1
Introduction to optical switches

S.J. CHUA, National University of Singapore, Singapore, and
B.J. LI, Sun Yat-Sen University, China

Abstract: A number of technologies are used for implementation of optical switches. It ranges from simple mechanical movements to deflect the light beam to using external stimuli to change the optical properties of materials. This chapter summarizes the mechanisms used for implementation of optical switches.

Key words: optical switches, thermo-optical switch, magneto-optical switch, micro-electro-mechanical (MEMS), electro-optical switch, liquid crystal optical switch.

Optical communication using semiconductor lasers as sources and optical fiber as the transmission medium is the only solution to handle the massive growth of both telecom and datacom traffic. A single strand of fiber offers a bandwidth of 25 000 GHz, and a cable containing about 1000 optical fibers can carry six billion simultaneous full-screen videophone conversations – one for every person on earth. With the introduction of new services such as high-definition television (HDTV) and grid computing, bandwidth demand is expected to rise. Grid computing provides on-demand access to both local and remote computational resources for storage and visualization and encourages the effective and productive use of expensive resources to simulate scientific, engineering and commercial applications. Three-dimensional (3D) movies, which are now introduced in cinemas, will soon see their emergence in the home entertainment arena.

To fully realize the potential bandwidth available on these optical fibers, other components of the optical network system have to be developed, ranging from detectors to multiplexers, buffers and switches to match the transmission rate and bandwidth. This book addresses the different technologies which could be applied to switching optical signals, applications of which depend on the topology of the optical network, the switching fabric and the switching speed required.

In general, a switch is concerned with the routing of message information in response to supervisory control signals. The message information could be large blocks of multiplexed traffic in the optical core network or a large number of lower bit channels to be delivered to the users in the optical access network. However, the application of an optical switch may not just be limited to the communication networks but will also be incorporated in the communication cores of a large multi-processor computer where the data rates may exceed 100 Gbit/s. With new schemes being experimented for secure communication and for computing using quantum phenomena, new architecture will be required for switches that do not interrupt the phase information of the quantum packets.

An optical switch functions by selectively switching an optical signal delivered through an optical fiber or an integrated optical circuit to another. Several methods are available and each relies on a different physical mechanism for its operation. The various physical mechanisms used are briefly summarized below, following the order of presentation in each of the chapters in this book.

1 Decrease in refractive index due to the presence of charge carriers in the semiconductor device forming the switch. By injecting charge carriers at a material interface, the refractive index at one side of the interface can be reduced, which can cause total internal reflection (TIR) to take place when a beam travels from a high to a low refractive index media at the interface. Thus, the beam is reflected rather than transmitted across the interface, enabling the beam to be switched. Changes in refractive index of one beam path relative to another cause a phase difference between the beams which can lead to constructive or destructive interference when they arrive at the outputs of the two different arms forming the beam paths. Electro-optical switches make use of this effect in an interferometric device.
2 Change in refractive index with temperature. Refractive index of materials generally decreases with increase in temperature. Thus by incorporating this property change into an interferometric device, for example, switching can be realized. This effect is made use of in thermo-optical switches.
3 Change in polarization of light as it travels through the medium interacting with the magnetic field. The rotation of the plane of polarization, known as the Faraday effect, is proportional to the intensity of the applied magnetic field in the direction of propagation of the light beam. With a polarizer at the output, the beam can be cut off when the rotation causes the plane of polarization to be perpendicular to the transmission axis of the polarizer. This effect is made use of in magneto-optical switches.
4 When a free-space beam is deflected by a micro-mirror, the deflected beam can be made incident at a number of optical fibers by precisely controlling the deflection of the micro-mirror. Such micro-mirrors can be implemented on micro-electro-mechanical (MEMS) systems often implemented by etching the silicon surface into arrays of flat beams and membranes. The movements of micro-mirrors, for example, form the basis of MEMS-based optical switches.
5 As light propagates through an optical gain medium, its wavelength, polarization, phase and amplitude can be changed and the gating function can be performed by putting an element sensitive to the property altered by the amplifier. Such elements can be a grating polarization beam splitter while a Mach–Zehnder interferometer can act upon variations in wavelength, polarization and phase. The integration of the semiconductor optical amplifier with the gating elements forms the basis of semiconductor optical amplifier (SOA) switches.
6 With optical nonlinearities such as the Kerr effect, changes in the refractive index of a material take place in response to an applied electric field. In the

case where the electric field is due to the light itself, it is known as the optical Kerr effect or AC Kerr effect. This causes a variation in index of refraction which is proportional to the local irradiance of the light. This refractive index variation is responsible for the nonlinear optical effects of self-focusing and self-phase modulation. As the beam propagates, it experiences a phase shift due to the change in refractive index that is related to the intensity of the beam itself. Thus by applying a gating element at the output of the medium, a switching action can be implemented.

7 In liquid crystals, the orientation of the rod-like molecules causes the polarization state of a linearly polarized light transmitted through the medium to vary. Thus, if the orientation of the rod-like molecules is continuously varied from the top to the bottom of a layer by 90°, through the application of a voltage across the layer, the state of the linearly polarized light transmitted through the layer will undergo a 90° rotation with respect to that at the input. With the use of a polarizer at the output, the beam is blocked if the output polarization is perpendicular to the polarizer axis, whereas it would be transmitted when the voltage is not applied. Thus, a switching function can be performed when the input signal is distributed over several outputs, for example, and with a polarizer at each end.

8 Photonic crystals are periodic optical nanostructures, typically a hexagonal patterned array of holes in an optical slab waveguide, designed to affect the motion of photons in a similar way that periodicity of a semiconductor crystal affects the motion of electrons. By appropriate choice of hole diameter and period, specific wavelengths of light cannot propagate through the guide. Thus by eliminating a row of these holes, the light can be guided through the regions where there are no holes. By changing the refractive index of the semiconductor where the light is guided, say by a control pulse, phase shift can occur. Such a phase change can be made the basis of a switching action.

9 By physically moving sideways two fibers aligned end-on using a piezoelectric element, switching action can also be performed. When they are perfectly aligned, transmission takes place and the signal can be switched between fibers.

10 Quantum confined stark effect is the change in the quantized energy in a quantum well when an electrical field is applied across the quantum well. This results in a reduction of the transition energy between the lowest quantized energy levels of the hole and electron. The optical absorption of the quantum wells is increased for a designed wavelength with the application of the external voltage. This effect is being made used of in quantum optical switches.

Each of the chapters deals with a different principle for the operation of the switch. However, they are considered in greater detail with discussions on the choice of materials, fabrication technique and treatment of the complexity of the switch design in affecting the performance and to satisfy the network topology and the switching speed. The control signal for the switches can be electrical in origin, viz. current or voltage, or it can be an external optical signal pulse which changes the physical properties and conditions of the switch material. In the all-optical network, the signal does not undergo any optical-to-electrical-to-optical (OEO) conversion in the transmission path from source to destination. In such a case, optical control can be achieved by the intensity of the signal beam in affecting the nonlinear optical properties, and this class of switches is important for implementation in an all-optical network.

For switches, several performance criteria are specified such as switching speed, insertion loss, crosstalk, on/off ratio, power consumption and reliability. Switching speed is defined as the time it takes for the connection to be made for the signal to be transferred from the input to the output ports. It is the time it takes for the output port to see the signal after the control signal has been activated. It is a function of the delay encountered within the switch and, depending on the physical mechanism employed for the switch, can vary from nanoseconds to microseconds. Insertion loss is the amount of power loss in the signal in coupling to the output port. Crosstalk is defined as the ratio of light power in the unwanted output port to the power in the desired output port. The unwanted signal that is leaked out contributes as noise on the unintended output ports. On/off ratio is the ratio of the power in the output port when the switch is on to the power when it is switched off. In the ideal case, when the switch is off, no signal should be transmitted. As many switches are operating millions of times a second in the system, their power consumption is by no means negligible. Thus, it is important to minimize the power required to perform a switching function. Finally, for the switch to be accepted, it has to be reliable and should meet the performance parameters under a wide variety of environmental conditions. Thus, while essentially any physical mechanism can be used for making a switch, it is finally the practicality and features such as physical size, cost and stringent requirements on performance that see the switch being commercially adopted.