup>25</sup> Reducing the on-chip power dissipation should increase the range of gate density on the MCMs before the thermal limit is reached.

#### The Future

Free-space technology is still young, but it does offer the hope of a larger scale of connectivity than the more mature electronics technology can achieve. Its potential strengths include:

- Lower signal energy per connection
- Lower on-chip power dissipation per connection
- Lower crosstalk between connections
- Low clock skew in the interconnection
- High connection density
- Large connectivity for new and advanced systems applications.

This technology offers not only a solution for high-performance digital systems that are connection intensive, but it also remains a promising way in which optics could radically alter system architecture and performance. However, we must understand that this interconnection technology is designed to enhance and extend the current electronic technology, not replace it.

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