PHOTONIC SWITCHES/GATES

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***Abstract*—Computers are getting faster and faster every year and so is the transistors count. The capabilities of digital electronic devices have excelled during the past 40 years but since 2010 the pace has slowed down because of no reduction in semiconductor gate delays and them power required to drive them. This has led to the emergence of new technology of photonic switches and gates which could reduce it further by representing 1s and 0s by bursts of light instead of electricity. Components made of optical diodes and switches offer those limiting characteristics over electronic switches.**

***Index Terms*—Optical Kerr Effect, Mach-Zehnder interferometer, Resonators, shot noise, Semiconductor Optical Amplifiers (SOP), Packet switching, Crossbar, Kerr cell, metal-oxide-semiconductors.**

I. Introduction

Switching is an elementary and essential operation in modern electronic devices and also is a basic operation in communication network and signal processing. The rapid development of high-rate data transfer fiber optics communication has created the need for high capacity repeaters and terminal systems for processing optical signals and, therefore a need for high-speed photonic switches. Various devices have been proposed to realize one or more of these functions, such as regeneration, fast switching, wavelength conversion and packet switching. The future Optical Computing would require large arrays of fast photonic gates, switches, and memory elements. But still hurdles need to be overcome before optical photonic switches could be used as a viable technology.

II. Photonic Switches

Photonic switches commonly also referred as optical switches are the components that either switch signals when they are in the optical form or they embrace the use of optoelectronic technology in the switching function. It establishes and releases connections among transmission paths in communication and signal-processing systems.

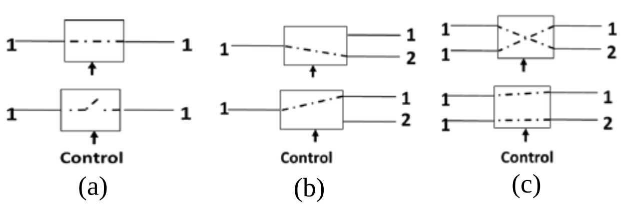

Fig. 1 (a) 1 X 1 switch. It is an on-off switch. (b) 1 x 2 switch connects line to either of two lines. (c) 2 X 2 crossbar switch connectivity

A switch is characterized by size, propagation delay time, switching time, throughput, switching energy, power dissipation, insertion loss, crosstalk and physical dimensions.

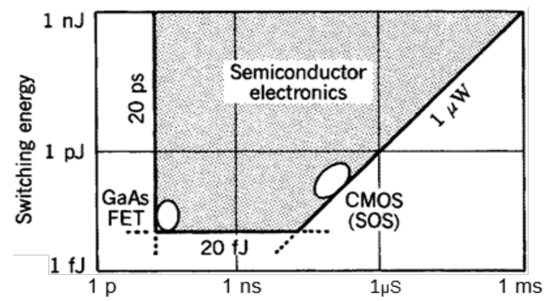

Fig. 2 Limits of switching energy, time, and power of silicon-on-sapphire (SOS) & complementary metal-oxide-semiconductor (CMOS)

Electronic switches uses either relays or semiconductor enabling logics to establish control on input and outputs. Semiconductor devices are bound by the following order of magnitudes for minimum switching time, switching energy and switching power.

Minimum switching time	= 10-20 ps
Minimum energy per operation	= 10-20 fJ
Minimum switching power	≈ 1 μW

III. Types of Photonic Switches

Switches can be configured from optical scanners and modulators. Optical modulator can be operated in on-off mode as 1x1 switch whereas scanner which deflects an optical beam in N possible directions can be used as 1xN switch. Modulation and deflection can be achieved by using different techniques which leads to different types of optical switches.

A. Opto-Mechanical Switches

It uses rotating (alternating) prisms and mirrors to deflect light beams. Piezoelectric are used for fast mechanical action and a drop of mercury moving in the capillary tube acts as a rotating mirror. The limitation and advantages are its low switching speed and low insertion & crosstalk respectively.

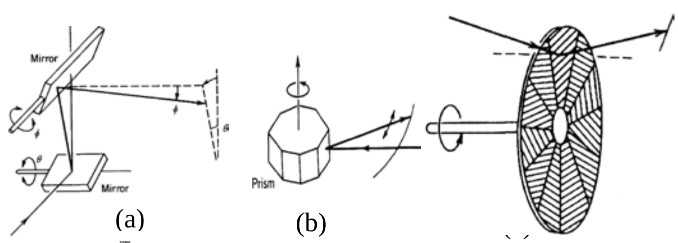

Fig. 3 Deflecting light into different directions using (a) rotating mirrors; (b) a rotating prism; (c) a rotating holographic disk

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B. Electro Optic Switches

Electro-optic materials alter their refractive indices in the presence of an electric field. This property enables their use as wave retarders and electrically controlled phase modulators which when placed between two cross polarizers serves as 1x1 on-off switch. Mach-Zehnder interferometer 1x1 switch operates at few volts with speeds that exceed 20GHz. The limitation and advantages are its low switching speed and low switching energy & power dissipation respectively. An N X N integrated-optic switch can be built by use of a combination of 2 X 2 switches.

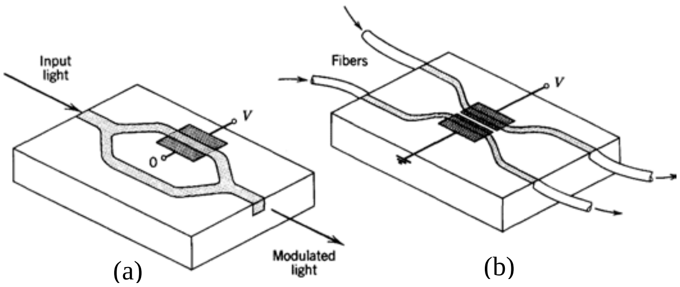


Fig. 4 (a) 1x1 switch Mach-Zehnder interferometer (b) A 2x2 switch using an integrated electro-optic directional coupler.

C. Acousto-Optic Switches

It uses Braggs Law, the property of deflection of light by sound. The power of the deflected light is controlled by the intensity of the sound and its angle of deflection by the frequency of the sound. An acoustic-optic modulator and acoustic-optic scanner acts as a 1x1 and 1xN switch respectively. N x M switch is obtained by different parts of acoustic-optic cell array sound waves of different frequencies.

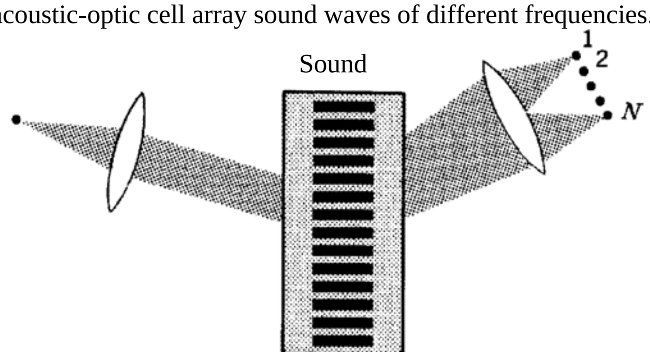


Fig. 5 Acousto-optic switch.

D. Magneto-Optic Switches

It uses Magneto-optic materials which under the influence of magnetic field alter their optical properties. A magnetic material act as polarization rotators in the present of magnetic flux density *B*, which when placed between two crossed polarizers, the optical power transmission is dependent on polarization rotation angle $\Theta = pd$. This property can be utilized for a 1x1 switch controlled by the magnetic field.

The required Magnetic field is applied by using two intersection conductors carrying electrical current. This system operates in a binary mode by switching the direction of magnetization. Arrays of magneto-optic switches can be constructed by integrating isolated 1x1 switch cells. Large arrays of magneto-optic switches of size 1024x1024 with switching speeds of 100 ns are now possible.

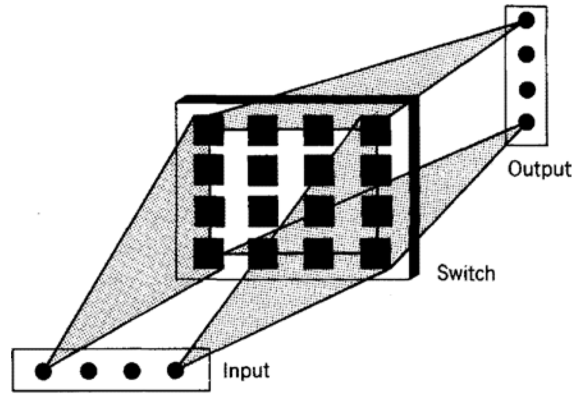


Fig. 6 4x4 magneto-optic crossbar switch. Each of the 16 elements is a 1x1 switch transmitting or blocking light depending on the applied magnetic field.

E. All-Optical Switches

In optico-optic switches light controls light with the help of a non-linear optical material. Nonlinear effects can be direct (*Kerr effect*) which occur at the molecular or atomic level when light presence alters the photon absorption rate or atomic susceptibility of the medium. The optical Kerr effect is the variation of the refractive index with applied light intensity. Indirect nonlinear optical effects involve an intermediate process in which electrical fields and charges play the role. Light creates an electric field hat modifies the optical properties of the medium. Nonlinear optical effects (direct or indirect) may be used to make all-optical switches.

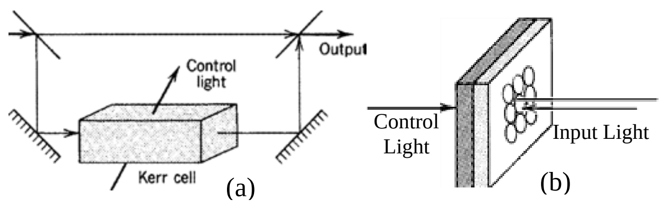


Fig. 7 (a) All-optical 1x1 switch using Mach-Zehnder interferometer exhibiting optical Kerr Effect. (b) An all-optical array of switches using an optically addressed liquid-crystal spatial light modulator.

Kerr medium optical phase modulation is converted into intensity modulation by placing the medium in one leg of an interferometer, so that as the control light is turned on and off, the transmittance of the interferometer is switched between 1 and 0. Array of switches are produced using optically-addressed liquid-crystal spatial light modulator. The control light changes the electric field applied to the liquid-crystal layer and hence alters its reflectance. Liquid crystal surface characterizes different reflectance at different places which act as independent controllers to switches.

IV. Information Switching And Switch Architecture

Information switching mechanism provides to interconnect inputs to outputs and is needed to efficiently utilize the network resources. It is required for resource sharing and has application in full mess connectivity C_2^N and switched connectivity (N/2) respectively. They are basically classified into *Circuit*, *Packet* and *Cell* switching. *Circuit switching* uses circuit setup, clearing and switches (exchanges). It leads to inefficient use of resources, is bursty in nature and has low utilization. *Packet switching* uses packetization and transfer of information (after source coding) and offers sharing. *Cell switching*, subset of packet switching has fixed packet size (e.g. ATM cells), uses virtual circuits, routing decisions (FIFO) and delivers information in order they are received. Optical switches have found their applicability in this field and have shown promising results for the future.

Other types of switching architecture includes Crossbar, Benes and Banyan. *Crossbar* switches have simple control but its complexity goes to O (n^2) where n is the number of inputs. Another drawback of it is that packet with different destination show different delay patterns through the switch. *Benes* network switch offers sequential route assignment and has O (n log n) hardware cost and O (log n) depth. Banyan/Batcher sorting network switch has self-routing capability and takes constant O (1) time to set up 2x2 switching element. However, cost O (n log n^2), and total latency O ($\log^2$ (n)) being major drawback can be improved by multiple output port scheme. Their switching configuration can be arranged at relatively low speed. The key component of the optical switches are Resonators which are especially useful in photonic logics, since they allow to build-up energy from constructive interference, thus enhancing optical nonlinear effects.

V. Advantages

Photonic switching apart from use in logical switching sense are used in wide range of implementations that are not suitable for implementing computing type logic interactions. Over log distances and at high data transfer rates, the loss in electrical lines is sufficiently large than that of photonic switches which comparatively uses a low amount of power. Reconfiguration speed of photonic switches is determined not only by the time required for switch to change its state but with also the processing time required to determine the appropriate state of the switch. A typical electronic switch uses *10-20fJ* of energy whereas a photonic switch uses $1aJ=10^{-3}jJ$ of energy with switching time a fast as 1.5ps.

VI. Applications

Photonic technology makes it possible to construct all optical network switch to avoid optical-to-electrical signal conversion for routing and this will reduce delays and losses and improve efficiency. Photonic switches and gates have applicability in areas of information technology and digital electronic devices. They can be used in reconfiguring long-lines high data rate cable works (protection and block switching), ultrahigh-speed (> 1Gbit/s) multiplexing and de-multiplexing, routing of wide-band signals in a wide-band BB, ISDN or CATV local network, building ultra-speed logic gates.

A. Routing

It implies operating time multiplexed data stream directly at extremely high data rate in real time. Presently the information transferred through the optical fiber with the speed of light must be converted at the end into the electrical signals that that are processed on conventional electrical chips. And also in some cases these signals are converted back into optical signals for retransmission, which in overall becomes an extremely slow process, allowing larger energy utilization. In optical switches the transfer.

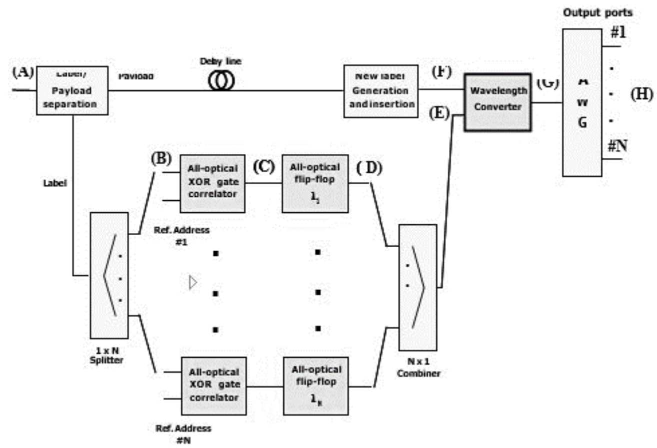


Fig. 8 All-optical packet router architecture.

B. Logical Operations

Fast photonic switches, those using electro-optic or magneto optic effects, can be used to perform logic operations and is thus included in semiconductor optical amplifiers (SOA), which are optoelectronic devices that can be used as optical switch and be integrated with discrete or integrated micro-electronic digital circuits.

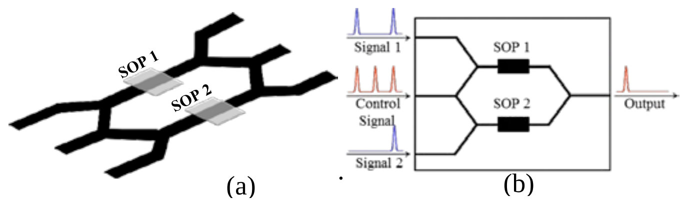


Fig. 9 (a) Mach-Zehnder Interferometer with one SOA in each arm commonly known as SOA-MZI. (b) XOR architecture based on a SOA-MZI. Two SOAs are symmetrically placed in each branch. XOR operation is achieved by XPM is the SOAs.

VII. Challenges

Photonic switches/gates will reduce power consumption is true over transmission of data over large distances and would also increase the information sharing mechanism. But over short distances the *shot noise* of an optical communication channel is larger than the thermal noise of an electrical channel which, means that more signal power/energy is required to achieve the same capacity. This limitation is prominent when the switching is performed repeatedly. Another limitation is the weakness of non-linear effects in the currently available materials, which make the switching energy larger. However light is a good for transmission since it does don't interact with itself or with the medium, leading to low attenuation, crosstalk and dispersion, these attributes becomes serious limitation when interaction us desired as in the logic gates. Researchers are constantly searching for alternatives to overcome these limitations and maximize the efficiency of the material behavior required.

VIII. On Going Researches

Optical computing is the future which uses light rather than electricity to perform calculations. Researchers and scientists believe that it could pay dividends for both conventional computers and quantum computers, largely hypothetical devices that could perform computations exponentially faster than classical computers. Here are some of recent developments in this technology across the world.

A. All-Optical Transistor

At MIT's Research Laboratory of Electronics researchers together with colleagues at Harvard University and the Vienna University of Technology have recently described an experimental realization of an optical switch which is controlled by a single photon, allowing light to govern the transmission of light. It is an optical transistor, the fundamental component of modern computing circuit. The switch consists of a pair of highly reflective mirrors. When the switch is on, an optical signal i.e. a beam of light can be passed through both mirrors and when the switch is off, only about 20 percent of the light in the signal can get through. This achievement lead us more closer to photonic/quantum gates which are sought to have promising results of high switching speed and low losses and would lead to the foundation of quantum computing.

B. Ring Resonators to Switch Light

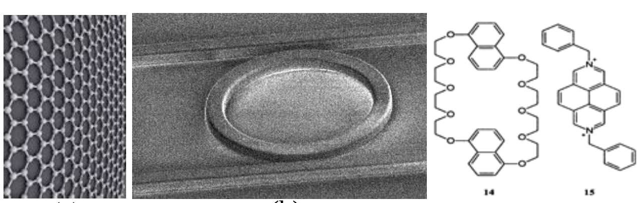
Researches at Cornell University have demonstrated a device for the first time which could allow one low-powered beam of light to switch another on or off. Such switching is supposed to be the key of future "photonic" microcircuits on silicon, in which light replaces the electrons.

C. Cadmium Sulphide nanowires to make Optical Switches

At University of Pennsylvania (Penn) researchers have an important advancement by fashioning all –optical photonic switches from Cadmium Sulphide nanowires and have combined them into logic gates, which are the fundamental component of digital electronic system and computer chips to process information. The advantage of using CaS nanowires is that they exhibit strong light-matter coupling, making them efficient in non-linear properties for manipulating light.

D. Photonic Switches made with Graphene Semiconductors

At the University of Bath and Exeter researches have created an optical switch with Graphene semiconductor, a future emerging material made of single layer of carbon which could boost internet speed by 100 times.



(a) (b) (c)

Fig. 10 (a) Graphene (b) By making a ring resonator either transparent or opaque to a particular wavelength of light, a photonic circuit can control it as a tiny photonic switch. (c) Molecular level implementation of XOR gates i by photo induced electron transfer (PET) mechanism.

IX. Conclusion

Use of optical processing in the field of high-speed and low-level functions allows routing functions to be completed comparatively less than a packet length which ensures that the switch is ready to route the next packet as soon as it arrives. This eventually leads to the reduction in the amount of complex electronics, and thus, a reduction in cost by ensuring data is routed and switched transparently in optical form, with a minimum amount of electronic processing. Therefore photonic processing provides promising solutions to avoid the limitations/drawbacks imposed by the nodes based on electronic processing. However, the photonic technology is still not enough mature enough to support all functionalities in an all-optical way.

But scientists are continuously working on finding new materials which can exhibit non-linear effects and thus can be used for the fabrication of photonic switches and their success will revolutionize the computing word and will laid the foundation for quantum computing performing large and complex calculation with reduced timing and losses and would lead to high speed data transfer.

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