# Switching to photonics

*Voice, video, and data will eventually be switched by hardware that exploits the interplay of photons and electrons*

Telecommunications in the future will rely on light as heavily in switching as it does today on light in transmission. The vast information-carrying capacity of optical fiber will be joined to the astounding connectivity of photonics.

Each new wave of switching hardware will have more photonics embedded in it. In 1995, the first specialized applications will be appearing. By 2000 there may not be purely photonic switching but there certainly will be abundant photonics; for example, photonic links will interconnect printed-circuit boards, multichip modules, and equipment frames. By 2010, optoelectronic switching fabrics could be bringing business community and residential customers alike a panoply of broadband services: video, high-definition television, and switched videotelephone conversations and conferences; fast data file transfers and information retrieval; data exchange for diskless workstations; and animated graphics, for example, all in addition to today's voice and data services.

A future photonic switching office for telecommunications will support more than 10 000 channels, each with a bandwidth greater than 150 Mb/s. The aggregate bit rate for the office's switching fabric will be greater than 1 million megabits per second (1 terabit per second). In contrast, today, channel bandwidths are 64 kb/s, and an electronic switching office handles an aggregate bit rate of less than 15 Gb/s.

**ENGINEERING FOCUS.** As of now, laboratories in industry and universities around the world are at work on a variety of photonic switching architectures and devices [see table, p. 45]. A few photonic switching devices have just come on the market, though they are still small arrays. In addition, some prototype hardware was demonstrated at the Telecom '91 conference in Geneva, Switzerland, last October. The focus now in many laboratories is on engineering—increasing capacity and performance while reducing size and cost. Still other concepts are in an early experimental stage.

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The work is proceeding along two divergent paths. Guided-wave photonics is better understood and more highly developed. It capitalizes on temporal bandwidth: combining a large number of users into a single physical channel, either through time multiplexing or wavelength multiplexing, in structures like optical fibers and star and directional couplers. These structures are bandwidth transparent (support any bit rate).

The alternative, free-space photonics, exploits spatial bandwidth: serving many users in parallel through many separate channels in structures like lenses, mirrors, holograms, and arrays of optical logic gates or optoelectronic integrated circuits. Essentially, guided-wave photonic switching supports many users on a small number of physical channels, while free-space photonics supports a large number of users on a large number of lower-speed channels.

**For future photonic switching offices, the aggregate bit rate will be an amazing 1 terabit per second**

**GUIDING WAVES.** Probably the most highly developed version of guided-wave photonic switching is based on directional couplers. Indeed, these devices have been the mainstay of photonic switching for 15 years.

A directional coupler is like a switchtrack on a railway: it sends light signals straight through or diverts them to an adjacent channel. These devices can handle massive bit flows easily, but they are relatively slow in switching a signal from one path to another. They also are subject to cross talk and signal attenuation and cannot be integrated on a large scale. Nonetheless, they have an important application: as protection switches for fiber transmission links. If a failure occurs on a fiber link, a directional-coupler-based fabric can reroute its traffic all at once to an alternative link. The microsecond reconfiguration time required is trifling.

Ericsson Ab, Stockholm, Sweden, and AT&T Co., Berkeley Heights, N.J., now offer directional coupler switches for sale in eight-by-eight arrays (eight inputs switchable to eight outputs).

A basic directional coupler consists of two optical inputs, two optical outputs, and one or more electrical control input [Fig. 1]. Couplers are usually made of a crystal of lithium niobate into which a titanium channel is diffused to create a lightwave guide, although there has been some work on gallium arsenide and indium gallium arsenide phosphide material systems. A change in voltage on the device's electrodes alters the optical properties of the material, rerouting the channels from the bar or bypass state to the cross or exchange state (from straight through to criss-cross).

Up to a point, two-by-two directional couplers can be integrated in a single fabric. One factor limiting fabric size is the attenuation by the device of signals passing through it. But the signal loss can be reduced by special interconnection network topologies. For example, the dilated Benes rearrangeable network limits loss to a logarithmic (instead of a linear) increase with switch size—they keep loss low until the switches become very numerous.

A further limit on fabric size is cross talk. To minimize cross talk, special networks are used to ensure that no two inputs on a directional coupler are active simultaneously. Again, the dilated Benes scheme keeps cross talk low, although others, like the the Ofman and extended generalized shuffle networks, are good too.

## Defining terms

**Connectivity:** effective number of connections to and from a device or other hardware.
**Fabric:** interconnection network hardware composed of switching nodes and links between them.
**Fully connected:** said of a switch in which any input channel can be connected to any output channel, provided another connection does not occupy part of the path.
**Nonblocking:** said of a switch in which any idle input channel can be connected to any idle output channel.
**Packet-switched network:** network that divides information into blocks, each containing address and control data.
**Photonics:** technologies based on interactions between electrons and photons.

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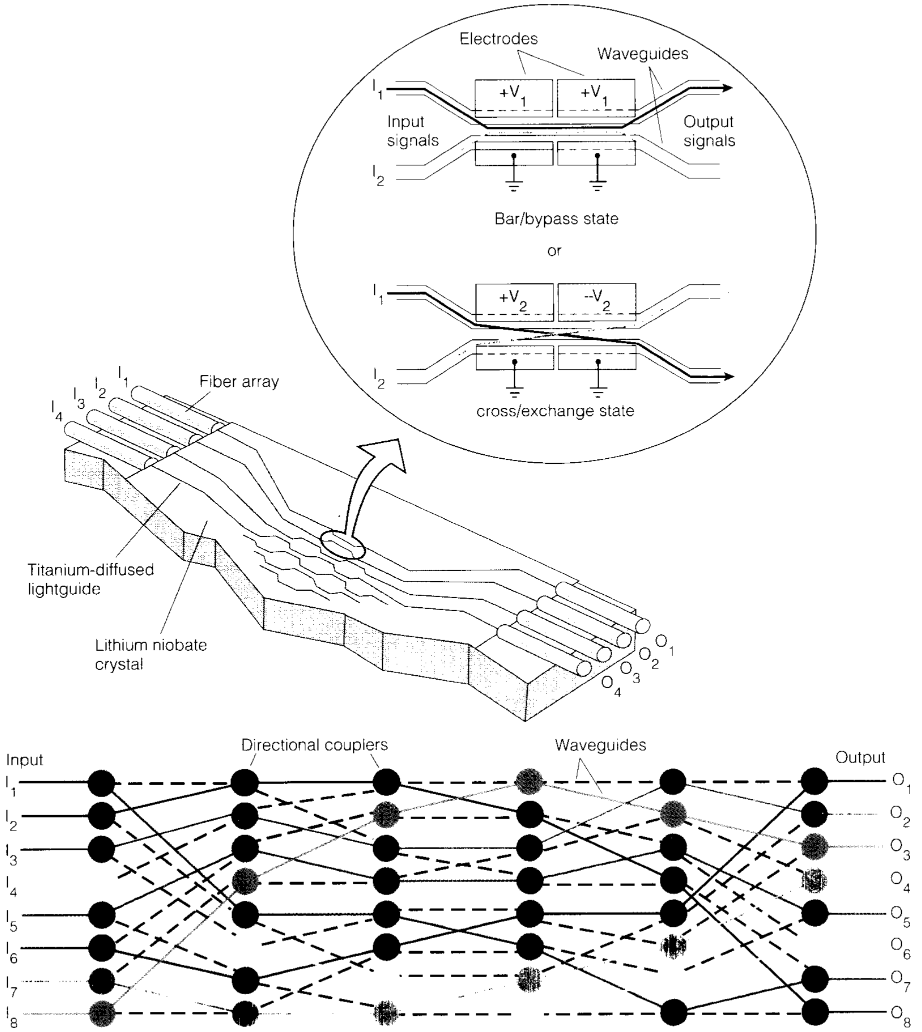
## Anatomy of a directional coupler




*[1] A directional coupler can route a light signal straight through (bar/bypass state) or switch it to an adjacent waveguide (cross/exchange state). Many such couplers can be connected together on a lithium niobate chip. When the couplers are joined in a pattern known as the dilated Benes network (an eight-input, eight-output version appears here), cross talk is minimized because any coupler can have only one of its inputs active at any instant. Color lines show one of many possible configurations of paths from inputs to outputs; dashed lines show unused paths that become active when the switch is reconfigured by altering the electrode voltages.*

Yet other limits on integration are the great length of directional couplers in relation to their width and the large minimum bending radius of the diffused waveguides. All these constraints add up to a maximum integrated array size of 32 by 32. Larger switching fabrics have to be built up by interconnecting 32-by-32 arrays.

Another approach to guided-wave switching is time-division, rather than space-division, multiplexing. The division can be done by interchanging time slots or by using multiple-access devices like star couplers.

In time-slot interchangers, users are assigned slots on a single channel. Switching is done by a reconfigurable fabric that rearranges the temporal positions of the slots according to each's destination. The slots are then separated and sent onward. The connection between users is virtual.

In multiple-access switching, however, the connection between users is real and physical, albeit intermittent. For example, a star coupler network combines all its input channels and distributes them equally to all its outputs. Decoders on the output ports, instructed by a central controller, select the input they want to receive.

**SLOT INTERCHANGE.** Most proposed photonic time-slot interchangers (TSIs), when an input arrives in a given time slot, send it directly to the desired output time slot in a single step, over an optical-fiber delay line. The photonic interchanger based on directional couplers chooses a fiber whose length will delay the input slot just the right amount to fit it into the output slot. Work on this is being done at NEC Corp., Tokyo, and AT&T Bell Laboratories, Murray Hill, N.J..

The input is divided into time slots composed of many bits, with a little dead time between slots. That way, the coupler need not switch too often, and its low switching speed is not a handicap. Time slots for voice, data, and video users may be freely mixed. AT&T Bell Laboratories' Disco system demonstrated the principle in an eight-by-eight switching fabric.

Another kind of time-slot interchanger shifts the input slots through intermediate time-slot stages until they are in the desired output slot. With this scheme, the intermediate stages do not have to be fully connected or nonblocking, as they do in the single-stage interchanger. This time-division system is analogous to a multistage space-division network. One such system has been proposed by researchers at the University of Colorado, Boulder.

Time-division multiplexing by multiple-access fabrics may use a passive shared medium such as an optical-fiber ring. For input and output, the ring is accessed either by passive taps such as fiber couplers or by active taps such as directional couplers. In a synchronous ring, each user is assigned a unique time slot in which to read information from the ring. Other users can send information to a user by entering it into the destination user's time slot. Access to the time slots is arbitrated by a central controller. Asynchronous, distributed-control schemes are another possibility.

Like time-division fabrics, wavelength division can rearrange input channels or share them through multiple access. A wavelength interchanger, for example, can switch a wavelength-multiplexed channel—one combining signals at different wavelengths. Since each user has a unique wavelength, a connection can be made between two users by converting a transmitter's wavelength to that of the appropriate receiver [Fig. 2].

In a wavelength interchanger recently proposed by NEC, the multiplexed input enters an optical splitter, where its power is divided equally among a group of internal channels. Each channel subjects the multiplexed input to coherent detection: the input is mixed with a monochromatic laser beam—tuned to a different wavelength for each channel—so that the information on the desired input signal is electrically extracted. This electrical information is used to modulate a fixed-wavelength output laser. The various output wavelengths are then multiplexed and sent on from the interchanger on a single optical-fiber channel.

A promising multiple-access wavelength interchanger is based on a star coupler, a device that combines all inputs and distributes them to all output channels. Each input has a unique wavelength. Each output channel has a tunable filter that a central controller tunes individually to match the wavelength of the input destined for it.

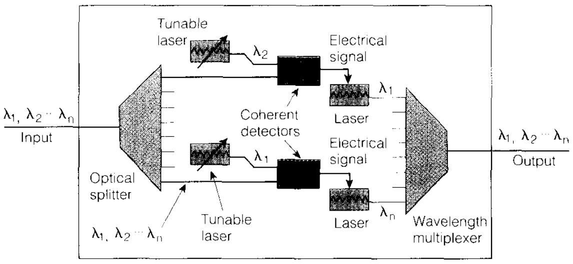
Several kinds of tunable filter are being pursued, including movable gratings, etalons (wavelength-selective interferometers), and coherent detectors. All devices have advantages and disadvantages. Movable gratings have good resolution but are slow. Etalons are fast but have less resolution. Coherent detectors offer both speed and high resolution, but are expensive to use because they need a tunable mixing laser.

**TIME-SPACE-TIME.** Multidivisional fabrics—those based on a combination of space-division and time-division multiplexing—promise huge throughput with rather little hardware. As yet, though, such systems are only in the concept stage. One proposal, from AT&T Bell Laboratories, calls for a 512-by-512 time-space-time photonic switch with an internal bit rate of 4.8 Gb/s. The 512 input lines, each at 150 Mb/s, are partitioned into 16 sections of 32 lines. Each section is time multiplexed into a single space channel, and all channels are fed to a 32-by-32 TSI, through a 16-by-16 space-division switch and then a 32-by-32 TSI, and finally demultiplexed into 512 channels, each at 150 Mb/s.

The challenge with time-space-time switching is timing. At 4.8 Gb/s, the bits will be only 208 picoseconds long, and, to prevent discontinuities in the output channels, they will have to be synchronized within 10 ps. The onus for the timing falls on the initial time-division multiplexer, unless an elastic store (one whose delay time can be varied) is placed at the input to the space-division switch. Control electronics will have to recognize 10-ps time differences.

To minimize the timing burden, components will have to be packaged with extreme care. For example, if optical fibers between the initial time-division multiplexer and the space-division switch differ by only 1 cm, their bit arrival times will differ by all of 50 ps (for an index of refraction of 1.5).

**RECONFIGURING FABRIC.** A wavelength-division-based photonic packet switch is another kind of a multidimensional fabric. It is basically a multiple-access fabric that rapidly and continually reconfigures itself to time-share channels. In the Hypass system proposed by Bellcore, Livingston, N.J., packets of information entering the fabric are briefly stored in a first-in, first-out (FIFO) buffer, then used to modulate a laser tuned to the wavelength of the designated output port. A star coupler eventually transports all channels to receivers at the output ports.




*[2] In wavelength interchanger, a multiwavelength input is divided among many coherent detectors. Heterodyned by a tunable laser, each coherent detector extracts an electrical modulation signal representing a discrete input wavelength and uses it to modulate a laser operating at a different wavelength. Any input wavelength can be switched to any output wavelength.*

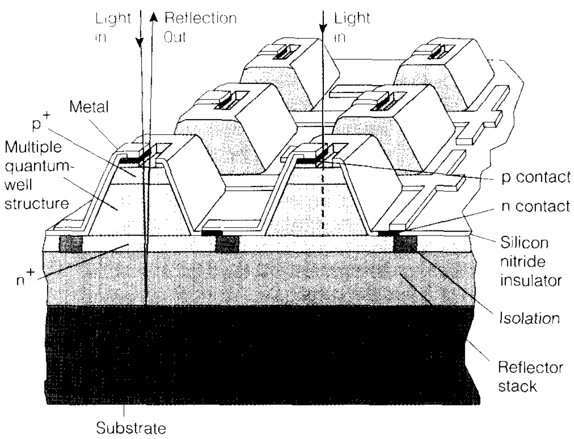
Control circuitry first checks the desired output port to see if it is busy, and, as soon as it is not, turns on and tunes the input laser to the wavelength of the receiver at the output port, finally commanding the FIFO buffer to send its stored information to the laser.

Free-space switching, although not as well-developed as guided-wave switching, is perhaps even more promising. Several laboratories are working on free-space systems based on two-dimensional optoelectronic ICs such as self-electro-optic-effect devices (SEEDs), double heterostructure optoelectronic switches, and vertical surface transmission electrophotonic device arrays.

**QUANTUM WELLS.** Of these devices, a symmetric SEED (S-SEED) is particularly useful. Its structure lends itself to fabrication in large arrays by batch-processing. An S-SEED is a pair of p-i-n diodes with multiple quantum wells in the intrinsic region [Fig. 3]. The diodes are electrically connected in series and reverse biased. One of the diodes is on (reflects light) while the other is off (absorbs light). Which diode is on is determined by the ratio of the powers of the light beams directed at each diode. The reflected differential light beams may then be processed through a lens or hologram to subsequent S-SEED arrays until they arrive at the required output channel.

The strength of S-SEEDs is that large arrays of small devices can be built. Using a gallium arsenide–aluminum gallium arsenide heterostructure for multiple quantum wells, workers at AT&T Bell Laboratories have fabricated, by molecular beam epitaxy, 128-by-256 arrays of S-SEED pairs. The weakness of the devices is that they require too much energy; at present they need about 1 picojoule to change state. Much more work also remains to be done on packaging.

Nevertheless, AT&T Bell Laboratories has built a 16-channel-input, 32-channel-output S-SEED-based fabric, an application-specific version of its 32-by-64 array. Operating at about only 100 kb/s, the fabric does not take advantage of the speed of S-SEEDs, but does demonstrate the feasibility of free-space optical interconnection and packaging. An incoming signal is routed to an output channel through six switching stages. At each stage, the signal is split in two and directed to an S-SEED pair. A control computer determines which of the pair accepts the signal. The S-SEED




*[3] Light entering a symmetric self-electro-optic-effect device (S-SEED) is either reflected or absorbed, depending on the ratio of power in the separate beams illuminating it and its neighbor. The multiple quantum-well structures are alternating layers of gallium arsenide and aluminum gallium arsenide, each layer about 10 nm thick.*

## Photonic switching technologies and players

| Switching method | Photonic devices | Developers | Current status (devices and systems) | Advantages/disadvantages |
|---|---|---|---|---|
| **Space division** | | | | |
| Guided-wave | Directional couplers | AT&T Co.; LM Ericsson, Stockholm, Sweden; Fujitsu Ltd., NEC Corp., and NTT Corp., Tokyo | 4-by-4, 8-by-8 prototype devices available; research lab prototype systems | Bandwidth transparent/small-scale integration; difficult synchronization and control |
| | Digital switches | Ericsson | | |
| | On-off shutters | Optivision Inc., Davis, Calif. | 16-by-16 product available | |
| Free-space | SEED technology | AT&T; University College, London | Products available; system demonstrators | Digital devices/high switching energy; difficult optomechanical packaging technology |
| | Pnpn technology (DOES, VSTEP, EARS, LAOS) | AT&T; Colorado State University, Fort Collins; NEC; NTT; University of New Mexico, Albuquerque; University of Southern California, Los Angeles | Research prototype devices; research lab experimental systems | |
| | Smart pixels | AT&T; NEC; NTT; University College, London; University of Southern California | Simple research prototype devices; research lab experimental systems | Digital devices/difficult optomechanical packaging technology |
| **Time division** | | | | |
| Time-slot interchange | Directional couplers, fiber delay lines | AT&T, NEC, University of Colorado, Boulder | Prototype devices available; research lab experimental systems | Bandwidth-transparent/small-scale integration; difficult synchronization and control |
| Multiple-access | Star couplers, tunable lasers, tunable receivers | AT&T; Princeton University, New Jersey | | |
| **Wavelength division** | | | | |
| Wavelength interchanger | Star couplers, tunable lasers, tunable receivers | NEC | Prototype devices available; research lab experimental systems | Bandwidth-transparent/small-scale integration; difficult synchronization and control |
| Multiple-access | Star couplers, tunable lasers, tunable receivers | AT&T; Bellcore, Livingston, N.J.; NEC; NTT; CSELT; Columbia University, New York City | | |
| **Multiple division** | | | | |
| Time-space-time | Directional couplers, fiber delay lines | AT&T | Prototype devices available; research lab experimental systems | Bandwidth-transparent/small-scale integration; difficult synchronization and control |
| Wavelength-space-wavelength | Star couplers, tunable lasers, tunable receivers | NEC | | |
| Packet switching | Star couplers, tunable lasers, tunable receivers | AT&T, Bellcore | | |
| | Smart pixels | AT&T; University College, London; University of Southern California | Research devices; research lab experimental systems | Digital devices/difficult optomechanical packaging technology |

SEED = self-electro-optic-effect device.
DOES = double heterostructure optoelectronic switch.
VSTEP = vertical surface transmission electrophotonic.
EARS = exciton-absorptive reflection switch.
LAOS = light-amplifying optical switch.
CSELT = Centro Studi e Laboratori Telecomunicazioni SpA (Telecommunications Research and Study Center), Turin, Italy.

output from one stage becomes the input to the next stage.

Still in the future are fabrics composed of smart pixels—chips with optical detectors on their input channels, electronic logic in the middle, and either microlasers or modulators on their output channels. The signal-processing ability of electronics plus the communication ability of optics will yield complex, high-speed switching.

Finally, free-space optical interconnection can be used to link either multichip modules (MCMs) or printed-circuit boards. One proposal, from Bell Laboratories, for 2-D optoelectronic ICs envisions a 1024-by-1024 network in which each of three stages is an electronic MCM with more than 3000 optical inputs and outputs—an unprecedented challenge for package designers. The bit rate for each input/output channel would be greater than 150 Mb/s.

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**TO PROBE FURTHER.** Author Hinton, with Joseph W. Goodman, John E. Midwinter, and Peter W. Smith, presented an IEEE Seminar via Satellite, "Photonic Switching in Communications and Computers," on Sept. 22, 1988. The three-hour program is available on videotape from the IEEE Service Center, Customer Service Department, 445 Hoes Lane, Piscataway, N.J. 08855-1331; 800-678-IEEE; outside the United States, 908-981-0060.

The Optical Society of America sponsors a topical meeting on photonic switching every two years, most recently March 6-8, 1991, in Salt Lake City, Utah. Proceedings are available from the society, 2010 Massachusetts Ave., N.W., Washington, D.C. 20036; 202-416-1980.

*Photonic Switching*, edited by H. Scott Hinton and John E. Midwinter, includes papers on switching network architectures as well as on devices and systems (IEEE Press, New York, 1990).

The *IEEE Journal on Selected Areas in Communications* published issues on photonic switching in August 1988 and 1990. ◆