CHAPTER 10

OPTICAL CROSS-CONNECTS

10.1 INTRODUCTION

Channel cross-connecting is a key function in most communications systems. In electronic systems, the electronic cross-connecting fabric is constructed with massively integrated circuitry and is capable of interconnecting thousands of inputs with thousands of outputs. The same interconnection function is also required in many optical communications systems. Optical (channel) cross-connection may be accomplished in two ways:

1. Convert optical data streams into electronic data, use electronic cross-connection technology, and then convert electronic data streams into optical. This is known as the *hybrid approach.*
2. Cross-connect optical channels directly in the photonic domain. This is known as *all-optical switching.*

The hybrid approach is currently more popular because there is existing expertise in designing high-bandwidth multichannel ($N \times N$) nonblocking electronic crossconnect fabrics. In this case, N may be in the order of thousands.

All-optical switching is used in high-bandwidth, few-channel cross-connecting fabrics (such as routers). N in this case is from 2 to perhaps 32, but photonic cross-connects with N in the range of up to 1000 are in the experimental and planning phases. An economically feasible and reliable 1000 $\times$ 1000 all-photonic, nonblocking, dynamically reconfigurable switch is currently a challenge, but the technology is promising.

10.2 OPTICAL CROSS-CONNECT MODEL

Optical cross-connect devices are modeled after the many-port model: that is, N input ports and N output ports, with a table that defines the connectivity between input and one or more outputs. Mathematically, this model may be represented by a matrix relationship. Figure 10.1 illustrates the model and the matrix of a cross-connecting device, where I_K is the amplitude of light at input port K, O_L is the amplitude of light at output port L, and $[T_{IJ}]$ is the transmittance matrix. In general, the transmittance terms T_{IJ} are functions of the absorption and dispersion characteristics of the connectivity path. Ideally, the T_{IJ} terms are 1 or 0, signifying connect or no connect, respectively, with zero connectivity loss and zero dispersion.

$$\begin{bmatrix} O_1 \\ O_2 \\ \vdots \\ O_N \end{bmatrix} = \begin{bmatrix} T_{11} \cdots T_{1N} \\ T_{21} \cdots T_{2N} \\ \vdots \quad \vdots \\ T_{N1} \cdots T_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix}$$

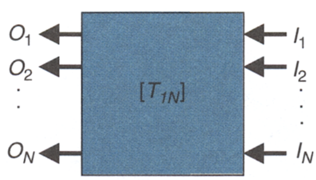

Figure 10.1 Modeling an optical cross-connect, mathematically and symbolically.

All-optical cross-connect fabrics are based on at least three methods:

- Free space optical switching [waveguide grating router (WGR), Mach–Zehnder interferometers]
- Optical solid-state devices (acousto-optic and electro-optic couplers)
- Electromechanical mirror-based devices

Other methods are based on the polarization properties of liquid crystals and other properties of materials. Optical switches based on liquid crystal technology have been announced offering high isolation, low insertion loss, and up to 40 channels.

10.3 FREE SPACE OPTICAL SWITCHING

Among the most promising switches with many input ports to many output ports is the generalized Mach–Zehnder WGR. In this device, a given wavelength at any input port appears at a specified output port (Figure 10.2). Thus we have an input-to-output connectivity map: that is, a switch. This type of free space optical switching is also known as *wavelength routing.*

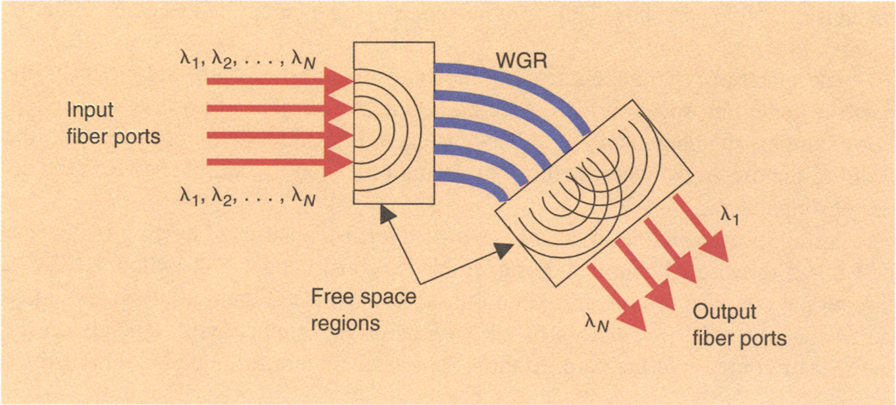

Figure 10.2 Free space optical switching based on the generalized Mach–Zehnder waveguide grating router.

In another type of free space optical switching, a laser beam is mechanically steered to one of many fibers. In a matrix of beams facing a matrix of fibers, for example, one of the source beams and a receiving fiber would be steered so that they faced each other to achieve connectivity in space. Upon redirecting the source (by a small degree) to face another fiber space, switching would be accomplished.

10.4 SOLID-STATE CROSS-CONNECTS

Solid-state optical cross-connect devices are semiconductor directional couplers. These devices can selectively change one of their optical properties on a path upon the application of a control signal (Figure 10.3). The optical property may be polarization, propagation constant, absorption, or index of refraction. Depending on the type of material, the optical property may change upon application of heat, light, mechanical pressure, electric current, or an electric field (voltage).

For example, current injection controls the refractive index of a semiconductor waveguide, whereas electric field application controls the index of refraction of fer-

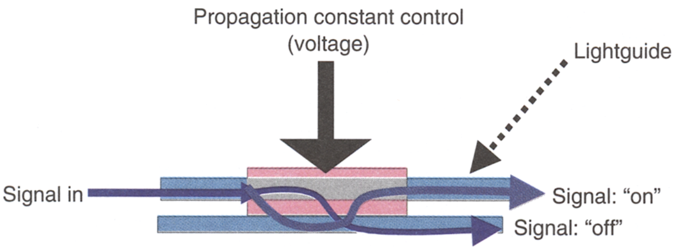

Figure 10.3 A solid-state optical cross-connect based on the principles of directional couplers.

roelectric $LiNbO_3$ crystals. Thin-film heaters may also be applied to control the refractive index.

The material type, the controlling mechanism, and the controlled property impact the switching speed of the device as well as the number of ports of the switch. For example, switches made with $LiNbO_3$ crystals exhibit switching speeds in the order of nanoseconds, whereas those made with SiO_2 on Si exhibit speeds in the order of under 1 ms.

A multiport switch, also called a *star coupler*, is constructed by employing several 2×2 directional couplers. For example, to construct a 4×4 switch, six 2×2 directional couplers are integrated on the same substrate (Figure 10.4). It should be noted that the total power loss of each input–output connectivity depends on the number of couplers in the path. In the 4×4 arrangement, each path contains three couplers.

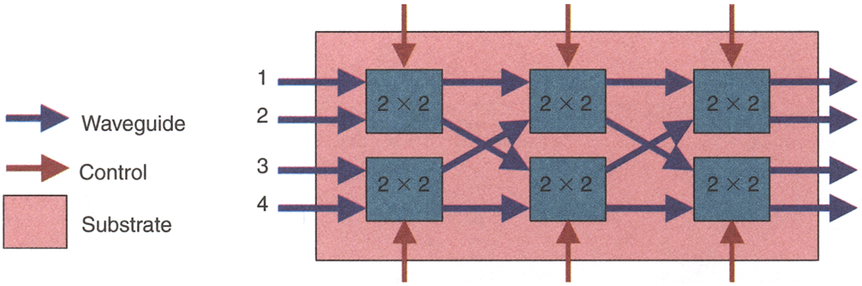

Figure 10.4 A star coupler multiport switch using several 2×2 $LINbO_3$ directional couplers.

Although the number of ports can be large (e.g., 128×128), losses are cumulative, and thus practical switches have a rather limited number of ports: for example, 16×16 or perhaps 32×32. Solid-state optical cross-connects are characterized by a number of parameters. In the following examples, descriptions in parentheses refer to a typical SiO_2 on Si device.

- Switching matrix (2×2, 4×4, etc.)
- Insertion loss (typically 1 dB)
- Isolation (typically 35 dB)
- Cross-talk (typically -40 dB)
- Switching speed (in the range of milli- to nanoseconds)
- Polarization-dependent loss (< 1 dB)
- Spectral flatness (typically $\pm$ 1 dB)
- Operating temperature (0–70°C)
- Operating voltage (typically +5 V)

- Number of inputs and outputs (e.g., 2 × 2)
- Whether they do or do not block an input

In addition, the package type (e.g., hermetically sealed), type of fiber connector, and physical dimensions are important parameters. For an example, a 2 × 2 optical cross-connect is a rather large device (~100 × 10 × 10 mm^3).

10.5 MICROELECTROMECHANICAL SWITCHES: REFLECTOR TYPE

Designers of optical cross-connect equipment have employed nanotechnology to micromachine tiny mirrors on a substrate that can be used to cause switching by reflecting optical beams. This technology, also known as microelectromechanical systems (MEMS), uses an outgrowth of semiconductor processing, which is a proven technology. (The new technology is expected to become as simple as a mere rubber stamp to create nanomolds, nanoparts, and nanomachines that may be used in communications and in other fields as well.) Using deposition, etching, and lithography, tiny machines (smaller than the human hair) are micromachined on a substrate. Such machines may be gears, linear stepper drives, pulleys, tweezers, bending beams, screws, electric motors, polished flat plates, and so on. Thus, a highly polished (with gold) flat plate (or a mirror) is connected with an electrical actuator and is placed vertically in the gap of three intersecting waveguides. This arrangement comprises an optical switch whereby the mirror may let an optical beam pass through or reflect it in a different direction. The mirror may move to accomplish this by one of many methods, depending on the fabrication technology. It may be connected, for example, so that by rotating the mirror between two positions a beam is directed to one of two directions (Figure 10.5a). It may be pulled down (when a voltage is applied) or up (when no voltage; Figure 10.5b). Similarly, it may be linearly pulled back from or inserted into an optical waveguide gap to change the direction of a beam. Figure 10.6 is a photomicrograph of a MEMS (of the type in Figure 10.5b). Another structure places the mirror in an electrostatic actuator (see below: Figure 10.8), and thus

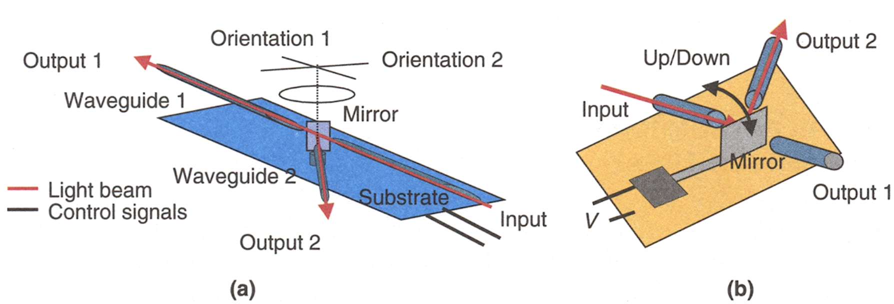

Figure 10.5 Micromachined mirrors can be rotated (a) or moved up/down (b) to construct optical switches.

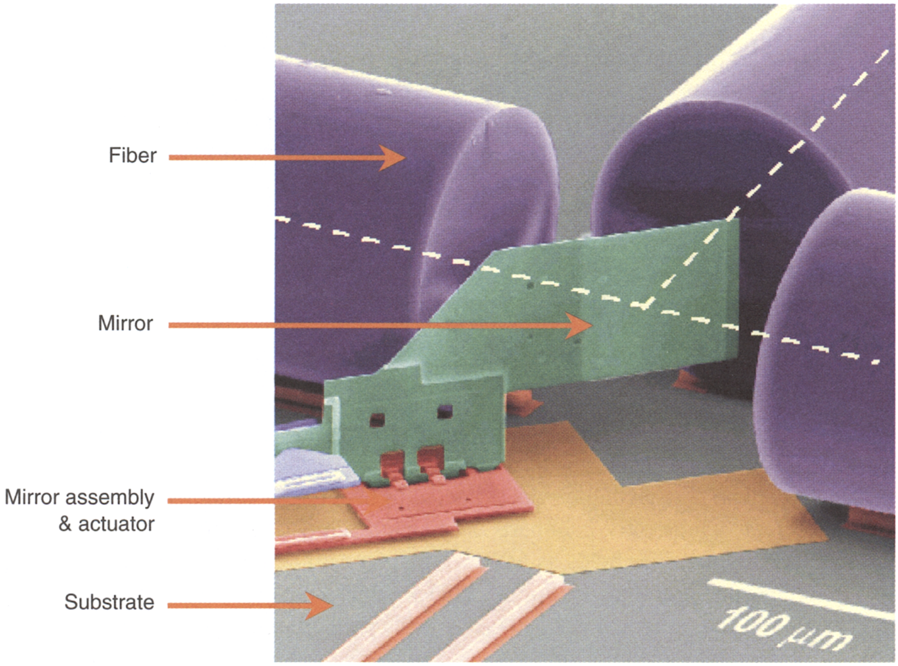

Figure 10.6 Photomicrograph of a microelectromechanical switch. (*Copyright © 1999. LUCENT Technologies. All rights reserved. Reprinted with permission.*)

it can be tilted in specific directions, based on the value of the applied voltage (in the order of 100–200 V). With reference to Figure 10.5, when the mirror is at one orientation it lets the light beam be coupled to waveguide 1 (and to output 1) and at the other orientation it allows coupling to waveguide 2 (and to output 2).

MEMS technology, although complex, uses well-known integrated circuit batch processing; thus, many MEMS devices may be manufactured on the same wafer, reducing the cost per system. MEMS have demonstrated low-loss connectivity (< 1dB), on–off contrast ratio of better than 60 dB, low switching power (2 mW), compact design and, when integrated with other devices, higher density multifunctional optical switching systems. However, MEMS technology is slower (~ 10 ms) than $LiNbO_3$ solid-state switches.

10.6 ELECTROMECHANICAL SWITCHES: MIRROR ARRAY

MEMS technology has expanded to integrate many mirrors on the same chip, arranged in an array. Based on this technology, each mirror, connected with a micromachined electrical actuator, may be independently tilted so that an incident light beam is reflected in a desired direction. Thus, an array of N mirrors can direct N optical input signals impinging on them to N positions in space, where output waveguides are positioned. The concept of a four-mirror switching array is shown in Figure 10.7 and photomicrograph in Figure 10.8. Clearly, this technique may be extended to construct an $N \times N$ mirror matrix, where N can be potentially 1000.

MEMS technology promises low-loss connectivity, compact design, and large interconnecting matrices. However, the precision of tilting the mirrors is very critical and as they are tilted, their orientation must always and consistently rest at exactly the correct angle; minor deviations in angle position may increase both optical

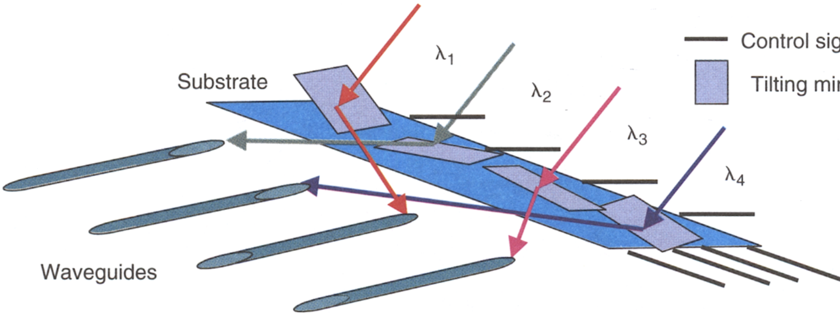

Figure 10.7 Multiple micromachined mirrors may be arranged in an N-mirror array or even in an $N \times N$ matrix configuration.

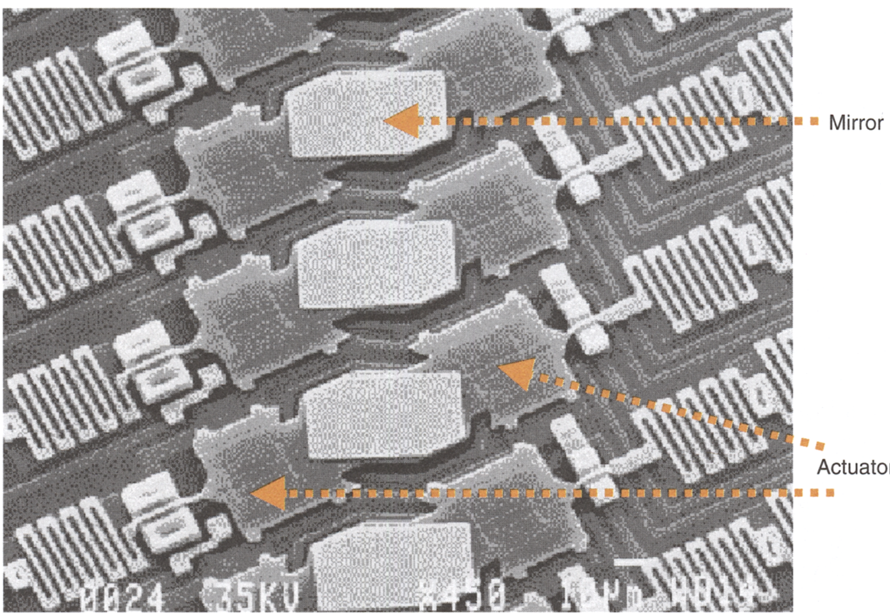

Figure 10.8 Photomicrograph of an array of micromachined mirrors (magnified 450 times). (*Copyright © 1999. LUCENT Technologies. All rights reserved. Reprinted with permission.*)

signal loss and cross-talk. Moreover, as a mirror changes position, the reflected light beam traverses the optical field of other output fibers, and thus caution should be taken to prevent the reflected beam from becoming coupled to these traversed output fibers. If coupling were to occur, it could contribute to the bit error rate of the signal at that output fiber. Current designs have demonstrated negligible coupled optical power in traversed output fibers. Figure 10.9 illustrates a conceptual application of MEMS when teamed with a grating to construct a space switch with channel drop capability (for add–drop capability see Chapter 11, exercise 7).

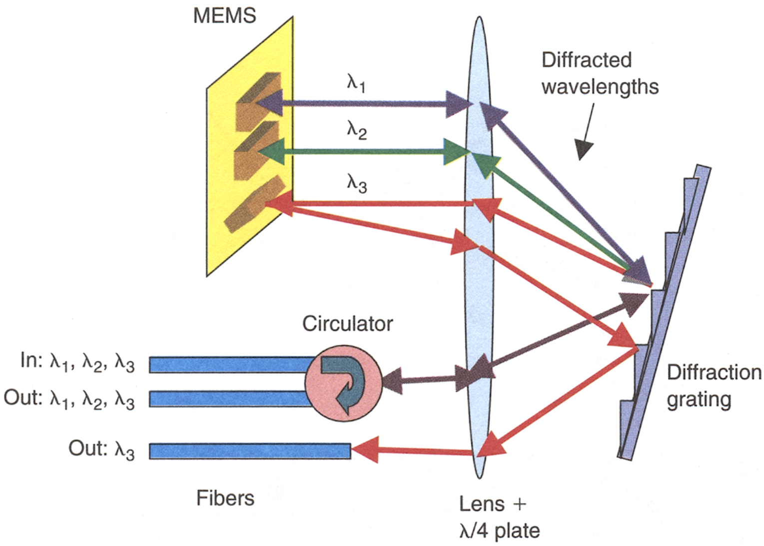

Figure 10.9 Conceptual diagram of a microelectromechanical space switch with a grating (red arrows denote the switched channel).

10.7 SWITCHING SPEEDS

Currently, the speed of optical switching devices depends on the materials used to make the switch, the principle on which the switch operates, and the design technology. Switching speeds vary from seconds to nanoseconds. Although speed is an important parameter, however, there are many more parameters that one should consider in the selection of the switch type. These include optical loss, dispersion, reliability, stability, switching/matrix size, external voltage (if any), temperature dependence, physical size, and cost.

Switching devices include

- Thermo-optic switching devices, in the order of few milliseconds (~2 ms)
- Acousto-optic switching devices, in the order of microseconds.
- Electro-optic ceramic compound switching devices, potentially in the order of microseconds

- MEM switching devices, in the order of microseconds
- SiO_2-on-Si planar devices, in the order of milliseconds or microseconds
- $LiNbO_3$ switching devices, in the order of nanoseconds
- Nonlinear electro-optic devices, based on polymers such as aminophenylene-isophorone-isoxazolone (APII), in the order of few picoseconds (still in the experimental phase)

10.8 POLYMERS

In general, polymers are not suitable materials in optical communications for the following reasons. For the majority of polymers, a strong absorption takes place in the region of 1.3–1.55 μm, that is, the usable spectral range in communications. The absorptive spectrum is due to overtones of carbon in the C—H bond. In particular, the 1.55-μm absorption is due to combination tones of the first C—H overtones and of other vibration modes.

However, the absorption peak may be shifted if H is replaced with heavier atoms such as deuterium, fluorine, or chlorine (e.g., deuterated fluoromethacrylate), which at 1.3 μm have an absorption profile close to that of a silica waveguide. Changing H to other atoms changes the refractive index to a higher or lower value.

10.9 PHOTOCHROMIC MATERIALS

Certain materials change their color reversibly when they absorb light. Such materials are known as *photochromic*. Photochromic materials either block light at a specific wavelength or transmit light at a wavelength different from the one absorbed. Thus, photochromicity may be applied in a variety of devices and applications. How fast color changes determines the type of application. Application examples are switching devices and optical memories.

Photochromicity is not a new application; it has been used for many years in color photography, but this process is not reversible; one would call this a write once read many times (WORM) application. Thus, AgCl in a gel compound has been used to absorb light; in this case Ag^+ changes to Ag^o agglomeration, which changes its color. However, the response time in this application is in the range of several minutes, which currently makes it unsuitable to communications.

EXERCISES

Consider the matrix relationship of Figure 10.1.

1. How many 1s can each row have?
2. What happens if a row has more than one 1?

3. How many 1s can each column have?
4. What happens if a column has more than one 1?
5. Under what circumstances could a row have more than one 1?

Consider the matrix relationship (ideal case) that describes a WDM Mach–Zehnder cross-connect.

6. Under what circumstances could a row have more than one 1?
7. What does it mean when a column has more than one 1?
8. From the various optical switches available, mention the fastest, one with medium speed, and a slow one.