OPTICAL ROUTING
IN
PACKET SWITCHED NETWORKS

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August, 2001

Optical Routing in Packet Switched Networks

By

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A Dissertation Submitted to the
Graduate School in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

Department: Electrical and Electronics Enginering
Major: Electronics and Communication

İzmir Institute of Technology
İzmir, Turkey

August, 2001

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ACKNOWLEDGEMENT

I would like to thank my supervisor Assistant Professor Salih Dinleyici for his support and guidance throughout my research.

I am also grateful to my co-supervisor Professor Acar Savacı for his encouragement. I would also like to thank Assistant Professors Sami Sözüer, Mustafa Altınkaya and Şevket Gümüştekin for serving on my thesis committee. Their advice and comments are greatly appreciated.

I would like to thank my colleagues for supplying me various documents and my wife Berna, being always by my side.

Finally, I would like to dedicate this thesis to the memory of my father to whom I learnt patience.

ABSTRACT

Ever-increasing demand for high capacities brought by Internet usage forces designing faster transport networks for carrying information packets. In the last ten years much attention has been focused on transporting packets directly over the optical transport networks. Researches in this area range from simple electronic and optical switching/routing methods to hybrid and more complicated all-optical packet switching systems. However, major bottleneck in all these methods is designing fast, reliable and inexpensive optical routing/switching devices.

In this thesis, a method for optical routing using fiber Bragg gratings is proposed. In this method, electronic interface is used only for routing information (routing table) update cycle while packet header extraction and switching is done in optical domain. Routing is performed optically by controlling the refractive index change in fiber gratings. Four bits of header (label) information is used for routing packets to three different output routes. The network is simulated and its performance is evaluated by special software of Virtual Photonics.

ÖZ

İnternet kullanımının getirdiği yüksek kapasite için sürekli artan istek, bilgi paketlerini taşıyan daha hızlı iletim ağları tasarlamayı zorlamaktadır. Son on yılda bu konudaki çalışmaların çoğu, paketleri doğrudan optik iletim ağları üzerinden iletmeye odaklanmıştır. Bu alandaki araştırmalar basit elektronik ve optik anahtarlama/ yönlendirme metotlarından, melez ve daha karmaşık tüm-optik paket anahtarlama sistemlerine kadar uzanmaktadır. Ancak bütün bu modellerin en önemli darboğazı hızlı, güvenilir ve pahalı olmayan optik yönlendirme/anahtarlama aygıtları tasarlamaktır.

Bu tezde, fiber Bragg ızgaralar kullanan optik yönlendirme metodu önerilmiştir. Bu metotta, paket başlık çıkarımı ve anahtarlama optik ortamda gerçekleşirken elektronik arabirim sadece yönlendirme bilgisi (yönlendirme tablosu) güncelleme evresi süresince kullanıldı. Yönlendirme, fiber ızgaralardaki kırınım indeksi değişimini kontrol ederek, optik olarak gerçekleştirildi. Dört bitlik başlık (etiket) bilgisi, paketleri üç farklı çıkış yönüne yönlendirmek için kullanıldı. Ağ, Virtual Photonics'in özel bir yazılımı ile simule edildi ve performansı değerlendirildi.

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CHAPTER 1

INTRODUCTION

The growth of Internet is increasing the range of future services demanding more network capacity and higher data rates. Network and system concepts are evolving accordingly using fiber-optics as the base environment.

Fibers are first used to connect electronic nodes by optical links where light inside the fiber carries the information. However, because of the lack of electronics in using the high (virtually unlimited) transmission bandwidth offered by fiber, optoelectronic or photonic elements are needed. Advances in semiconductor devices are based on this requirement and soon, the bottleneck of electronics, switching, is turned into optical.

On the other hand, Internet Protocol (IP) became popular with the Internet and its applications, and the packet switching systems for Internet are progressed with the introduction of Asynchronous Transfer Mode (ATM). By the interaction with optics, packet switching is evolved to optical where optical switches route data packets. At this time, a milestone for optical technology, Wavelength Division Multiplexing (WDM), is found where multiple wavelengths are used to carry data in a single fiber. Optical networks and IP soon converged, thus transmission and switching for routing IP packets are realized optically.

Today, optical transmission and switching of data is achieved but to accomplish faster transmission, processing has to be in optical domain too. Recent study is continuing to reach the all-optical aim, eliminating optic/electronic conversion and vice versa. In this thesis, processing and routing packets based on the information embedded in their headers is studied using fiber Bragg gratings. For establishing a base for this study, optical techniques in lightwave communications is given in Chapter 2. A brief review for Internet and networking takes place in Chapter 3. Optical packet switching is a commonly used technique and it is investigated with the summary of header recognition and contention resolution concepts in Chapter 4. The projects announcing various kinds of switching models are named here as well. Finally, the proposed routing model using fiber Bragg gratings is described in Chapter 5. Routing is performed depending on the refractive index change in fibers. Then, the operability of router is simulated by the Virtual Photonic's Photonic Transmission Design Suite (PTDS) with four bits of header information and the results are given accordingly.

CHAPTER 2

OPTICAL TECHNIQUES IN LIGHTWAVE COMMUNICATIONS

2.1 Introduction

Optical techniques are evolving in lightwave communications where optical waves are used as the carrier. Thus, on the optical channel that is mostly fiber, signal transmitting and receiving have to be designed optically or more strictly photonically to meet the needs of lightwave communications.

Photonics deals with photons. This results with the "speed of light" which brings high speed in processing, communication, computing and switching. Photons are uncharged and do not interfere with one another as electrons do. Therefore photonic processing is insensitive to electromagnetic interference and naturally shows massive parallelism with easy and full interconnection capability (with no soldering) in three-dimension (3D). Optical components are small and lightweight, have low power consumption and high reliability with simplified operation and management. They also have low-loss transmission, fast switching and high bandwidth capacity which present and near-future technology requirements demand.

Beginning with the fabrication of fibers, invention of laser and advances in semiconductor optical devices, new researches for new optical materials, components, devices, architectures, algorithms and systems have begun. First result was the interaction between electronics and optics technologies named as optoelectronics. But the components of this hybrid system are limited by the speed of its electronic part. So the current demands lead from "almost-optical" to "all-optical", where all the processing, computing, communication, networking, etc. is done mostly or only optically.

Naturally optical elements are used to achieve "all-optical" base and they split according to their usage. In this chapter, some of the photonic techniques and components used in lightwave communication will be introduced.

2.2 Photonic Elements and Techniques

There are many photonic elements and techniques used in various types of lightwave technology. It is almost impossible to classify these according to their technologies being involved. This is partly because of the difficulty in separating the technologies and partly because the elements and techniques are used in more than one technology.

In this section, some of the important elements and techniques will be reminded with the guidance of their technological aspects.

2.2.1 Basic Elements

For optics we need light and its sources. There are two major sources used in optical systems: Light Emitting Diodes (LEDs) and LASERs (acronym for Light Amplification by Stimulated Emission of Radiation). They both provide monochromatic but less and more spatially coherent light, respectively. LEDs have wide spectral width (30-60 nm) and relatively large angular spread with low power (~100 μW). LASERs have sharper spectral linewidth (2-4 nm) which allows operation at high speeds and they are capable of emitting high power (~100 mW). Both are sometimes called transmitters and have various types depending on the structure of semiconductor.

Mirrors, prisms and beam splitters are the classical optical elements used frequently in optical processing. Mirrors and prisms are used to change the direction of beams of light while beam splitters are used to split a beam of light into two or to join beams into one. Lenses are the well-known elements that are used in three main ways: to collimate, to image and to perform Fourier-transform [1]. Microoptics or small-size integrated optic technology is also used for constructing miniature elements compatible with the small size of the optical beams transmitted by fibers.

Optical amplification is done through stimulated emission, the same mechanism used by lasers. The elements used for amplifying are essentially semiconductors and fibers. Thus, semiconductor lasers use semiconductors as the gain medium, whereas fiber lasers typically use Erbium-doped fiber as the gain medium. Raman, Brillouin, Fabry-Parot amplifiers and Praseodymium-Doped Fiber Amplifiers (PDFAs) are examples of such amplifiers just to name a few. But the best known examples are

Erbium-Doped Fiber Amplifiers (EDFAs) and Semiconductor Optical Amplifiers (SOAs) [2,3].

In the receiver side of a lightwave communication channel, semiconductor detectors are used especially in optical receivers where the optical signal is converted into electrical form and the data transmitted through the optical communication system is recovered. Photodetectors are the main elements for detecting light intensity which avalanche photodiodes, p-i-n photodiodes, photoconductors and photomultipliers are the examples of those. Materials for photodetectors are generally based on Ge (1,88 μm) and Si (1,15 μm) while compounds like AlAs (0,57 μm), GaAs (0,87 μm), GaP (0,55 μm) and InP (0,92 μm) are also formed and used [4].

Logical elements are also used in optical for computing applications where they are mostly named as logic gates. They are based on nonlinear effects where one beam of light effects another. AND, OR, NOT, XOR gates can be implemented by optical nonlinear devices with threshold-like characteristics in the form of optical bistable devices such as Fabry-Perot resonators [1]. Integration of interconnections and logic at the gate level permits parallelism at the lowest and most efficient level, therefore it is going to be used in the proposed system given in Chapter 5.

2.2.2 Gratings

A grating is a periodic modification of an optical medium and its optical properties, such as (mostly) refractive index. When a beam of light is directed upon a grating, interference patterns occur due to constructive or destructive addition of harmonics and a diffraction pattern is created.

Gratings have been widely used in optics to separate light into its constituent wavelengths. This is "wavelength multiplexing" but there are other benefits such as filtering, switching and add/drop functions. These benefits arise in different grating technologies and the gratings took different names according to their technologies. But the basic depends on Bragg's law.

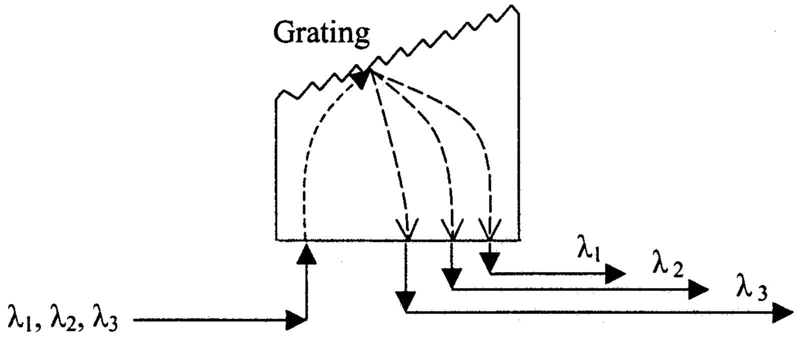


Figure 2.1 Wavelength multiplexing using graded-index (GRIN) rod

Bragg gratings: In general any periodic perturbation in the propagating medium serves as a Bragg grating. Acoustooptic devices are quite common example of such a grating which will be mentioned later in acoustooptic SLMs. Principle of operation depends on this periodic perturbation which is usually refractive index of the medium. This is formulated as:

$$\lambda_B = 2n_{eff}\Lambda \tag{2.1}$$

where n_{eff} is the effective refractive index of the medium and Λ is the period of the grating. λ_B is called the Bragg wavelength, which is the wavelength of the light in the medium where the maximum reflectance occurs at Bragg angle.

There are many applications of Bragg grating. They can be used in wavelength stabilization, dispersion compensation and as a filter (fixed or tunable) for wavelength based applications. [2,3,5]

Fiber gratings: Gratings are written in fibers by using the photosensitivity of certain types of optical fibers. They are classified as either short-period or long-period gratings based on the period of the grating. If the grating period is around the wavelength (typically 0,5 μm), grating is referred to a short-period grating, which is also called Fiber Bragg Grating (FBG). On the other hand grating periods that are much higher than the wavelength refer to a long-period grating. Their main advantages are low loss (0,1 dB), ease of coupling (with other fibers), polarization insensitivity and simple packaging [3,5].

Waveguide gratings: Waveguide gratings are found their best use in switching, multiplexing and routing by the leading and most popular technology Arrayed

Waveguide Grating (AWG). An AWG is a device consisting of two multiport couplers interconnected by an array of waveguides (Figure 2.2). It is a generalization of the Mach-Zehnder interferometer where several copies of the same signal, but shifted in phase by different amounts, are added together. Therefore, AWG devices are referred as PHASed-ARray gratings (PHASARS). They also sometimes named as Waveguide Grating Routers (WGR) because of their routing capability [2,3,6].

Various kinds of AWG multiplexers, including silica-based, have been fabricated. They support different number of channels with different spacing ranging from 15 nm in 8-channel to 0,2 nm (25 GHz) in 256-channel AWG [5].

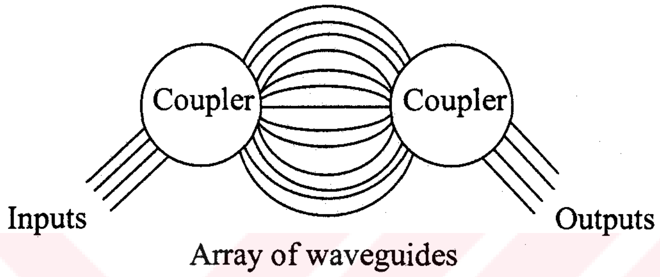


Figure 2.2 An arrayed waveguide grating (AWG)

2.2.3 Couplers, Switches, Multiplexers

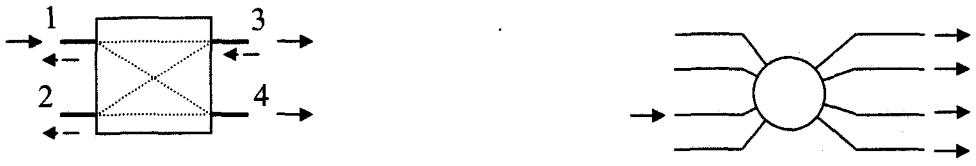
In a lightwave communication system there are number of components which help to direct the light beams to their appropriate destinations. Couplers, switches and multiplexers/demultiplexers are the main elements, which will be presented in this section.

2.2.3.1 Couplers

In the optical domain couplers are simply used to split or combine light beams. Various types of couplers exist and used for guiding light. Examples of them such as two fibers twisted and fused, T-couplers, directional couplers or star couplers are shown in Figure 2.3. Integrated optic devices or micro-optics technology equipment are also manufactured.

(a) Fused fiber coupler

(b) T coupler



(c) Directional coupler

(d) Star coupler

Figure 2.3 Examples of couplers

In the T-coupler, a signal at input 1 reaches both output points 2 and 3; a signal at either point 2 or 3 reaches point 1. In the four-port directional coupler, a signal at any of the input points 1 or 2 reaches both output points 3 and 4; and a signal coming from any of the inputs 3 or 4 in the opposite direction reaches both points 1 and 2.

However, star coupler is mostly used to combine the optical signal entering from their input ports and divide it equally among their output ports. So it acts as a key component in many architecture as in broadcast-and-select networks and gives its name to these networks as optical star networks.

In the optical star networks, Wavelength Division Multiplexing (WDM) is used and the star topology is preferred to route each wavelength. This is done in two ways so there are two types of star couplers used in optical star networks: transmissive and reflective.

A transmissive star coupler is named as a *transmissive* $n \times n$ *star coupler* or shortly $n \times n$ *star* because it divides the power entering any of its n input ports equally among its n output ports. A reflective star coupler is named a *reflective n-star coupler* when power entering any of the n ports is divided equally and reflected back out of all ports.

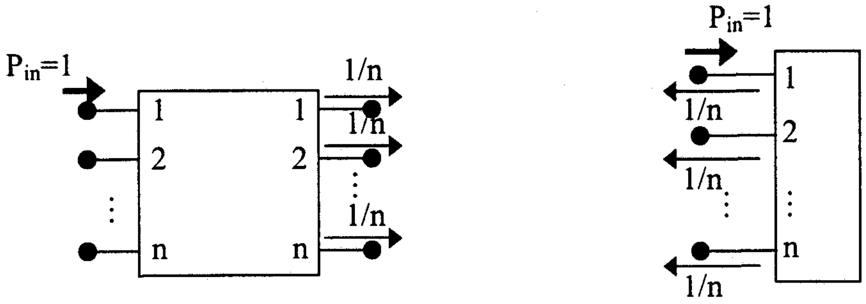
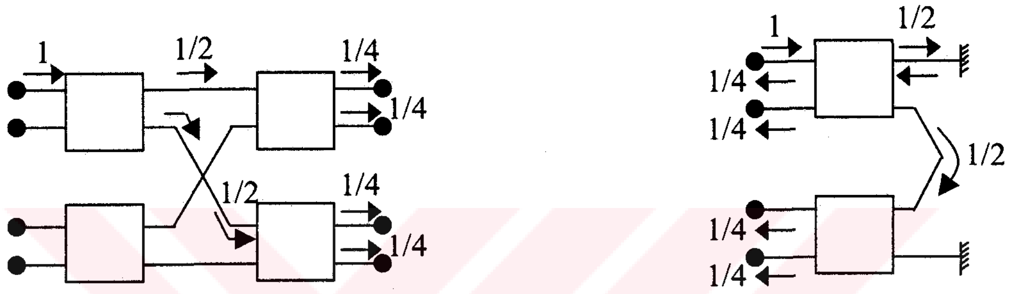


Figure 2.4 Transmissive and reflective star couplers

The simplest form of the $n \times n$ star is the 2×2 star and it can be used as a main element to construct larger $n \times n$ or *n-stars* [7].



(a) Four 2×2 stars

(b) Reflective 4-star

Figure 2.5 Examples of larger stars

These larger stars can also distributed in clusters thus achieving a geographically distributed network and saving in the number of fibers required for building any distributed network [8].

2.2.3.2 Switches

A switch can be abstracted as a device that takes a set of N signal inputs and is able to reproduce them in any permuted order at the output. It is characterized by different parameters such as size, switching time and energy, crosstalk, power dissipation and loss. But in terms of switching function, switches are divided into two types: blocking and nonblocking. A switch is said to be nonblocking if it is capable of realizing every interconnection pattern between the inputs and the outputs. If not, the switch is named as blocking. Nonblocking switches are also divided into two groups. A wide-sense nonblocking switch can connect any unused input to any unused output without rerouting any existing connection. But a strict-sense (or strictly) nonblocking switch can connect regardless of the connection rule and algorithm. Also there is a broader class of nonblocking switches called rearrangeably nonblocking switches where rerouting of connections could be done.

The basic switch architecture is the $N \times N$ crossbar switch. It is also called as a space switch because it separates the signals in space [9,10].

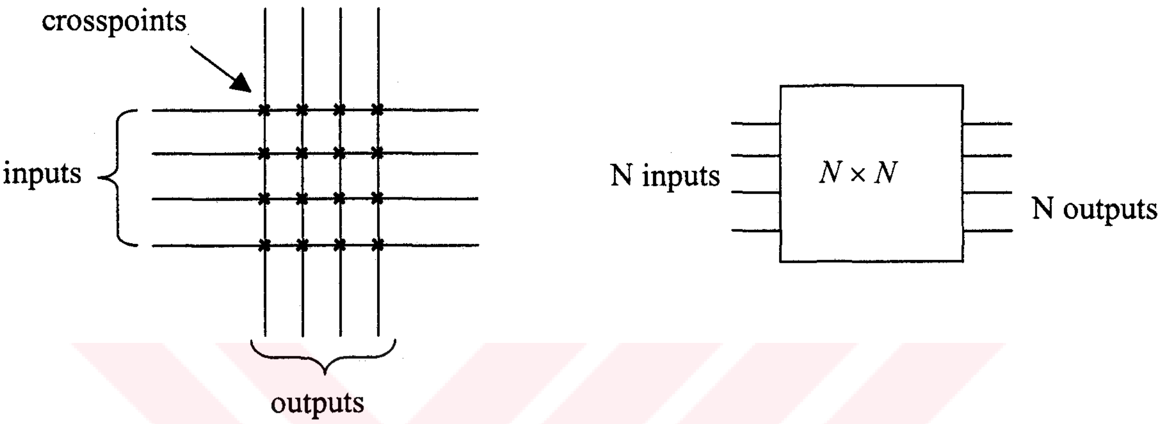
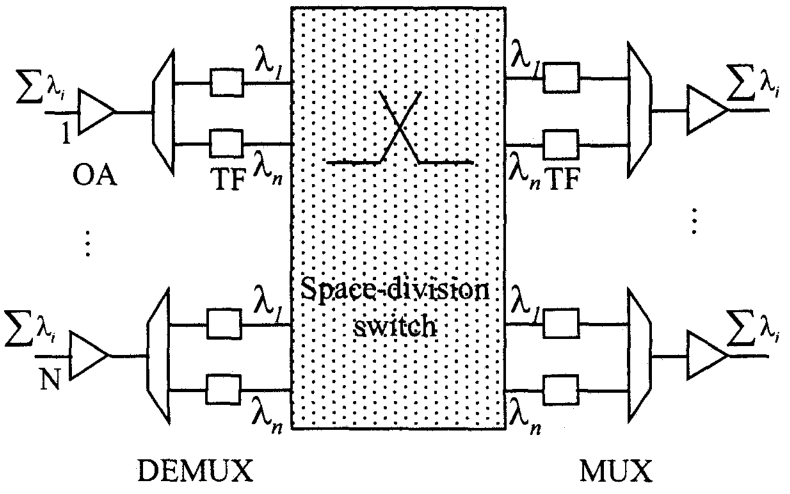


Figure 2.6 $N \times N$ Crossbar switch concept

The crosspoint count of a switch is often used as a measure of its complexity. Therefore it is desirable to reduce the number of crosspoints (N^2 *for* $N \times N$). This is usually done by building larger switches from stages of smaller crossbar switches. Architectures also vary according to configurations done by the 2×2 switches, such as Beneš, Spanke, Slepian or Clos but mostly crossbar [3,11].

Optical switching can be done by the use of one of these architectures but notice that the technology also differs. Optical modulators can be used in different type of technologies and switches are called optomechanical, electrooptic, acoustooptic, magnetooptic, thermooptic or all-optical switches [4].

There is also an important switching architecture used in WDM systems. This switch is known as Optical Cross Connect (OXC) and sometimes called as frequency or wavelength-selective switch. It is composed of multiplexers, demultiplexers and space switch as shown in Figure 2.7 [9]. Each of the N input carries n WDM channels. After demultiplexing, the nN channels are switched through a $nN \times nN$ space-division switch. Switch permutes all the channels and then they are multiplexed into N output.



OA=Optical Amplifier, TF= Tunable Filter

Figure 2.7 Architecture of an optical cross connect

2.2.3.3 Multiplexers/Demultiplexers

Multiplexing is the transmission and demultiplexing is the retrieval of more than one signal through the same communication link. Time Division Multiplexing (TDM), Frequency Division Multiplexing (FDM) are the known examples of multiplexing. On the other hand, a new one depending on wavelength, WDM is becoming popular as a rising technology and it will be mentioned in the next section.

Multiplexers and demultiplexers in WDM systems are basically optical filters. These filters are based on selective absorption, transmission and reflection of wavelengths.

The most important application of these optical filters is adding/dropping wavelength and this kind of multiplexer is known as Optical Add/Drop Multiplexer (OADM). Basically an OADM extracts the signal on a specified wavelength channel and transmits a new signal on the same wavelength channel. An OADM could drop and add one fixed wavelength channel. Alternatively, switch elements could be incorporated into the OADM so that it can be dynamically configured to drop and add the selected wavelength channels as shown in Figure 2.8.

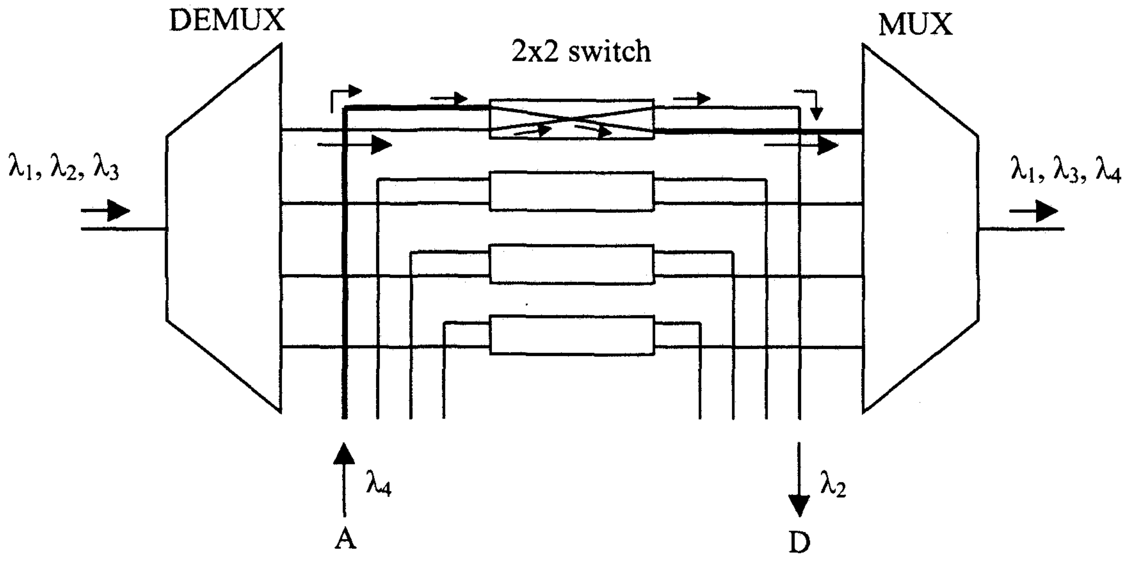


Figure 2.8 Optical add/drop multiplexer

2.2.4 Wavelength Division Multiplexing

The developments of the fiber optic system initiated wide-ranging research for optical communication systems. The researchers made innovations in the lasers and in the optoelectronic components as mentioned before. But the increasing demand for bandwidth implies that the capacity of transmission must be increased. And there are two fundamental way of increasing the capacity: Time Division Multiplexing (TDM) and Frequency Division Multiplexing (FDM). In the optical domain both are used with optical, means as optical TDM or OTDM and optical FDM or OFDM. But there is also another type of multiplexing in lightwave communications depending on the color (wavelength) of the carrier but different in detection (direct/heterodyne) and separation (optically before/electronically after photodetection) [12], that is, Wavelength Division Multiplexing (WDM) where wavelengths or colors are the carrier frequencies.

OTDM provides a way to increase the bit rates on each channel. It has the potential of increasing the bit rate for a single optical carrier up to Tbps ranges. Complementary, WDM provides a multiple channel increase by different wavelengths. Therefore, what combination of OTDM and WDM to use in systems is an open-ended question but the major technology seems to be WDM because of the potential offered to optical networks.

With the introduction of WDM, all-optical structures are based on wavelength dimension. Optical components such as multiplexers/demultiplexers, OADMs, OXCs, star couplers as well as switches and routers are designed based on WDM technology. And they are named with wavelength as wavelength switches, wavelength routers, wavelength add/drop multiplexers (WADMs), wavelength cross connects (WXCs). Also the network consisting of these elements took the name WDM network.

WDM network architectures can be classified into two categories: broadcast-and-select and wavelength routing [3].

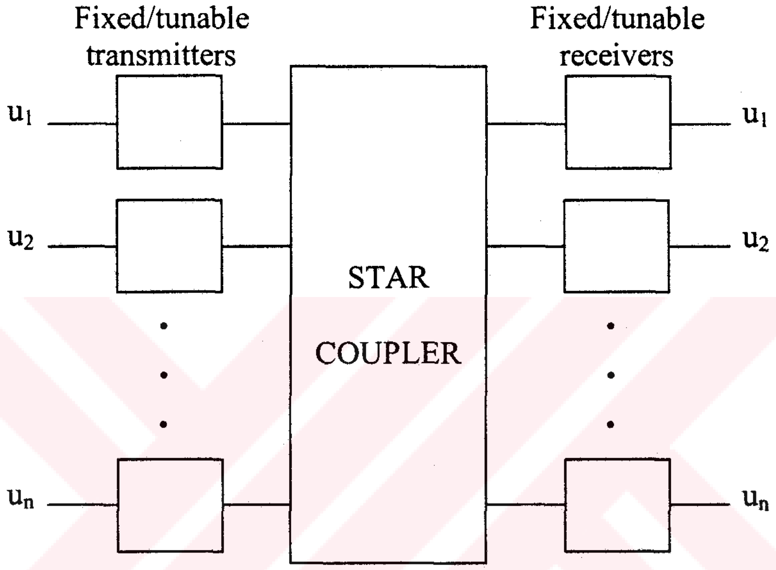


Figure 2.9 Broadcast-and-select network

The broadcast-and-select form of network works by assigning a single optical frequency (wavelength) to the transmit side of each port in the network, combining the signals at the center of the network in an optical star coupler, and delivering a fraction of power from each signal to the receive sides of all ports.

By means of a suitable Media Access Control (MAC) protocol, when one node wants to talk to another, the tunable receivers tune for interchange. The entire inner structure consisting of fiber strands and star coupler is completely passive, unpowered and therefore extremely reliable and easy to manage. But the number of nodes in these networks is limited because the wavelengths cannot be reused and the transmitted power split among all the receivers in the network.

Therefore, wavelength routing architecture seems to be more practical but also sophisticated solution for the WDM network architecture that provides significant advantages by switching and routing optical signals based on their wavelengths. In this architecture the nodes are capable of routing different wavelengths. WXCs, WADMs are the elements of this network and the overall system is named as a Wavelength Router (WR) or Wavelength Routing Switch (WRS) [13].

Wavelength routing networks can be classified either static or reconfigurable depending the elements they contain. If a network does not have any switches or dynamic wavelength converters (described below) it is a static network, otherwise it is called reconfigurable or dynamic because of the capability of the network to change routes at nodes [14].

A wavelength converter is an optical device that converts data from one incoming wavelength to another outgoing wavelength. Without wavelength conversion an incoming signal can be optically switched to any output port but only on one wavelength. With wavelength conversion this signal could be optically switched to any output port on any wavelength. Therefore different physical links can be established where bit rates, protocols become insensitive, thus transparency is provided.

Figure 2.10 shows different types of wavelength conversion. If each wavelength is converted only to itself, then there is no conversion. If each input wavelength is converted to exactly one wavelength, fixed conversion is done. But if each input wavelength can be converted to a specific set of wavelengths, at least one less from all, conversion is named as limited while full conversion implies all possible connections are established.

(a) No conversion

(b) Fixed conversion

(c) Limited conversion

(d) Full conversion

Figure 2.10 Wavelength conversion types

There are three fundamental mechanisms for wavelength conversion:

1. Optoelectronic: Conversion is done by converting each individual wavelength to electronic signals and then retransmitting by lasers at the appropriate wavelengths. This is the least expensive approach but optical-electronic conversion destroys protocol transparency.
2. Optical gating: Conversion is based on intensity modulation. Two types of modulation is used: Cross Gain Modulation (CGM) and Cross Phase Modulation (CPM). Both use nonlinear effects in Semiconductor Optical Amplifiers (SOAs). The transparency is limited to only intensity modulated signals.
3. Wave mixing: Occurs in either passive waveguides or SOAs. Examples such as three-wave and four-wave mixing arise from nonlinear optical response, that is, the phase relationship between the interacting signals. The advantage is that it offers full transparency because the effect does not depend on the modulation format and the bit rate [3].

All these mechanisms with the different types of converters seem to be in the majority of the future WDM networks. With the extensive use of WDM, advances have come rapidly. WDM classifications such as Wideband WDM, Narrowband WDM, Dense WDM (DWDM) and Ultra-Dense WDM (UDWDM) have allowed the carrying capacity of optical fiber to increase rapidly. Initially WDM allowed the number of wavelengths carried on a single fiber to 8. With DWDM this has risen up to 100. 1022 channel system operating with 9,5 GHz. channel spacing is the example of UDWDM. The literature often uses the term DWDM, but this term does not denote precise number of wavelength channels. Channel spacing is an important figure in classification and International Telecommunication Union (ITU) specified these channel spacings selected from a grid of frequencies referenced to 193,100 THz. (1552,524 nm). According to ITU-T Recommendation G.692, spacing is 100 GHz. (0,8 nm). Alternative suggestions include 50 GHz. (0,4 nm) and 200 GHz. (1,6 nm) where the rapid growth in this technology and the advances in all-optical networks will open new windows for future [15,16,17].

2.2.5 Spatial Light Modulators

A Spatial Light Modulator (SLM) is as device that can spatially modify or amplify some of the optical characteristics (phase, amplitude, intensity, and polarization) with the ability of storing patterns [18]. They can be classified basically in two: electrically addressed and optically addressed SLMs. However they are mostly named with the underlying technique and numerous implementations of SLMs have been proposed and implemented over the years. In this section some of them are going to be reminded [1,4,6,19,20,21].

Photographic film: It is the oldest SLM, although it is primarily considered a recording medium. A known example is the movie. The illuminating light is modulated by the movie films and thus images are formed on the screen.

Photodichroic SLMs: They are similar to photographic film. They change color when illuminated with a certain wavelength. This kind of effect is used in the sunglasses that became darker when there is intense illumination.

Deformable SLMs: These SLMs are the examples of electrically addressed SLMs and their shape is changed by some devices and techniques. One of them is the photoplastic device where the deformation of the plastic is done with an electric field, modulated by a beam of light. Another type is the micromechanical SLM. This is an array of miniature leaves etched with integrated circuit technology. Light incident on the array will be reflected at different angles from different leaves. A similar concept is used in the deformable mirror SLMs or Deformable Mirror Devices (DMDs). Note that these technologies are used for switching such as in MicroElectroMechanical Systems (MEMS) which will be mentioned later in this thesis.

Magnetooptic SLMs: They are two dimensional electrically addressed SLMs comprised of a matrix of elements (magnetooptic matrix) based on a magnetooptic effect known as the Faraday effect. They have a storage capability but are limited by addressing speed and wiring complexity.

Electrooptic crystal SLMs: These are two dimensional optically addressed SLMs that are based on electrooptic effect in which the crystals change their index of refraction when an electric field is applied to them. This effect is known as the Pockel's effect and these SLMs are mostly known as Pockel SLMs or Pockel's Readout Optical Modulators (PROMs). They are fabricated from various electrooptic crystals but mostly $Bi_{12}SiO_{20}$

(bismuth silicon oxide, BSO for short) as shown in Figure 2.11. PROMs can be used for incoherent-to-coherent conversion, amplitude and phase modulation, and optical parallel logic operation.

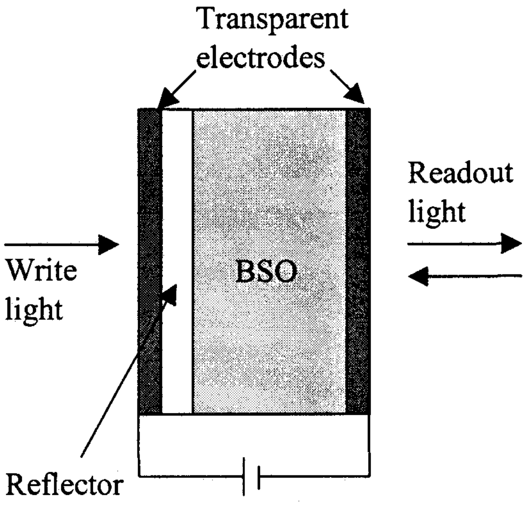


Figure 2.11 PROM

Liquid crystal SLMs: Best known and most familiar type of optically addressed SLM is liquid crystal SLM or usually called Liquid Crystal Light Valve (LCLV).

The LCLV is a hybrid device. Its structure is mainly a thin layer of nematic liquid crystal followed by a dielectric mirror, a light blocking layer and a photoconductor, all sandwiched between two transparent conductors as shown in Figure 2.12.

When an electric field is applied to the crystal, molecules reorientate along the direction of the field, thus changing the refractive index of the medium. When there is no light, most of the voltage drops on the photoconductive layer, while liquid crystal layer is affected less. When illuminated with a writing beam, the voltage across the photoconductor is reduced and the voltage applied to the liquid crystal is increased. Hence, the orientation of the molecules changes, the readout beam is effected.

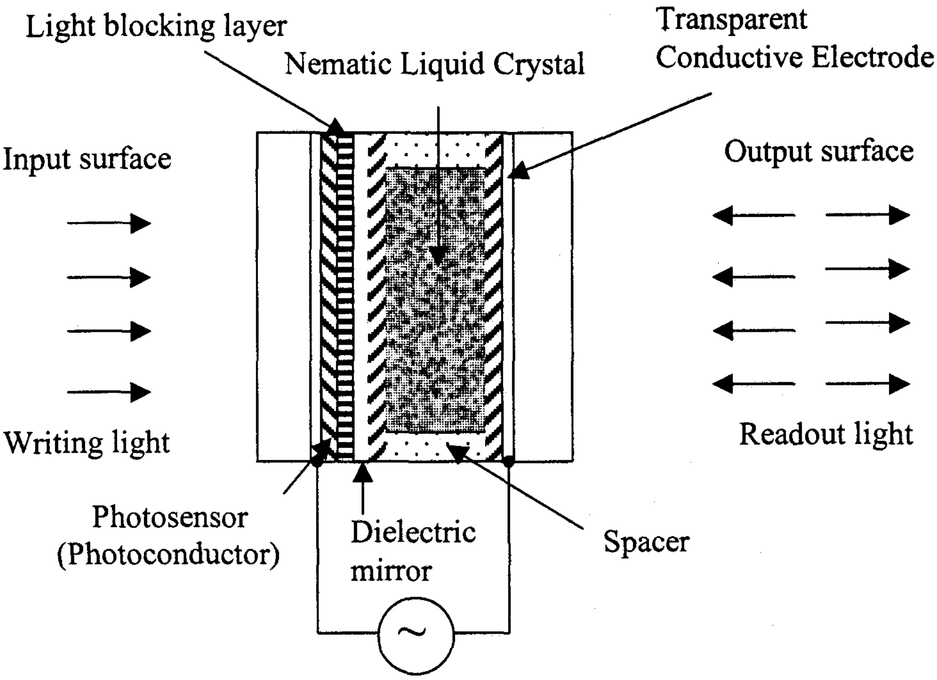


Figure 2.12 Side view of a LCLV

The dielectric mirror plays an important role by providing optical isolation between the input incoherent light and the coherent readout beam thus LCLV is used in incoherent-to-coherent conversion applications as well as switching, wavelength converting, optical neural networks, holography and optical computing.

Electron-trapping and photorefractive materials: They can emit different output photons that correlate spatially in intensity with input photons. Photons are absorbed, free charge carriers are generated by excitation from impurity energy levels (write) to an energy band and the conductivity of the material is increased. Some of the electrons tunneled and remain trapped at a level until stimulated by infrared light (read) so that these materials can also be used to store optical information.

An example of electron trapping material is SrS doped with Eu and Sm as given in the Figure 2.13 while $LiNbO_3$ (lithium niobate) is the mostly used example for photorefractive materials as well as BSO and $Bi_{12}GeO_{20}$ (BGO) [18].

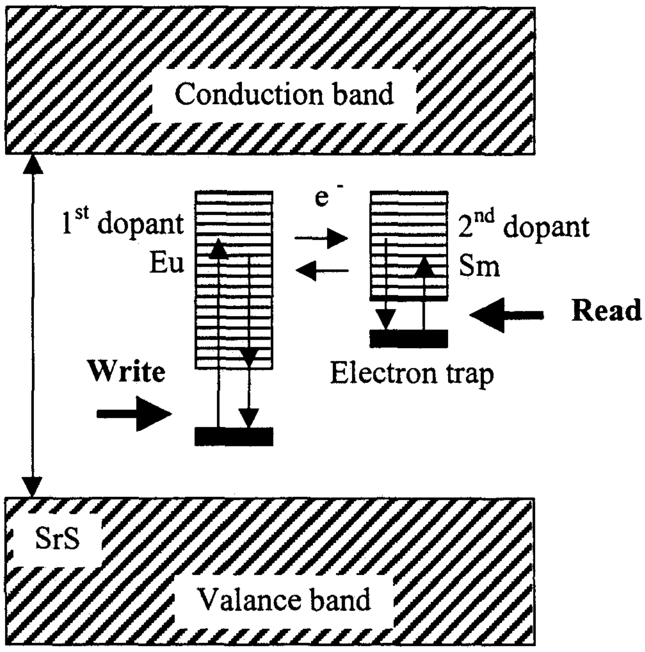


Figure 2.13 Band-gap structure of an electron trapping material

Acoustooptic SLMs: They use the interaction of light waves with acoustic (sound) waves, which produces a Bragg diffraction effect. The underlying mechanism is simply the change induced in the refractive index of an optical medium by the presence of an acoustic wave. This acoustic wave is emitted by a transducer as shown in Figure 2.14 [18].

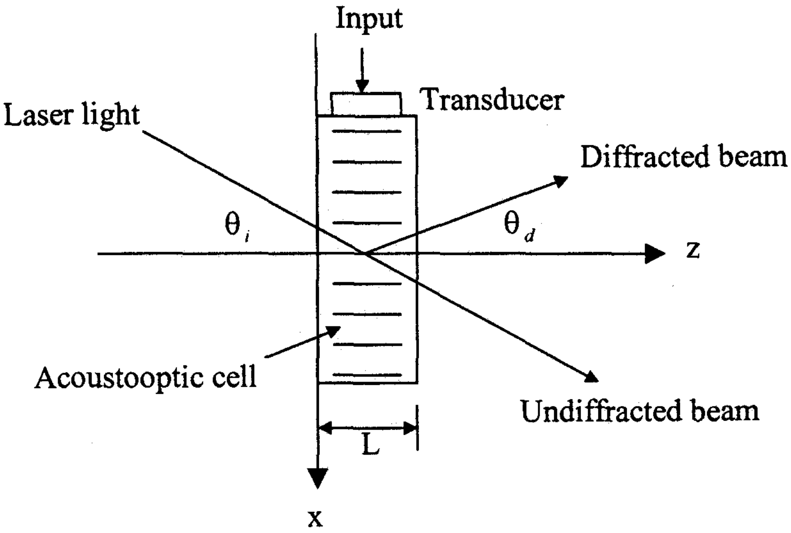


Figure 2.14 Operation of an acoustooptic cell

At a certain angle θ_i, a coherent diffraction occurs at an angle θ_d. This angle is known as the Bragg angle and it is given by:

$$\theta_d = arcsin\frac{\lambda}{2\Lambda} \qquad (2.2)$$

where λ and Λ are the light and the acoustic wavelengths, respectively. And this principle is named as Bragg diffraction or Bragg grating. Depending on this principle, AcoustoOptic Tunable Filters (AOTFs) are designed. AOTFs are capable of selecting several wavelengths simultaneously and also used to construct a (multi)wavelength router [3].

- Quantum Well SLMs: They are based on quantum phenomena and depend on the potential barrier generated at the interface of different semiconductor layers. An example of quantum well SLMs is the Self-Electrooptic Effect Device (SEED). The SEED consists of a resistor connected in series with a p-i-n diode detector with intrinsic region is made of Multiple Quantum Well (MQW) layers (Figure 2.15). SEEDs can be fabricated in arrays and they operate at high speed (switching response time of 30 ns) with low energies. They exhibit optical bistability and classified as a hybrid bistable optical device.

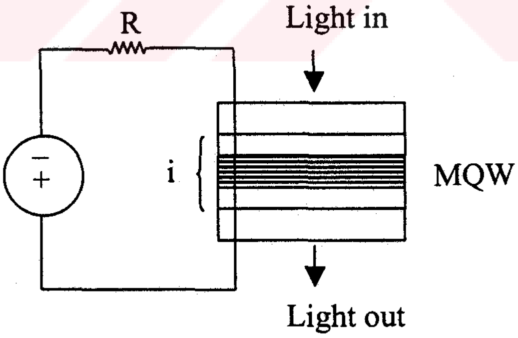


Figure 2.15 Schematic diagram of SEED

Optical bistability is a nonlinear phenomenon of optical hysteresis where the output depends upon whether the present input level was achieved by lowering from a higher level or raising from a lower level as given in Figure 2.16. It is used in optical bistable switches and other bistable optical devices such as Fabry-Parot etalons and optical interference filters [1,6,18].

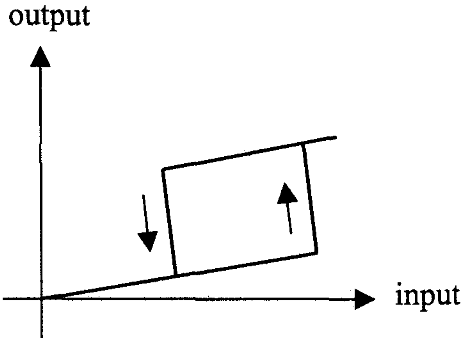


Figure 2.16 Input-output characteristic of a bistable device, displaying hysteresis

2.3 Other Topics

There are some other techniques that become research areas in lightwave communications. Two of them are of concern: holography that is directly related to optics, and optical neural networks, which can be classified as a hybrid area. Holography is based on the wave nature of light while optical neural networks is a wide area of optical networks based on artificial neural systems.

These two techniques have various applications but in this section a short, introductory knowledge will be given.

2.3.1 Holography

2.3.1.1 Method

Optical signals can be presented in the form of holograms for developing methods to store, process and display information. This indicates the importance of holography where intensity and phase distribution of light is of concern. It has been recognized that for an object illuminated with coherent light, the fringe pattern generated by the interference between the wave scattered off the object and a coherence reference wave, contains all the visual information (amplitude and phase) about the object. This interference pattern, or so-called interference grating, can be recorded photographically. Then, if the reference wave alone is used to illuminate this photographic film, it is scattered by the film so that a new wave generates which is identical to the original wave reflected from the object. Thus, the result is the formation of an image (virtual or real) by the wave reconstruction method (Figure 2.17) [22,23].

Holography is, making or study of holograms, which actually means the recording of complete information. It is also obvious that the amplitude and phase distributions of the object wave have been modulated. That is why sometimes hologram is called a modulator.

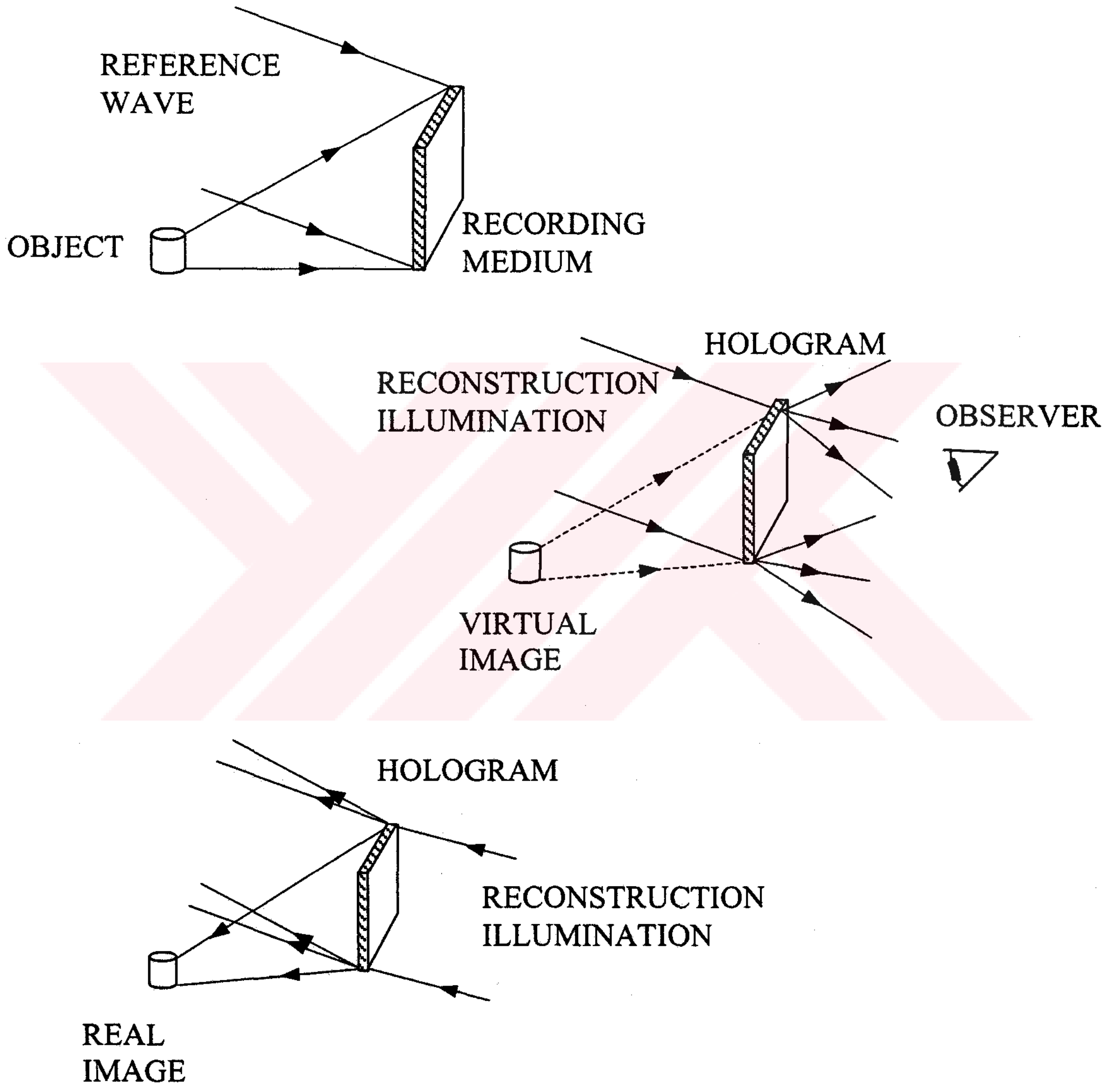


Figure 2.17 Formation of a hologram

Because of the need for coherent source, holography waited for the invention of laser. With the introduction of laser, holography received more attention and became a practical method of photographically recording optical information. After that, hologram types and producing techniques are increased with the ones who worked on that.

2.3.1.2 Classification of Holograms

One can classify holograms in different ways because there is no universally classification agreed on the types of holograms. Some terms are being preferred over others. Some of these are based on the type of recording media (thin or surface hologram, thick or volume hologram), type of modulation (amplitude modulation, phase modulation), hologram recording and reconstructing configuration (Fraunhofer hologram, Fresnel hologram, image plane hologram, Fourier Transform hologram, etc.), degree of coherence or the techniques used in recording (microwave or infrared hologram, acoustical hologram, computer generated hologram, etc.). The detailed information can be found on the references, in related books and documents [6,24,25,26,27].

2.3.1.3 Holographic Optical Elements

Holographic Optical Elements (HOEs) can be defined as holographic versions of common optical elements, such as lenses and mirrors. The advantages of holographic optical elements become apparent when you consider any application that requires a lens. Lenses are typically bulky, and are always curved. Holograms, on the other hand, are flat, and very thin. They can be more inexpensive, lightweight and compact than lenses. Any lens can be duplicated holographically, but the hologram thickness will always stay the same.

Holographic optical elements are already in use inside supermarket check-out scanners that automatically read the bar patterns of the Universal Product Code (UPC). A laser beam passes through a rotating disk composed of a number of holographic lens-prism facets. These rapidly refocus, shift and scan the beam across a volume of space, ensuring that the code will be read on the first pass across the device.

HOEs are also used in Head-Up Displays (HUDs) in airplane cockpits. These allow reflected data to appear on an otherwise transparent screen in front of the pilot's face and yet not obscure the view. They are used in office copy machines and solar concentrators as well [28].

2.3.2 Optical Neural Networks

Optical information processing or optical computing depends on the advantages of optics that is named in Section 2.1. With the adaptation of classical neural network theory to optics, optical neural network is born.

After the interest in neural networks in the early 1980s, Psaltis and Farhat [7] first introduced the idea of optical implementation for a neural network in 1985. Since then much effort has been given to realize optical neural networks.

2.3.2.1 Neural Networks

A neural network consists of a collection of processing elements named as *neurons* that communicate by sending signals to each other over a large number of weighted connections [29].

The mathematical model of a neuron is given in Figure 2.18 by McCulloch and Pitts (1943):

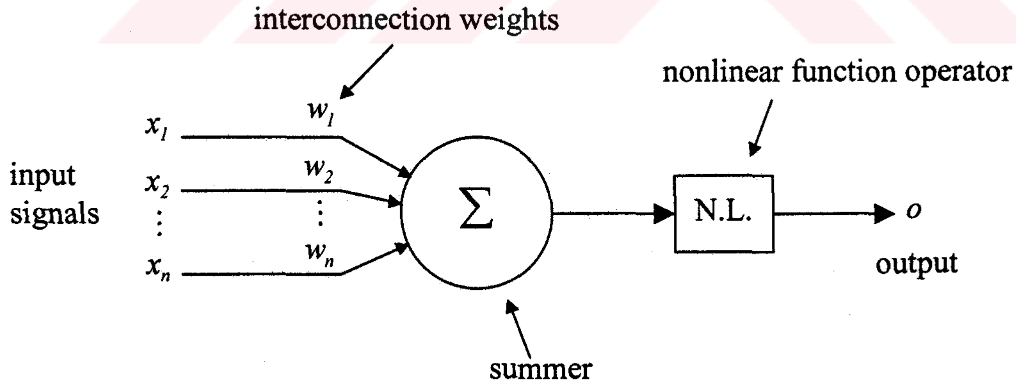


Figure 2.18 Mathematical model of a neuron

The processing of each neuron is determined by a nonlinear transfer function *f(net)* that defines the neuron's output as a function of the input signals and interconnection weights as in Equation 2.3. The weights can be changed or the interconnection strengths can be adjusted by a learning law.

$$o = f(net) = f\left(\sum_{i=1}^{n} w_i x_i\right) \tag{2.3}$$

The learning law allows the neuron's response to adapt itself to the environment, and there are two kinds of learning: supervised and unsupervised. In supervised learning, the network is taught by a teacher, responsible for supplying the input and output (desired) data. In unsupervised learning, self-learning is done by trials with only the inputs are given.

Many neural network models have been developed. The main distinction between them depends on the propagation of data. In the feed-forward networks data flow is from input to output and no feedback connections are present. On the other hand, in recurrent networks feedback connections are used to introduce data cycles between input, output and also hidden layers. They are not very simple because of the multiple layers, extra biasing, threshold or feedback they offered. Perceptron, Delta, Hebbian, Winner-Take-All, Backpropagation are some examples of learning rules and algorithms. Hamming, Hopfield and Kohonen, etc. are the name of the networks while classifiers, associative memories and self-organizing maps are the examples of the neural network classes just to name a few and to be a general reference [7,29,30].

2.3.2.2 Optical Implementation of Neural Networks

The general advantages of optics are seen in all methods of optical neural networks but especially in interconnection constraints. Very high fan-in (number of input signals) and fan-out (number of distributed signals) capability of optics with the large degree of parallelism, is the key factor to achieve unconstrained interconnections between neurons and neuron layers [31]. Implementations vary according to the technology or device involving. The use of optical fiber, holographic correlators, and optical matrix multiplication implementation schemes are mostly referred ones. There are also several architectures for different interconnection or networking design. These include multistage and multilayer solutions [7,32]. After the Farhat's proposal on the optical implementation of the Hopfield model, several other optical implementations and optical neural network architectures have been proposed. Associative memory using

Liquid Crystal Light Valves (LCLVs), hybrid optical neural networks using programmable Spatial Light Modulators (SLMs) and holographic implementations are some examples of those. Numerous papers have been published in this area related with these [7].

CHAPTER 3

INTERNETWORKING

3.1 Introduction

The merging of computers and communications, resulted with the computer interconnection, namely computer networks. Information exchange through this interconnection is established with the networking devices such as hubs, switches and routers, etc., on a communication medium such as copper wire, fiber optics, microwaves and satellites. The collection of these networks is named as internetwork or shortly *internet* while the administration of it is called as internetworking. The best known one, Internet, is a specific worldwide internet connecting companies (.com), governments (.gov), universities (.edu), etc.

In the implementation of network many challenges must be faced, especially in the areas of connectivity, reliability, network management and flexibility. The history of internetworking from time-sharing networks to Local Area Networks (LANs), Metropolitan Area Networks (MANs) and Wide Area Networks (WANs) evolved with these concepts. Today the Internet interconnects large number of computers and networks throughout the world.

The evolution of networking is determined by the combined effect of three different factors: transmission, switching and protocols [33]. It is well known that transmission and switching usually rely on hardware devices, whereas protocols are based on software resources. This chapter essentially deals with Internet, Internet Protocol (IP) and switching/routing based on IP.

Data traffic is rapidly growing and the Internet traffic is estimated to double every six months. The bottleneck seems to be switching which is actually the network connectivity for the support of any service. In general view, networking offers two different type of service: connection-oriented and connectionless. In the connection-oriented service, the service user first establishes a connection, uses the connection and transfers the data, and then releases the connection as in the telephone system. In the connectionless system, each message carries the full destination address and is routed independently from all the rest as in the postal system.

Networking is based on the switching operation and the switching mode of a network indicates whether the network nodes are circuit switches or packet switches. Circuit switches are position-based, in that the arriving bits are switched to a different output position. This position is determined by a combination of one or more of three dimensions such as space, time and frequency (wavelength). Synchronous Optical NETwork (SONET) and Dense Wavelength Division Multiplexing (DWDM) technologies are the two examples of mostly used circuit switched networks:

SONET: It is the standard for transport of data over optical media between two fixed points. It is developed with the advances in the optical transmission and in the accuracy of clocks. The system consists of switches, multiplexers and repeaters all connected by a fiber. A master clock that controls the sending of the bits at extremely precise intervals establishes the synchronization. The different streams are multiplexed by byte interleaving using the TDM technique.

In North America and Japan the basic SONET signal is named as STS-1 (Synchronous Transport Signal-1). It has a bit rate of 51.84 Mbps. Higher rates are multiples of this rate. In Europe the basic rate is STS-3 or 155.52 Mbps and is called STM-1 (Synchronous Transport Module-1). The STS hierarchy based on this rate is named as Synchronous Digital Hierarchy (SDH). The rates of the both standards are given in Table 3.1 [3,13].

Table 3.1 Transmission rates for SONET/SDH

Carrier	**SONET signal**	**SDH signal**	**Bit rate (Mbps)**
OC-1	STS-1		51.84
OC-3	STS-3	STM-1	155.52
OC-12	STS-12	STM-4	622.08
OC-24	STS-24		1244.16
OC-48	STS-48	STM-16	2488.32
OC-192	STS-192	STM-64	9953.28

DWDM: The WDM technology enabled to carry a number of wavelengths on a single fiber as mentioned in the previous chapter. Commercial DWDMs combining up to 16 wavelengths were introduced in 1996. The WaveStarLambdaRouter from Lucent Technologies based on the patent-pending technology from Bell Labs supports 256 wavelengths. Most DWDM equipment is designed to work with SONET and named as SONET/DWDM in the optical link networks. With this technology SONET/SDH speeds up to 40 Gbps today, offering more than 10 Tbps of total switching capacity. This technology depends on the MicroElectroMechanical Systems (MEMS) technology that will soon support 400 wavelengths. (MEMS is a device technology using lithographic fabrication techniques to create miniature mechanical components. For optical networking application of MEMS, an array of freely moving microscopic mirrors are tilted and being rotated around micromachined hinges to route optical signals in different wavelengths) [15,19,34].

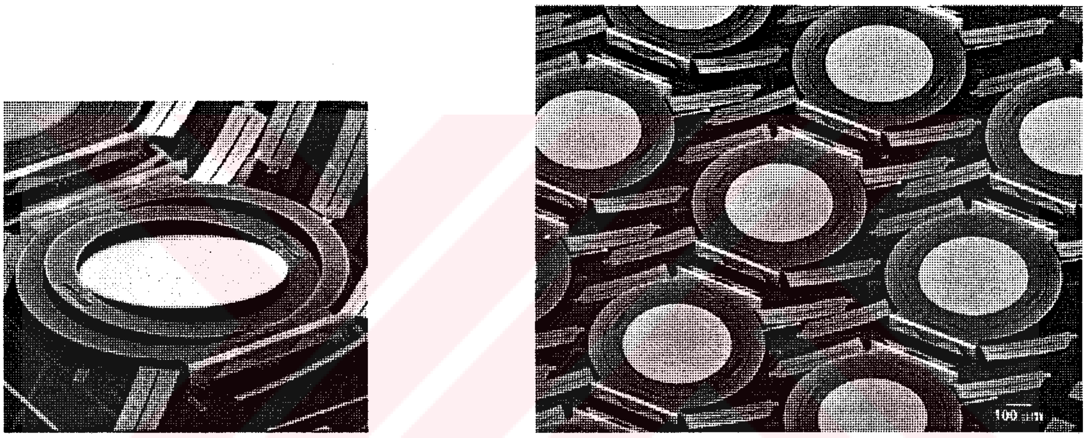


Figure 3.1 Fabricated micromechanical tilt-mirrors [15]

Packet switches are label-based where the packet headers are the labels. They use information in the packet headers to decide how to switch or route a packet. IP networks and Asynchronous Transfer Mode (ATM) networks are the examples of packet switched networks (in fact ATM networks combine the good features of circuit switched and packet switched networks) used in the Internet. Multi-Protocol Label Switching (MPLS) is an improving example of packet switching where the labels encapsulate IP packets [35].

ATM: It is a connection-oriented service that the information is transmitted in small fixed-size packets called cells and the technology is named as cell switching. The cells are 53 bytes long containing 5 bytes header and 48 bytes user data. The header cell identifies the virtual path for routing the ATM cells. The cell delivery is not guaranteed but the cells in the same connection reach the destination in the order they are sent from the source, thus eliminating the need for sequence numbers and buffering [13].

The ATM network is capable of transporting various bandwidths on fixed length cells and these cells were designed to be transported over the SONET architecture. Today IP packets are carried over ATM. However, as this traffic increases, it becomes necessary to transport both directly over SONET rather than the alternatives shown in Figure 3.2.

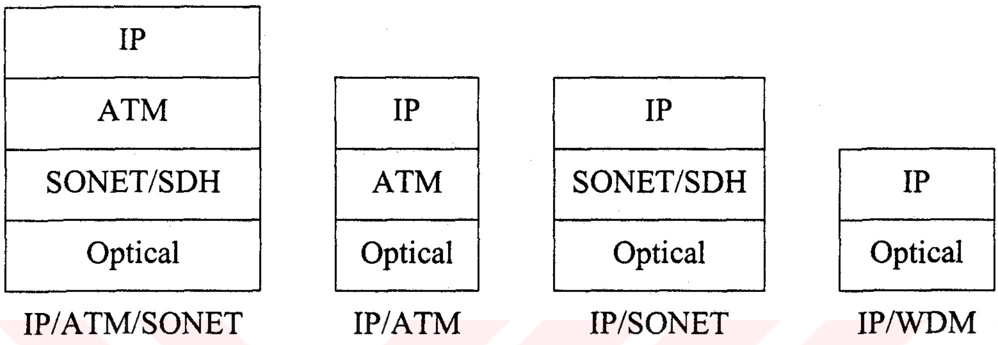


Figure 3.2 IP transport alternatives

MPLS: It is actually an implementation of a technique called label switching based on the encapsulation of IP packets with labels. Label switching has two main procedures: IP switching and tag switching. IP switching requires an underlying ATM link layer, where label corresponds to an ATM virtual circuit/path identifier (VCI/VPI). In tag switching, tag is attached to packets depending on their link layer packet format. MPLS is a variation of tag switching where labels (tags) act as a shorthand representation of an IP packet header that contains the address of the packet to be routed. The packet handling nodes or routers are called Label Switched Routers (LSRs) and they forward packets by making switching decisions based on the MPLS label. Therefore routing can be separated into two parts as label-based and protocol-based and can be modified independently. In other words, there is no need to change the forwarding machinery when changing the routing strategy [13].

But in this chapter only packet switching based on IP will be of concern. This is because of the Internet, becoming the dominant for all new network services. To understand the IP, OSI layering and Ethernet technology will be introduced [36,37,38].

3.2 OSI Layer

Network architectures are established by a set of layers and protocols. The standardization of the protocols used in various layers is done by the International Standards Organization (ISO) in 1984. The reference model developed by ISO is named as Open Systems Interconnection (OSI) and considered as the primary architectural model for intercomputer communications. Many networks do not strictly follow the OSI model and various models have been designed and used for different technologies but the model helps in understanding the design of packet-switched network architectures.

The OSI model has seven layers. The network functions performed by the layers are given in Table 3.2.

Table 3.2 OSI layer

OSI Layer	Function Provided
Layer 7- Application	Specialized network functions such as file transfer, virtual terminal, electronic mail and file servers.
Layer 6- Presentation	Data formatting and character code conversion and data encryption.
Layer 5- Session	Negotiation and establishment of a connection with another node.
Layer 4- Transport	Provision for a reliable end-to-end delivery of data.
Layer 3- Network	Routing of packets of information across multiple networks.
Layer 2- Data Link	Transfer of addressable units of information, frames and error checking.
Layer 1- Physical	Transmission of binary data over a communication medium.

The seven OSI layers use control information in communicating with their peer layers in other computer systems. This information takes typically one of two forms: headers and trailers. Headers are added to the data from application layer to physical layer and thus establishing data encapsulation, and stripped off from the data in the opposite direction in each layer as given in Figure 3.3.

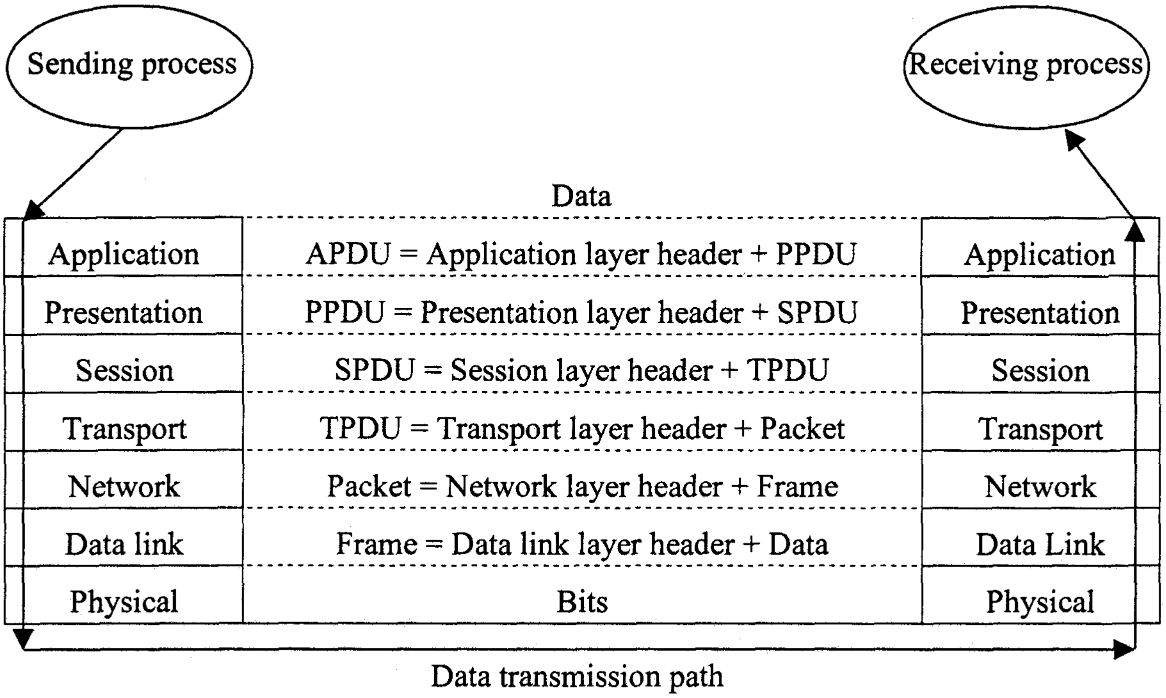


Figure 3.3 Data encapsulation

Note that the unit exchanged is named with the protocol name and the data unit, such as Application Protocol Data Unit (APDU) but the data in physical layer is named as bit, where frame and packet are the names given in the data link layer and network layer, respectively.

Internetworking occurs essentially in the network layer but the provision is done by a connection-oriented Transmission Control Protocol (TCP) or by a connectionless User Datagram Protocol (UDP). Today Internet or IP is based on the TCP and mostly pronounced as a protocol family TCP/IP. Thus there is also a TCP/IP reference model similar to the OSI but different in some concepts. There are also other layered models defined for the technologies such as ATM or SONET (Figure 3.4). These technologies also carry IP where they are called as "IP over ATM" or "IP over SONET" as mentioned before and figured in Figure 3.2.

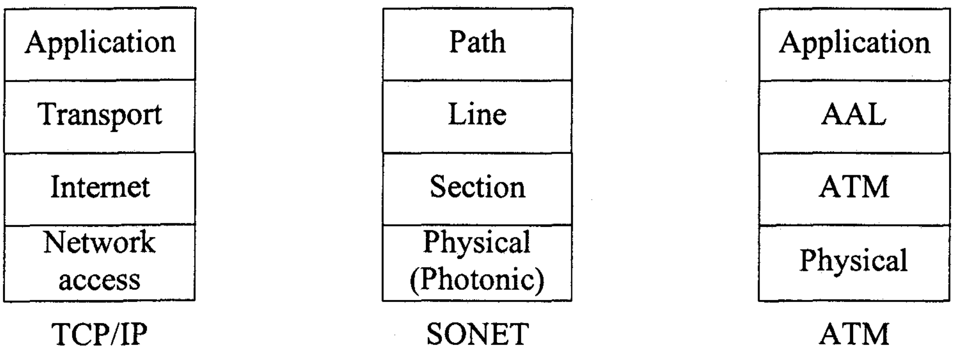


Figure 3.4 Different layer models

3.3 Ethernet

There are many physical implementations either in LAN or WAN. The Institute of Electrical and Electronics Engineers (IEEE) has produced several standards for LANs. These are known as the IEEE 802 including Carrier Sense Multiple Access with Collision Detection (CSMA/CD), token bus and token ring. The most common one in computer networks is the Ethernet or IEEE 802.3. It is based on the CSMA/CD idea that can be summarized as following: When a station wants to transmit, it listens to the cable. If the cable is busy, the station waits, otherwise transmits immediately. If two or more stations simultaneously begin transmitting, they will collide. The colliding stations terminate their transmission, wait for a random time and repeat the whole process again.

Ethernet basically performs three functions [37]:

1. Transmitting and receiving formatted data or packets.
2. Decoding the packets and checking for valid addresses before informing upper layer software.
3. Error detection within the data packets or on the network.

These functions are performed in the OSI data link layer, therefore the data in the Ethernet envelope is named as Ethernet frame. Its format and the descriptions of the fields are summarized in Figure 3.5.

Preamble	Destination address	Source address	Type field	Data field	FCS

Preamble	Receiving clock synchronizer.
Destination address	The address of the immediate recipient of the packet.
Source address	Address of the sender of the packet.
Type field	Indicates what type of data in the packet: TCP, XNS, etc.
Data field	Contains upper-layer software headers and user data.
Frame Check Sequence (FCS)	Contains a 4-byte Cyclic Redundancy Check (CRC) value to ensure the integrity of the packet.

Figure 3.5 Ethernet frame format

The packets in the network have the source and destination addresses as given in the Ethernet frame. These addresses are also called as physical addresses or Media Access Control (MAC) addresses. They are globally unique, and each one is six bytes (48 bits) long. Each vendor of a LAN interface card must register its use with IEEE. IEEE will assign the vendor the three bytes of the total six bytes address. The last three bytes can be assigned by the vendor. For example 02 60 8C 00 00 00 is for 3Com and 08 00 20 00 00 00 is for SUN Microsystems written in the hexadecimal format.

For LAN interfaces there are three types of physical addresses: unicast, multicast and broadcast. In the unicast, one machine is identified, so there is one number assigned per machine. In the multicast, a group of stations is identified. In this way, a single station may transmit a packet to more than one station. In broadcast, the packet is sent to all stations. However, these addresses result a heavy traffic, thus dividing the network into separate divisions became a good solution. The interconnection devices for connecting these networks are known as bridges, switches and routers. Bridges operate at the ISO data link layer. They verify checksums on the data packets that they are trying to forward and discard packets that have bad checksums. They forward frames based on the MAC addresses in the packet. Switches forward and flood traffic based on the MAC addresses too. They are also data link layer devices like bridges but designed to switch data frames at high speeds. Routers however, operate at OSI network layer and connect more than one network. They work with the network numbers embedded in the data.

Network number is not the same as physical address that identifies a station on the network. The combination of the network number and the physical address on the network will uniquely identify any station on the network. Therefore both of them are essential in the routing and their importance will be understood in IP.

3.4 Internet Protocol

The Internet Protocol (IP) is a network layer protocol that contains addressing information and some control information that enables packets to be routed. It is a connectionless network service and the switching is done by packet switching.

At present two versions of the IP exist: IP version 4 (IPv4) and IP version 6 (IPv6) which are described in RFC 791 and RFC 2460, respectively. (Documentation of the Internet protocols and policies are specified in technical reports called Request For Comments (RFCs), which are published, reviewed and analyzed by the Internet Engineering Task Force (IETF)). The description of IP includes the following very important elements:

- IP defines the basic data unit (datagram) and specifies the format of the datagrams to be sent through the Internet.
- IP software carries out the routing functions based on the IP addresses.
- IP contains a set of rules for how hosts and routers should handle (e.g. forward) the datagrams, how and when error messages should be generated, and when datagrams can be discarded.

IPv6 is designed to overcome the limitations of IPv4, such as limited number of addresses, complex header and poor security. The growing need to redefine the header in order to obtain efficient routing is also a major driver. But today Internet is still based on IPv4 therefore following discussion and features of the protocol are based on IPv4.

IPv4 packet format is shown in Figure 3.6 and the description of the fields is given below.

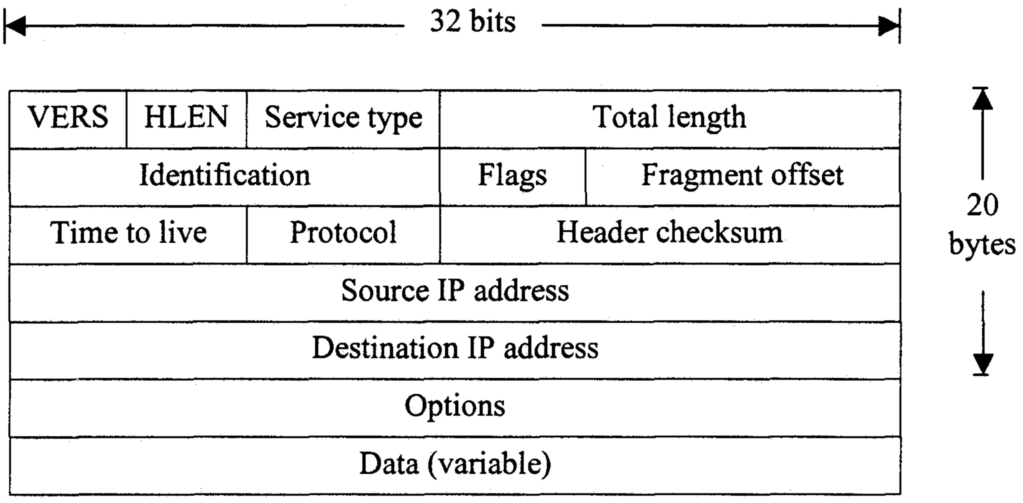


Figure 3.6 IPv4 packet format

VERS: Indicates the version of the IP.

HLEN: Indicates the header length of the datagram in 32-bit words.

Service type: Specifies the service for the upper-layer protocol.

Total length: Specifies the entire length of the IP packet, including the data and header.

Identification: Contains an integer used for fragmentation.

Flags: Bits for controlling the fragmentation.

Fragment offset: Indicates the position of the fragment's data relative to the beginning of the data in the original datagram.

Time to live: Counter showing at which point the datagram is discarded.

Protocol: Indicates which upper-layer protocol receives incoming packets after IP.

Header checksum: Helps to ensure IP header integrity.

Source address: Specifies the sending node.

Destination address: Specifies the receiving node.

Options: Allows IP to support various options such as security.

Data: Contains upper-layer information.

Each IP packet has an IP header of at least 20 bytes. The header indicates the source and destination network addresses of the message. To facilitate routing of packets, these 32-bit network address (called as IP addresses) are grouped by a 4-byte (a set of four 8 bits or octets) separated by dots from 0.0.0.0 to 255.255.255.255 represented in decimal format known as dotted decimal notation.

IPv4 organizes its users/devices into a simple two-level addressing hierarchy consisting of network number and host number. Because of the needs for small networks as well as large networks, the 32-bits long address space is divided into classes as given in Table 3.3.

Table 3.3 IP address classes

Class	Begins with	Network	Host number
A	0	7 bits	2^{24}-2^{*}
B	10	14 bits	2^{16}-2
C	110	21 bits	2^{8}-2
D	1110	assigned for multicast	
E	11110	reserved for future use	

* one address is reserved for broadcast address and one address is reserved for the network

Class-based addressing was the original organization of IP addresses. However, addressing the millions of computers around the world results in very large addressing database. The management of these addresses is simplified by partitioning the address space. This is called *subnetting* and IP networks can be divided into smaller networks called *subnetworks* or *subnets*. Addressing is now classless and the routing is named as Classless Inter-Domain Routing (CIDR) (RFC 1519) where the addresses are divided into blocks of variable size. In CIDR, a group of addresses that have a common prefix are grouped as a subnet and this common prefix serves as a network number for the whole group. A 32-bit subnet mask written in the same notation as IP addresses accompanies each IP address. It has binary 1s in all bits specifying the network and subnet fields, and binary 0s in all bits specifying the host field. Routing is based on that subnetting where a router maintains a set of destination address prefixes in a routing table and looks up to find the longest prefix in this table. This is called "longest prefix match" and used to determine the next hop of a packet from the prefix that matches the first few bits of the destination address of the packet.

In general, router can be described as a device used for information exchange within and between subnetworks. A collection of subnetworks that are connected together is named as Autonomous System (AS) and the routers exchanging information within ASes are called interior routers. They use Interior Gateway Protocols (IGPs) such as Routing Information Protocol (RIP) (RFC 2453) and Open Shortest Path First (OSPF) (RFC 2328). The routers that move information between ASes are called exterior routers and these routers use an Exterior Gateway Protocol (EGP) such as Border Gateway Protocol (BGP) (RFC 1771). There are also several control protocols monitoring the operation of the IP, such as Internet Control Message Protocol (ICMP) (RFC 792), Address Resolution Protocol (ARP), Reverse Address Resolution Protocol (RARP) (RFC 903), Bootstrap Protocol (BOOTP) (RFC 951).

Whatever the router is, there are some basic processes to be performed. When an IP packet arrives, the router extracts the IP destination address and performs a logical AND operation with the subnet mask to obtain the network number. This number is looked up in the routing table to find its corresponding output port identifier. If the packet is for a local host, router uses its ARP. Using this protocol, a router searches its ARP table to locate the MAC address for a given computer name. Otherwise the packet is for a distant network, therefore the router looks up its routing table to determine the address of the router that it will forward to by RIP or OSPF. RIP is based on the distance-vector algorithms while OSPF is a link-state routing protocol. RIP is the original IGP but OSPF became a standard and is working well in large ASes unlike RIP. With the RIP or OSPF information, any router knows the length of the shortest path (may not be the fastest) to route the packet.

There are many networks and protocols dealing with error, flow and congestion control and serving for the best effort and quality of service. Networking considers all these issues. But as far as routing is the concern of this thesis, the main aim of this chapter is to give some brief information about IP packet routing for establishing a base for optical packet switching. Therefore the following summary for routers depending on the processing of IP packets will be sufficient.

- Routers work on a connectionless basis and therefore they do not guarantee delivery of any packet.
- They operate at the network layer. So they forward packets based on the network addresses not on the physical or MAC addresses.
- They only route packets that are directly addressed to them. They do not watch the LAN traffic and they do not establish sessions with other routers on the internet.

- When the router receives the packet, it will look at the final network address (embedded in the IP header of the packet) and determine how to route the packet based on the protocol it is using and the information in its routing table.

CHAPTER 4

PHOTONIC PACKET SWITCHING

4.1 Introduction

Circuit and packet switching have been used for many years to establish internetworks. However, the Internet is growing fast and demanding more network capacity and higher data rates. Today, circuit and packet switching are evolving to their optical counterparts, namely, optical circuit switching and optical packet switching, with the evolution of fiber-optic communication systems and photonic switching nodes.

In optical packet switching the main idea is to investigate if optics could be helpful to increase the bandwidth and the speed of packet switching nodes beyond the limits of electronics. The enabling technology for this aim is Wavelength Division Multiplexing (WDM) (also called optical frequency division multiplexing). In networks based on WDM systems, each interconnecting fiber may support many wavelengths and with this enormous bandwidth available on fiber, WDM can provide an optical transmission system with extremely high data rates (over 10 Tbps). The optical system combining WDM channels with optical cross connects (OXCs) is called as Optical Transport Network (OTN), providing a base (or global) transport infrastructure for future applications.

Research on optical (or mostly called photonic) packet switching has been conducted over a number of years and is still continuing. In this chapter, firstly some basic knowledge on photonic packet switching will be given, including the issues on synchronization, header recognition and contention resolution. Examples of switching configurations and architecture realizations for building OTNs will be given afterwards.

4.2 Issues on Photonic Packet Switching

Photonic packet switching consists on the packet header recognition, control and routing achieved in photonic domain. Switches optically route packets based on the information (such as destination address) carried in the header. This information is generally in fixed-size packets (cells) because the main switching technology was Asynchronous Transfer Mode (ATM) at the time when photonic packet switching is first introduced [33]. But today, IP packets are carried in a network of photonic packet switches (in OTNs), after segmented into these fixed-size cells and reassembled at the destination. Variable length of cells can also be used, which will be an integral multiple of a unit length, but a tradeoff in complexity has to be faced [39]. If the packets are of fixed length, the recognition of the boundaries is much simpler, then header recognition, contention resolution, control and routing functions may be done easily.

Figure 4.1 shows the packet format consisting of a header and a payload separated with guard times, placed inside fixed time slots (cells) [40].

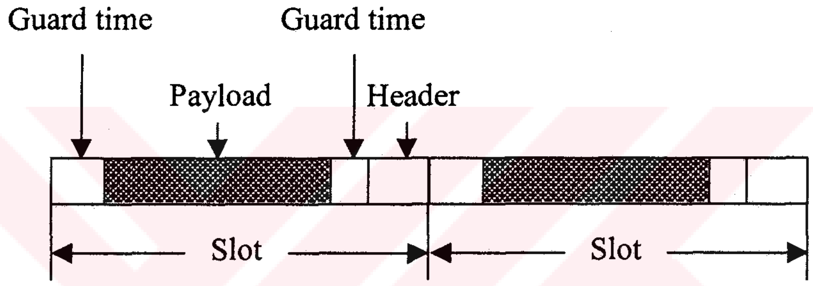


Figure 4.1 Packet format

This packet enters the photonic packet switch given in Figure 4.2 [41]. As shown in this diagram, the important issues for switching includes the synchronization, header replacement, routing and buffering functions. Packets are synchronized first, and became ready for processing. Header recognition (header information extraction) and replacement (packet header removal and inserting the new header to the payload) is done next. Buffering and routing functions are used here as well as for sending them to the required output ports. Control circuits at present remain electronic dependent until achieving their functionality and processing power with photonics technique.

There are many challenges in all these issues and techniques vary according to the photonic components, routing techniques and switching architectures, which form the photonic packet switch and the photonic packet switched network. Now, the most important ones are going to be discussed.

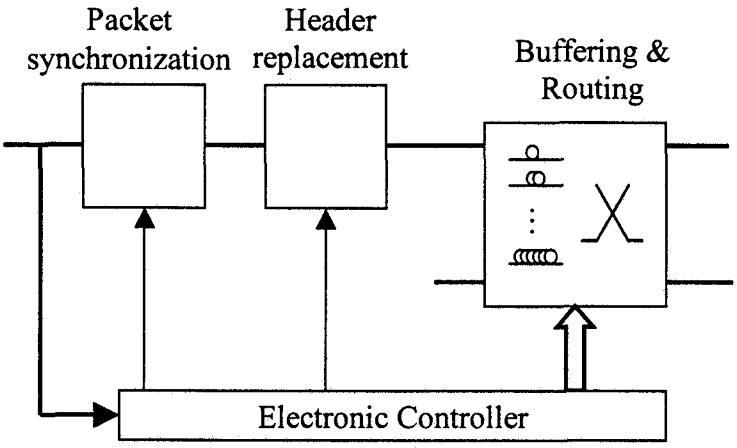
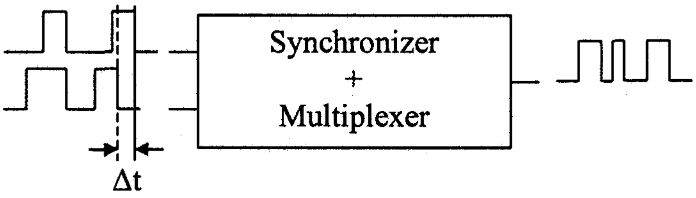


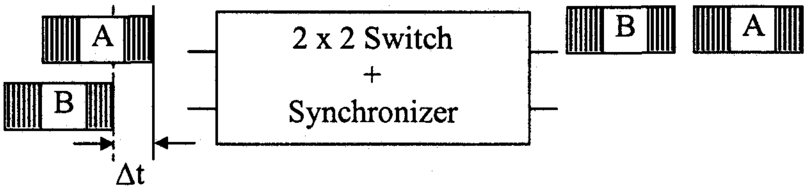
Figure 4.2 Photonic packet switch

4.2.1 Synchronization

For efficient switching and routing in optical networks, synchronization of incoming data signals is a critical function. Synchronization can be defined as the process of aligning two pulse streams in time. Such alignment can be on a bit-by-bit or a packet-by-packet basis as shown in Figure 4.3 [42]. Bit synchronization is of particular importance in TDM systems where it is important to avoid bit overlap in the time domain. On the other hand, packet synchronization is used to avoid or simplify contention and increase switching efficiency.



Bit synchronization



Packet synchronization

Figure 4.3 Bit-by-bit and packet-by-packet synchronization

For achieving simplicity as mentioned above, optical packet switched networks are typically designed for fixed-size cells. But packets can arrive from different links into a node at different times. Also these nodes cannot be designed as integer numbers of the packet duration, and a temperature change effects the packet propagation speed (typical figure of 40 ps/°C/km), thus synchronization or delineation of them is essential [40].

In a synchronized network, packets are placed together inside a fixed time slot, which has a longer duration than the header and the payload, to provide guard time (Figure 4.1). In most cases optical buffering is implemented by using fiber loops or delay lines which helps the packets to be aligned with a local clock reference.

Asynchronous networks offer a different solution without the synchronization stage where the packets need not to be aligned. Packets go through the same amount of delay (using fixed-length fiber delay lines) in the same relative position in which they arrived, with the condition of being no contention. In the presence of contention (which may occur in synchronous networks as well), some kind of contention resolution, as given in the Section 4.2.3, must be used.

4.2.2 Header Recognition and Replacement

The header contains routing and other control information to be processed as mentioned in previous chapter. When a packet arrives at photonic packet switch, the header and the payload of the packet are separated. Header is processed by the control unit electronically [43]. At this time, the payload remains optical throughout the switch, thus achieving payload optical transparency, where transparency refers to no optical to electronic (O/E) and electronic to optical (E/O) conversion is required. Full optical transparency and all-optical networks is the eventual goal of researchers where the data can ideally pass through the switch without any limitation, thus header is processed optically. In this section, examples of these researches will be of concern.

For header replacement, recognition of the header has to be achieved. There are several optical data processing methods for this aim. One technique uses the address portion (four bits of information) of an incoming packet (5 byte header field of an ATM packet) to detect and send a control signal to the switch [44]. In a novel packet architecture, minimization of the numbers of optical sampling gates in the header recognition and packet demultiplexing blocks is proposed [45]. Optical header/payload discriminator, optical header and optical address translator for header recognition techniques analyzed using delay line decoders in [46]. Spatial frequency processing and spectral holography, are the other techniques performed experimentally. Fiber based techniques are also implemented such as the one using the matched filters to correlate addresses and another using tunable fiber Bragg gratings as reconfigurable optical correlators. Fiber Bragg gratings provided wavelength dependent tunable time delays for each different wavelength, individually assigned for header bits. Optical decoder is used to determine the header bits that match the header code of the optically encoded look-up table [47]. A noncorrelational technique depending on a phase-dependent neighbor-to-neighbor interaction of solitons resulting in cross phase modulation is proposed but has not yet been demonstrated experimentally [42].

In above techniques as well as others, the header replacement is achieved by blocking of the old header and inserting the new one at proper time. One common technique in header replacement is to transmit the header at a much lower bit rate than the packet itself [3]. The low rate of header (less than 10 Gbps) is suitable for electronic processing, while the payload is processed optically in high (Tbps) ranges. Other proposed solutions depend on the serial/parallel processing of the bits and wavelength. The packet header could be transmitted on a wavelength that is different from the payload data. This approach suffers from fiber dispersion (typical 20 ps/nm/km) which results in different propagation speeds for packets transmitted on different wavelengths.

Among several different techniques, two of them, SubCarrier Multiplexing (SCM) and Code Division Multiplexing (CDM) have been attracted increasing interest in the processing of packets and it will be mentioned shortly.

SCM: SCM is one of the techniques used in TDM and FDM (WDM). It uses subcarrier modulation to multiplex multiple data streams onto a single optical signal. Multiple carriers at different frequencies are combined to modulate the optical transmitter. At the receiver, subcarriers are separated and the data is extracted [3]. In the application of this technique in header processing, the header is transmitted on a separate subcarrier channel on the same wavelength, which payload data is encoded at the baseband while header bits are encoded on properly chosen subcarrier frequencies at a lower bit rate, as shown in Figure 4.4 [40].

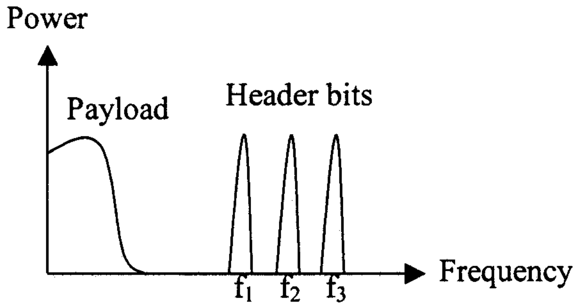


Figure 4.4 Header and payload in SCM

CDM: It is generally referred as Code Division Multiple Access (CDMA) technology. The applications of CDMA vary especially on wireless systems and the importance of CDM or CDMA comes from its ability to connect wireless and wired networks seamlessly. The principle of CDM is based on spread-spectrum techniques. The concept is to spread the energy of the signal over a frequency band that is much wider than the minimum bandwidth required to send the information. Optical CDM (OCDM) uses the same analogy but instead of frequency spread/despread, time spread/despread technique is adopted as shown in Figure 4.5. An optical short pulse, having much higher frequency spectrum than the data bandwidth, is spread over one bit duration T by the encoding. Spreading the spectrum is accomplished by means of a code that is independent of the signal itself. The receiver uses the same code for despreading and recovers the data with the matched filtering technique [48].

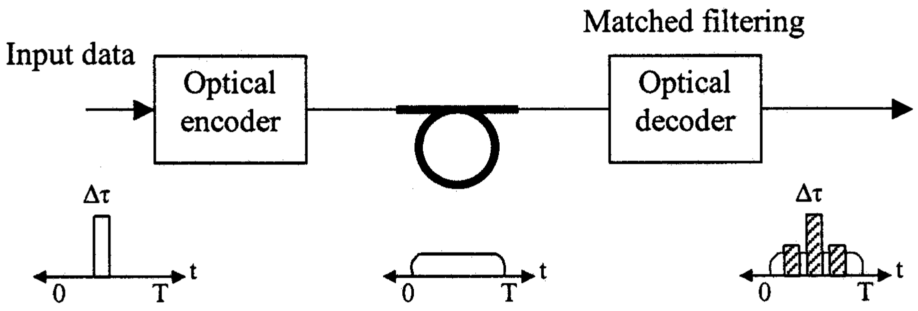


Figure 4.5 Principle of OCDM on time spread/despread basis

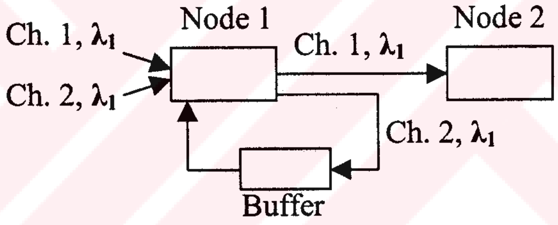
Applications of OCDM to photonic networks are summarized in three categories as: high bit rate point-to-point transmissions, gigabit multiple access, and optical path networks using optical codes [48]. These issues will not be covered in this thesis. But, the general features for OCDM method that attracted attention, can be summarized as following [49]:

- CDM encoders and decoders do not require optical memories that are difficult to realize.
- The synchronization is easier.
- CDM codes are suitable for expressing routing information. And by using standard codes for previously known links (channels), routing can be done easily.

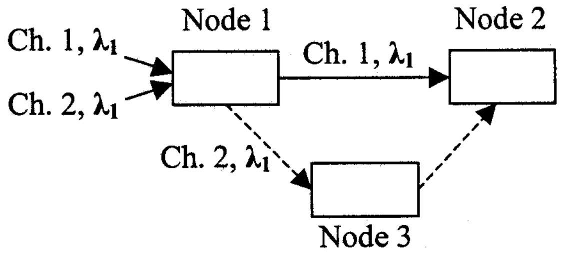
4.2.3 Contention Resolution

After the replacement of the header, another important issue is the contention resolution. Contention occurs whenever two or more packets are trying to leave the switch from the same output port. Resolution of contention is done mainly in three ways: buffering, deflection routing and wavelength conversion [40,41,42].

(a) Buffering:



(b) Deflection routing:



(c) Wavelength conversion:

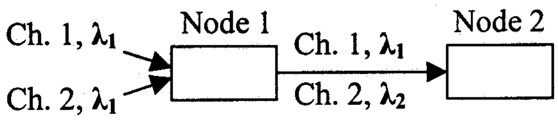


Figure 4.6 Resolution techniques

4.2.3.1 Buffering

To preserve data in optical form, it is desirable to implement the buffer memory optically. So far optical memory is still on research table and thus the main elements in packet buffering are electronic Random Access Memories (RAMs). Earlier proposed photonic packet switching systems have used RAMs, however, limited speed of RAMs constrains the speed and capacity of photonic packet switches. Also the electronic/ photonic interface add complexity and loss. Therefore there has been much effort to develop optical RAMs but unfortunately useful optical RAMs for photonic packet switching has not yet been found. At present, using fiber delay lines incorporating with the other components such as Semiconductor Optical Amplifier (SOA) gates, optical couplers and wavelength converters is the alternative approach.

In electronics, routing contention is usually resolved by a store-and-forward technique but in photonic buffering that uses fiber delay lines, resolution is done by travelling type or recirculating type buffering. In travelling type buffers, fiber delay lines are adjusted to multiples of one packet duration, T, between space switches as given in the Figure 4.7. The storage time is (pre)determined by the duration of a packet propagating through the optical fiber length.

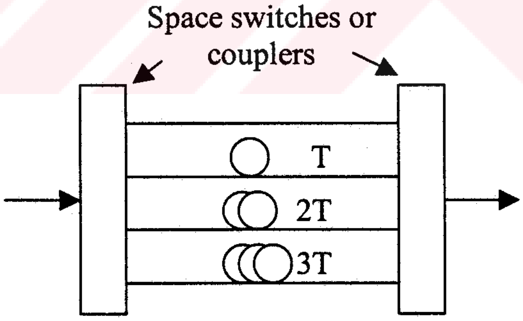


Figure 4.7 Travelling type buffer

In recirculating type, fiber delay lines form the loop with one circulation time equal to one packet duration, as shown in Figure 4.8. The circulation number determines the storage time and this gives flexibility to change and adjust the packet storage time. But the signal amplification needed in this type to compensate the power loss, results in the accumulated spontaneous emission noise, which limits the maximum buffering time.

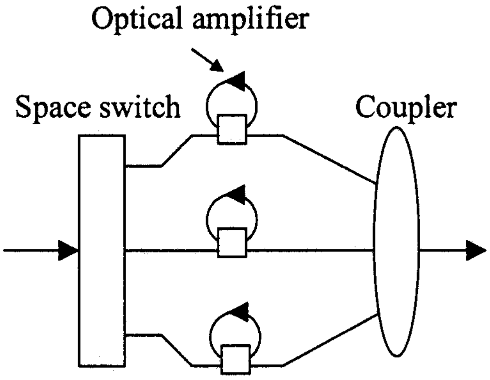
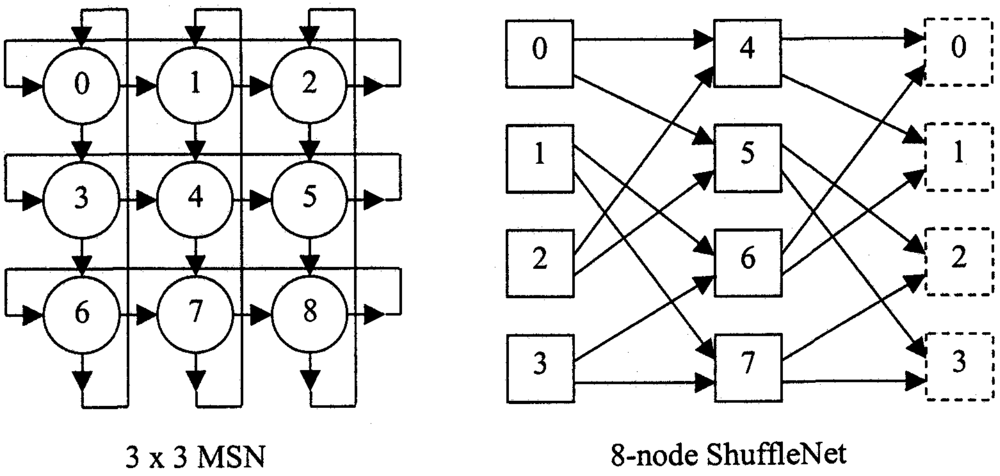


Figure 4.8 Recirculating type buffer

4.2.3.2 Deflection Routing

Deflection routing was invented by Baran in 1964 and used as an alternative to buffering. In this type of routing, packets are misrouted by the switch (as in the Node 1, Figure 4.6-b). If two or more packets need to use the same output link, only one of them will be routed while others are forwarded to other paths (misroutes). Misrouting will naturally change the paths to a longer route greater than minimum distance routing.

Some logical topologies used for network performance simulation, namely, the Manhattan Street Network (MSN) and ShuffleNet have carried out studies on deflection routing. Different routing strategies, delays, average number of hops (the number of switches a packet has to traverse between the source and the destination node) for each packet is determined with the help of these architectures given in Figure 4.9.



3 x 3 MSN

8-node ShuffleNet

Figure 4.9 The Manhattan Street Network and ShuffleNet

Generally deflection routing refers to the use of no or little optical buffer. Deflection routing, which uses no buffers is sometimes called as *hot-potato* routing where packets are always moving as "hot-potatoes" until reaching their destinations [40,50].

4.2.3.3 Wavelength Conversion

Buffering and deflection routing have their advantages but after the introduction of WDM, wavelength domain presents another dimension of solution: wavelength conversion. It is the technique of transferring the information modulated on an optical carrier with a wavelength to another optical carrier of a different wavelength as mentioned in Chapter 2.

In general, wavelength conversion approach is used with WDM to eliminate optic-electronic-optic (O/E/O) conversion. In packet switching schemes, it works with both buffering and deflection routing to overcome the difficulties of both technologies. (For example, wavelength conversion has been shown to reduce the number of buffers). It also allows the reuse of wavelength by transferring data to any available wavelength, thus reducing contention.

Different network structures and many wavelength-shifting schemes have been demonstrated including O/E/O conversion, Cross-Gain Modulation (XGM), Cross-Phase Modulation (XPM), Difference Frequency Generation (DFG), and Four Wave Mixing (FWM). The great part of the converters proposed in literature using these schemes is based on the SOA nonlinearity [3,42].

4.3 Photonic Packet Switched Network Architectures

Issues mentioned above are used individually or incorporating with each other to establish many photonic packet switching architectures. Two of them are mostly used: broadcast-and-select type and wavelength routing based. In this section, switch architectures and the project studies for realizations of both will be summarized. Optical space switches are the key components with either architecture and the Staggering switch is the important example for these, thus will be introduced. $LiNbO_3$ (lithium niobate) and SOA gate switches are most promising because of their switching speed in a range of several nanoseconds. They have also low crosstalk and low power loss, especially the integrated ones. The integration is needed in the space switch based architecture because of the number of crosspoints (or SOA gates) required increases dramatically as the switch size grows.

The Staggering switch is the best known type of optical space switch consisting of two rearrangeably nonblocking space switches interconnected by a set of unequal delay lines as shown in Figure 4.10. The $N \times M$ space switch operates as the scheduling stage that distributes packets to the delay lines in such a way that, when packets arrive at the switching stage ($M \times N$ space switch), there are no output collision [51].

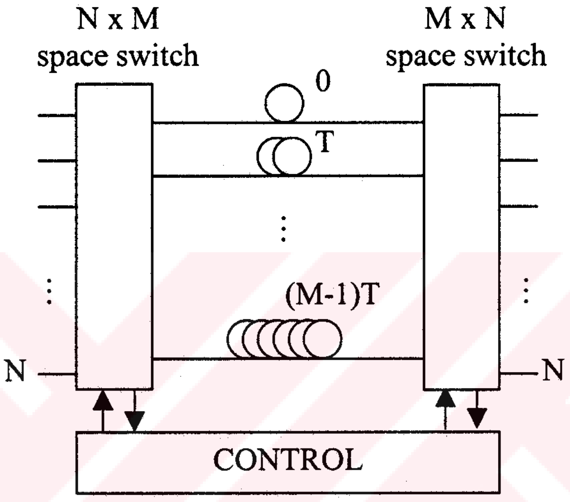
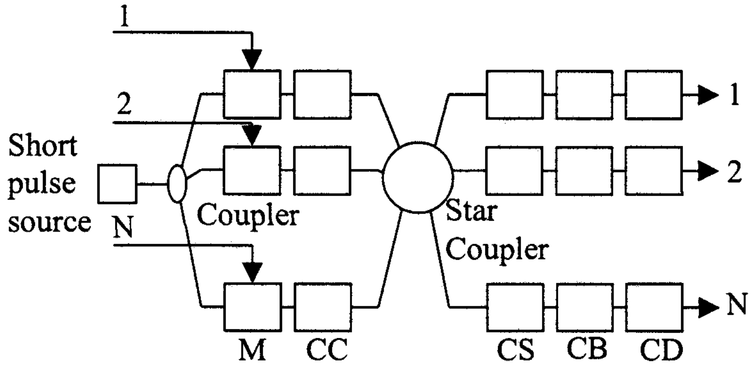


Figure 4.10 Staggering switch

Broadcast-and-select approach has been widely used in photonic networks. Star coupler multiplexes and distributes the all information signals as mentioned in Chapter 2. The ULPHA switch reported as an ULtrafast PHotonic ATM switch, is an example for this type of switches. In this switch, (Figure 4.11) ATM cells are modulated by the sequence of ultrashort optical pulses and broadcast by an ultra high-speed optical TDM channel. Cells are time-multiplexed (compressed in time) and coded. The difficulty of requiring high-speed cell coders is overcome by the bit-interleaved multiplexing technique. As a result, it offers a very large switching capability in Tbps range [41].



M: Modulator, CC: Cell Coder, CS: Cell Selector, CB: Cell Buffer, CD: Cell Decoder

Figure 4.11 ULPHA Switch

European Advanced Communications Technology and Services (ACTS) KEys to Optical Packet Switching (KEOPS) announced a broadcast-and-select space switch using single stage forward buffering for contention resolution as shown in Figure 4.12 [43,52].

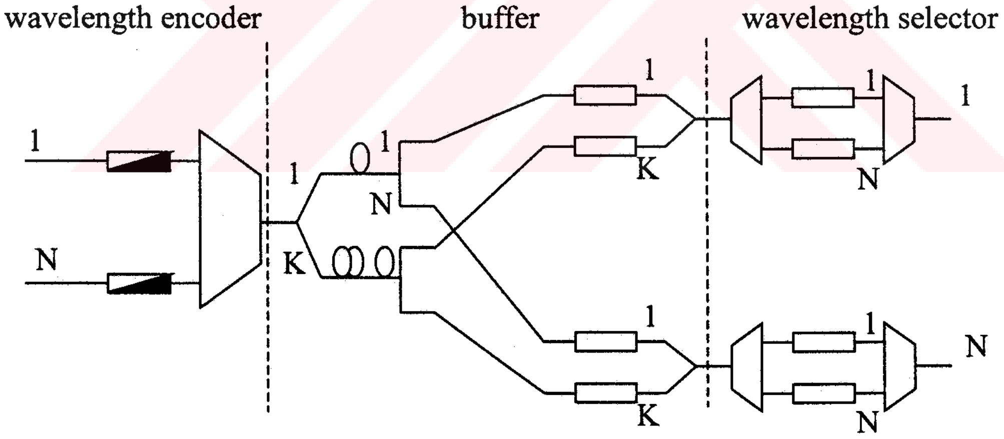


Figure 4.12 The KEOPS broadcast-and-select switch fabric

The switching fabric consists of three blocks: encoding, time-switching including buffering, and a wavelength selection block, respectively. The wavelength encoder block consists of N fixed wavelength converters, one per input. The buffer block consists of K fiber delay lines and a space switching stage. Finally, the wavelength selector block consists of *N* wavelength channel selectors implemented by demultiplexers and optical gates.

The switch converts the wavelength of the incoming packets to a fixed wavelength. Then all these wavelengths combined and distributed through the fiber delay lines having different delays. *KN* optical packets are directed to their destination output ports without any collisions. Demultiplexer breaks up the *N* wavelengths and chooses one to transmit out. A control unit manages all these operations in switch fabric.

Another broadcast-and-select type of switch was proposed using wavelength accessible recirculating loop buffers [41,43]. It is implemented through a coupler which combines up to *M* input wavelengths and then distributes the combined signal to *N* tunable optical filters (TOF) and *M* fixed optical filters (FOF) as shown in Figure 4.13.

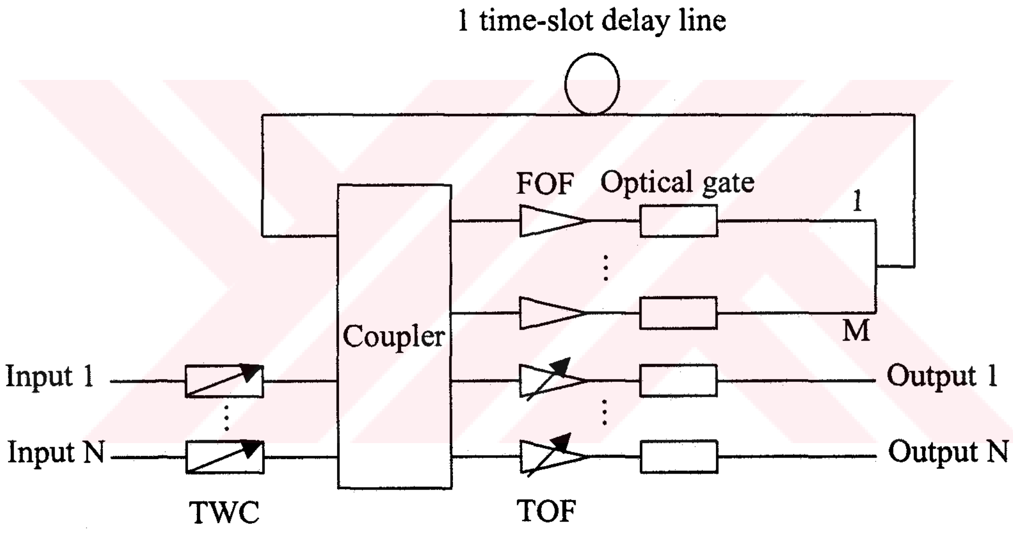


Figure 4.13 Broadcast-and-select switch with recirculation buffering

In this type of switch, up to *M* optical packets are fed using tunable wavelength converters (TWC) into the coupler, up to *N* of them are routed to the output ports while the remaining ones are recirculated in the 1 time-slot delay line to be fed back to the coupler at the beginning of the following slot.

Architectures also proposed on wavelength routing and various switches are established and used in projects. Frontiernet packet switch is one of them where Arrayed Waveguide Grating Multiplexer (AWGM) is used [41]. It is described as a photonic time division multiplexing interconnection network (highway switch) that uses optical frequency as routing information. It is used for large capacity packet switching nodes especially for photonic ATM switches. The advantages of it are its output-buffering scheme overcoming the bottleneck for contention resolution between input highways and no splitting loss as encountered in broadcasting star configuration [53].

In Wavelength Switched Packet NETwork (WASPNET) a switch was proposed in one part of the project depending on the AWG. It actually applies wavelength conversion plus buffering for contention resolution.

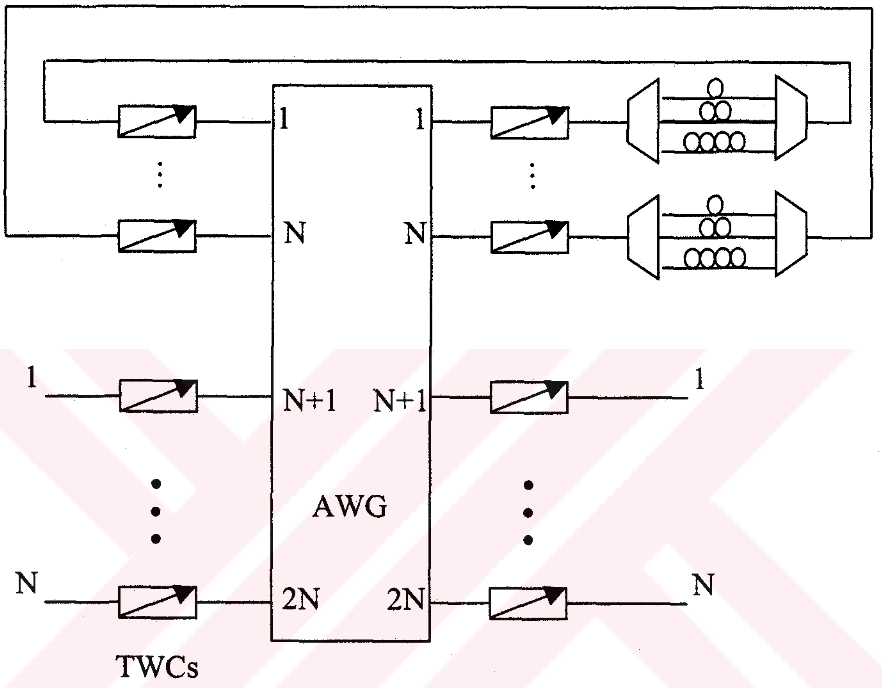


Figure 4.14 The WASPNET switch

The configuration of this switch is shown in Figure 4.14 where it consists of a $2N \times 2N$ AWG, *N* set of fiber delay lines and *4N* TWCs. The first *N* TWCs on the right of the AWG are used to select optical packets to be recirculated by the fiber delay lines to resolve contention. The other *N* TWCs are used to convert optical packets to the wavelengths required by the switch output interface depending on some kind of priority. Thus in WASPNET, not only design and routing, but also network control are considered. The SCattered Wavelength Path (SCWP) and SHared Wavelength Path (SHWP) schemes are the two network control methodologies that were identified. Also a WDM version of this switch architecture is proposed using demultiplexers and multiple planes of wavelength routing switch fabrics [43,54].

Another case of optical buffering is the fiber loop memory switch concept introduced in the Research and Development in Advanced Communications in Europe (RACE) Asynchronous Transfer Mode Optical Switching (ATMOS) project. The buffer is based on a fiber loop delay line containing multiple wavelength channels. Packets (cells) are routed based on their wavelengths and other information carried in the packet such as destination address. When contention occurs they are looped. When contention is resolved, the packet is switched to the destination link. Optical filters are adjusted to identify the correct cells for output [32,40,55].

The other models of switches such as Shared Memory Optical Packet (SMOP) switch, Switched fiber Delay Lines (SDL), COntention Resolution by Delay lines (CORD) and Switch with Large Optical Buffers (SLOB) are used in different architectures like WASPNET, ATMOS and KEOPS. Researches on photonic packet switching nodes are continuing with new projects and developments.

CHAPTER 5

OPTICAL ROUTING USING FIBER BRAGG GRATINGS

5.1 Introduction

The rapid increase in Internet traffic necessitates fast packet switching networks, and optical routing became an important issue after the wide use of optical transmission. Current trend in optical routing is based on wavelength division multiplexing which also increased the transmission bandwidth offered by fiber. In photonic packet switching, various schemes for optical routing are established as given in the previous chapter. The aim in all solutions is to accomplish fast switching with reliable, flexible, low noise and low power (energy) switching/routing architecture.

Like cross connects, multiplexers/demultiplexers, couplers and switches used in various photonic packet switching schemes, Fiber Bragg Gratings (FBGs) can be used as a switching/routing element. Recalling the advantages of FBGs as mentioned in Chapter 2 and using photonic packet switching issues (e.g. header recognition and replacement) as summarized in Chapter 4, a routing model using FBGs is proposed. In this chapter, the proposed routing model will be presented and the results of the simulations will be given, respectively.

5.2 The Proposed Routing Model

As in other switching/routing models, transmission speed is the most important function to be taken care in designing phase. In this respect, there are three levels of speed introduced: packet level, bit level and routing table updating. Naturally, the aim is to realize packet switching to be fast as possible. Bit level switching is required only for header recognition, which has to extract header bits fast enough. However, the processing of header bits may be rather slow unless processing time is no longer than one packet duration. On the other hand, routing table updates may be relatively slow and might be performed in electronic domain without slowing down the switching time of the router.

For the routing model, the switch architecture is designed which basic blocks of it are shown in the Figure 5.1. In this architecture, a packet arrives at the beam splitter (B/S) which puts the packet into two paths. In one path, the packet is sent to fiber delay lines where it will stay during the processing time. In the other path, the packet is directed to optical computing unit for processing. First the header bits are extracted in the header recognition (HR) unit and then converted from serial to parallel by S/P converter. Parallel bits are fed into the optical computing unit, responsible for decision and routing of the packet. Computing unit is composed of an array of Bragg grating assisted D-fibers, arrangable in multilayer configuration. Grating is modified by semiconductor laser arrays, which are controlled by the control unit as to update routing table information. This unit also controls optical computing unit output, driving the output switch to select the desired route.

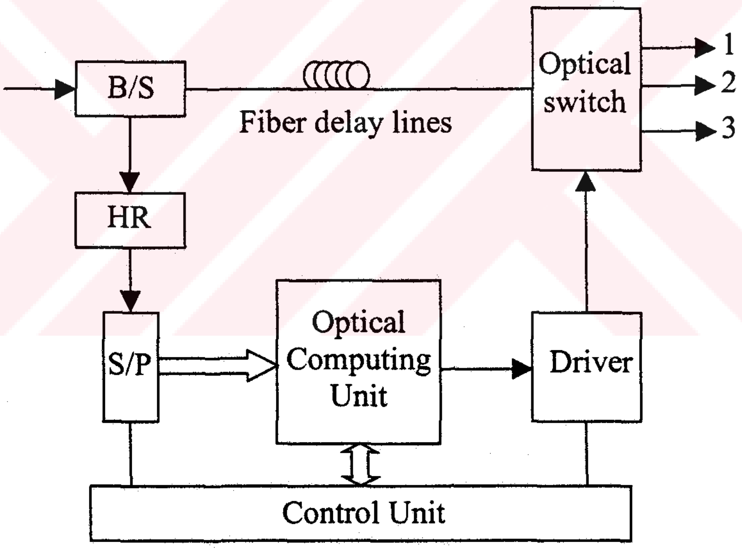


Figure 5.1 Basic blocks of switch model

For the simulation in optical domain, VirtualPhotonics's Photonic Transmission Design Suite (PTDS) is used. Its general view and the simulated project worksheet can be seen in Figure 5.2.

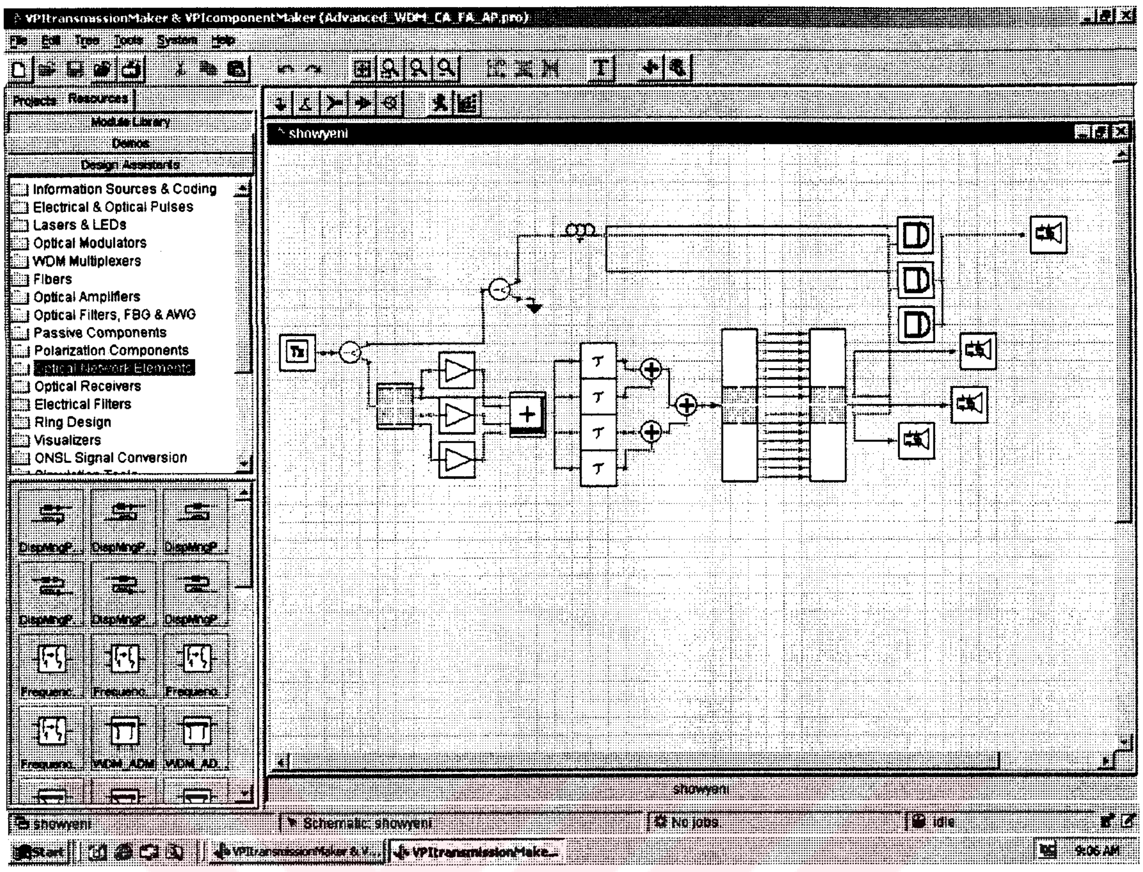


Figure 5.2 General view of the simulator

In the simulation, the system is designed for four bits of header information. These bits are used to route the packet through three different outputs as shown in Figure 5.3. Randomly selected groups of inputs are routed to the outputs as defined in the Table 5.1. Outputs are observed by the visualizers.

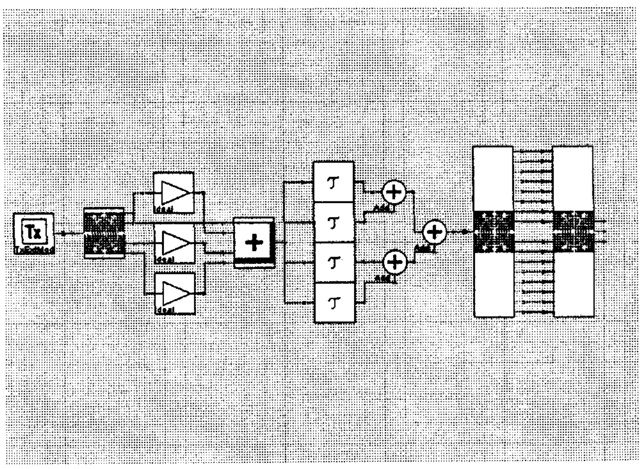
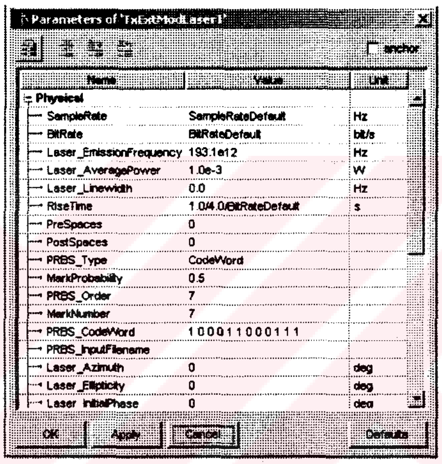


Figure 5.3 System designed for three outputs

Table 5.1 Inputs routed to different outputs

Inputs	Outputs
0001, 0101, 1001, 1100	1
0010, 0110, 1000, 1010, 1101, 1110, 1111	2
0000, 0011, 0100, 0111, 1011	3

In the system, the recognized four bits of header information is simulated with the Tx External Modulated Laser source with 1mW average power where bits are written in the codeword of the module as shown in Figure 5.4.



Name	Value	Unit
Physical		
SampleRate	SampleRateDefault	Hz
BitRate	BitRateDefault	bit/s
Laser_EmissionFrequency	193.1e12	Hz
Laser_AveragePower	1.0e-3	W
Laser_Linewidth	0.0	Hz
RiseTime	1.0/4.0/BitRateDefault	s
PreSpaces	0	
PostSpaces	0	
PRBS_Type	CodeWord	
MarkProbability	0.5	
PRBS_Order	7	
MarkNumber	7	
PRBS_CodeWord	1 0 0 0 1 1 0 0 0 1 1 1	
PRBS_InputFilename		
Laser_Azimuth	0	deg
Laser_Ellipticity	0	deg
Laser_InitialPhase	0	deg

Figure 5.4 Parameters of laser source Tx

These bits are converted from serial to parallel by S/P converter as shown in Figure 5.5.

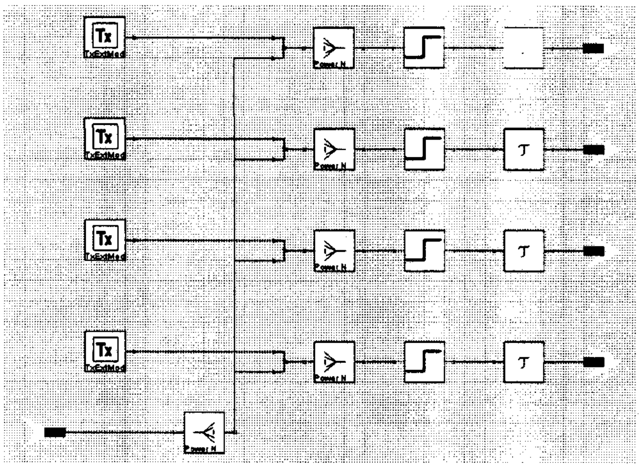


Figure 5.5 Serial-to-parallel converter

The paralleled four bits are converted to decimal by the gain blocks tuned to 1, 2, 4 and 8 mW and the adder unit is used (Figure 5.6) to obtain the overall power value of the input bits (e.g. binary 1001 to decimal 9 mW).

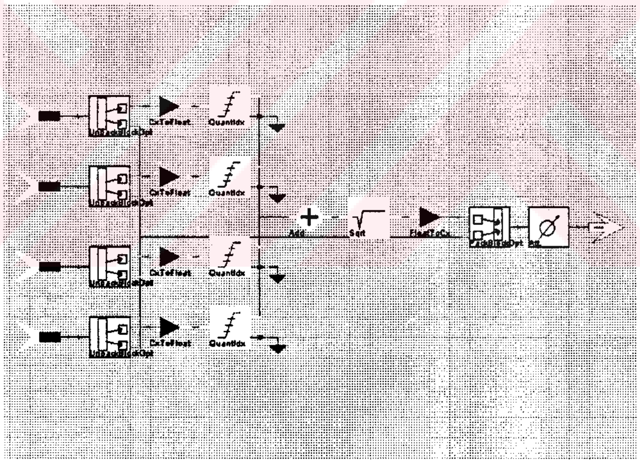


Figure 5.6 Adder

Then, selector unit (Figure 5.7) is used to assign this decimal power level to corresponding output at the constant 1 mW power level.

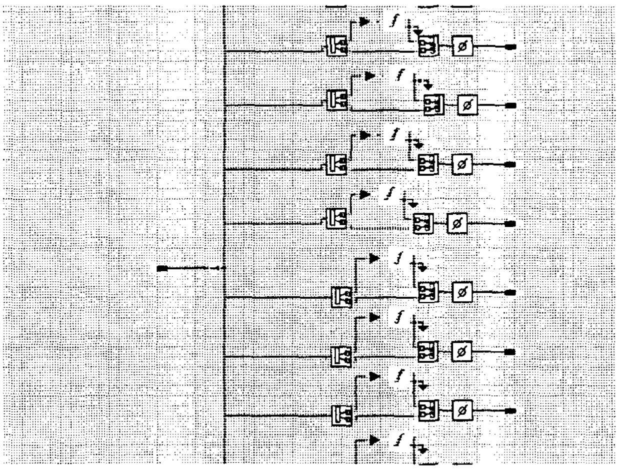


Figure 5.7 Selector

The selected input entering the grating block drives the proper grating (one of sixteen) and this block is designed to route through the outputs according to the Table 5.1.

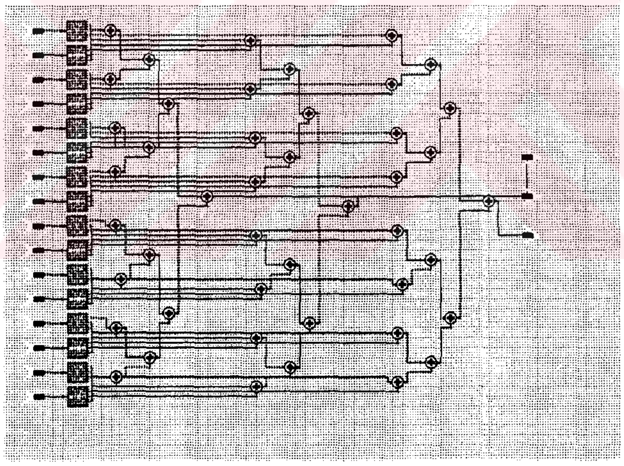


Figure 5.8 Grating and routing block

Each of the grating blocks has three outputs selecting the proper output (Figure 5.9) and simulated by three gratings which one of them is shown in Figure 5.10.

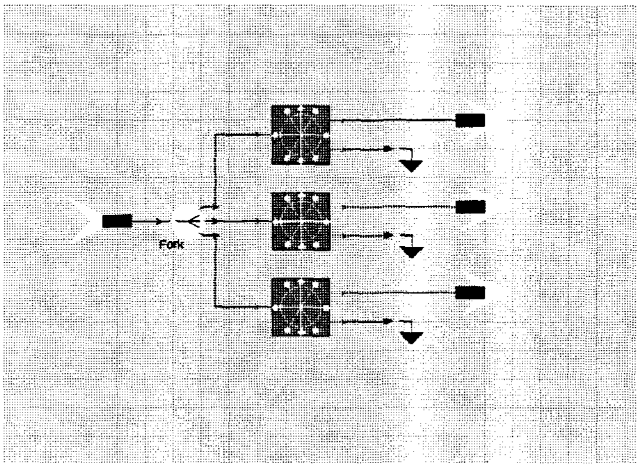


Figure 5.9 Grating blocks selecting proper output

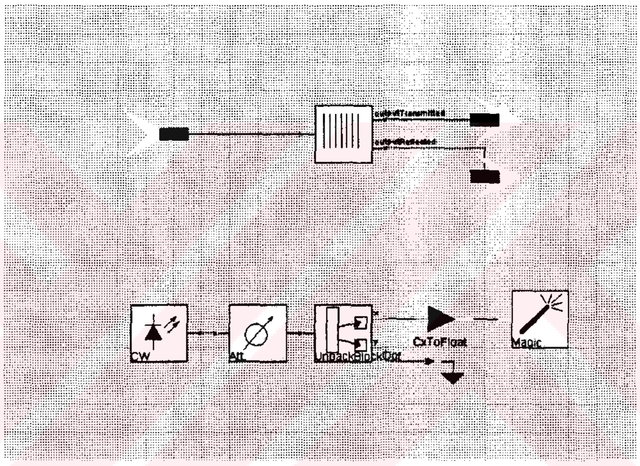
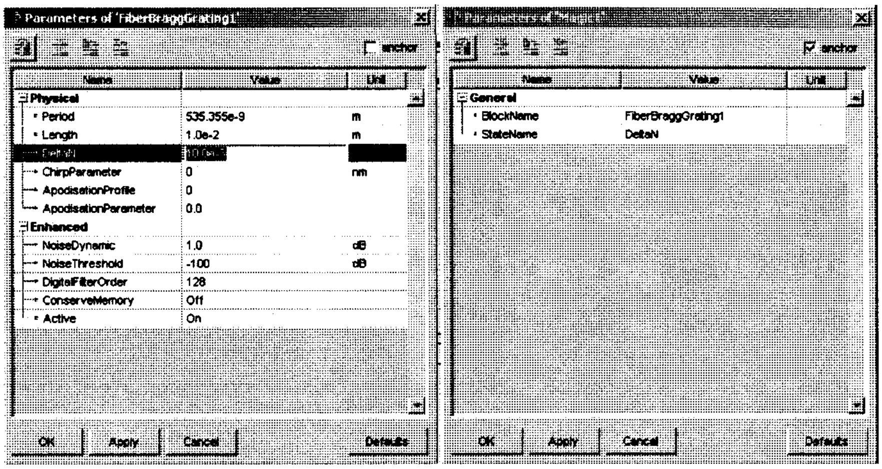


Figure 5.10 Structure of a grating block

In this structure, continuous laser source is used to control the refractive index of the grating by a simulation tool called magic. By defining the DeltaN (refractive index change) value to be controlled by magic as shown in Figure 5.11, grating can be used as a switch depending on the value entered to the magic by the laser source. When there is no value (DeltaN=0), all the input power given to the grating will be transmitted, no reflection will be seen. Otherwise, depending on the value of DeltaN, some of the power will be transmitted and some of the power will be reflected. But after a certain value (simulated as 10^{-3}), all the input power will be reflected and no transmission will occur. Using this phenomenon, transmitted power can be transferred/routed to the desired destination.



Name	Value	Unit
Physical		
Period	535.355e-9	m
Length	1.0e-2	m
DeltaN	[illegible]	
ChirpParameter	0	nm
ApodisationProfile	0	
ApodisationParameter	0.0	
Enhanced		
NoiseDynamic	1.0	dB
NoiseThreshold	-100	dB
DigitalFilterOrder	128	
ConserveMemory	Off	
Active	On	

Name	Value	Unit
General		
BlockName	FiberBraggGrating1	
StateName	DeltaN	

Figure 5.11 Parameters of magic and grating

For the simulation examples, four bits of information is given and results are visualized in each step. For input given as 11 (binary 1011) as shown in Figure 5.12, results for each step are obtained as following:

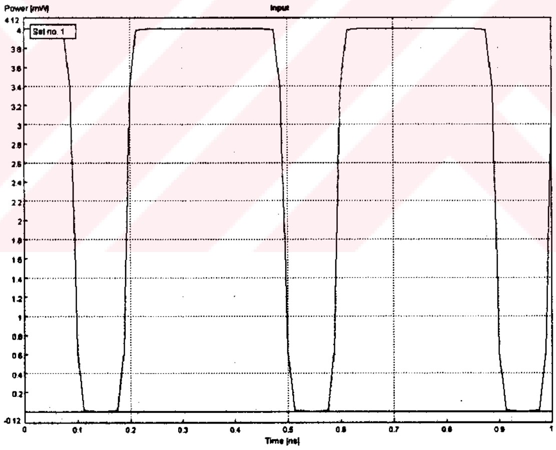
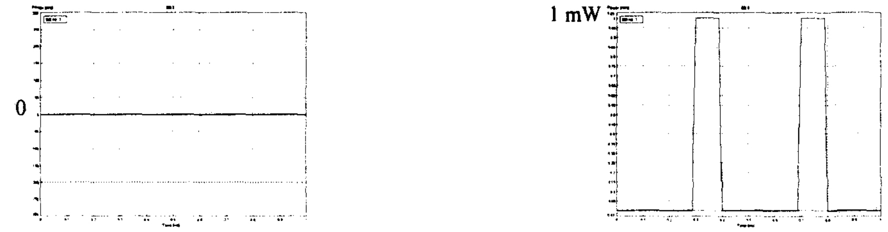


Figure 5.12 Input 11 (binary 1011)

Each of the paralleled bits (from least significant (bit 0) to most significant (bit 3) take the value 1mW according to the input.

Bit 0 Bit 1



Bit 2 Bit 3

Figure 5.13 Input 11: Bit 0,1,2 and 3

Each bit is multiplied by a gain factor depending on their significance. Bit 0 is multiplied by 1 while bit 1 is multiplied by 2, bit 2 is multiplied by 4 and bit 3 is multiplied by 8. Thus, after converting bits from serial to parallel, conversion from binary to decimal is accomplished by summing these with the adder unit. For the example 11, output of the adder is given in Figure 5.14. This figure shows the output as 11 mW in the time interval of each bit and then it is converted to the constant value (for four bits) to show the decimal value fed into the selector input.

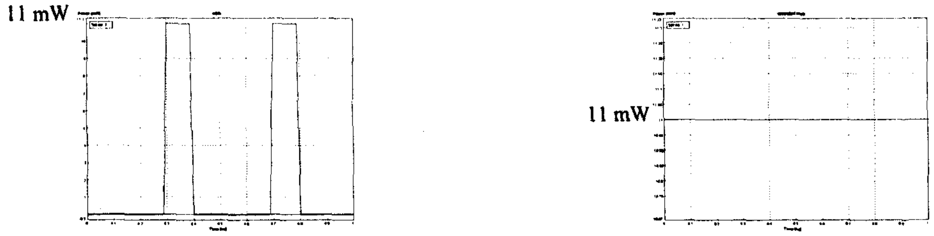


Figure 5.14 Input 11: Sum

To be sure, the selector outputs can be visualized. For “11”, the output gives 1 mW power while the others like “9” gives no output as expected and shown in Figure 5.15.

Figure 5.15 Input 11: Assigned 11 and assigned 9

After "11" is selected and routed by the grating module, outputs are obtained as in Figure 5.16. As given in Table 5.1, the output for 11 (binary 1011) should be 3. Simulation results shown in Figure 5.16 verify this suggestion by having the output 1 and output 2 as almost zero, and output 3 as 1 mW power.

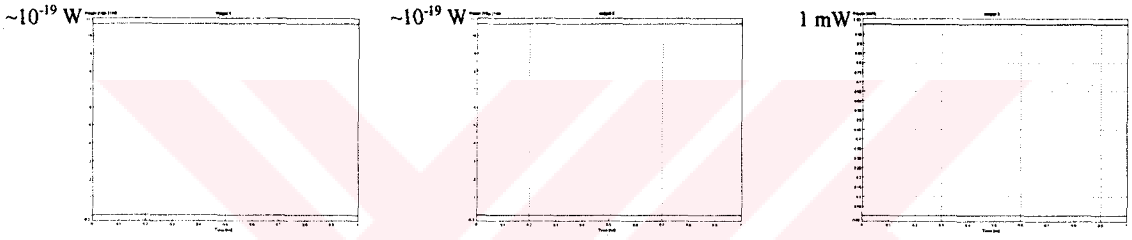


Figure 5.16 Input 11: Outputs 1,2 and 3

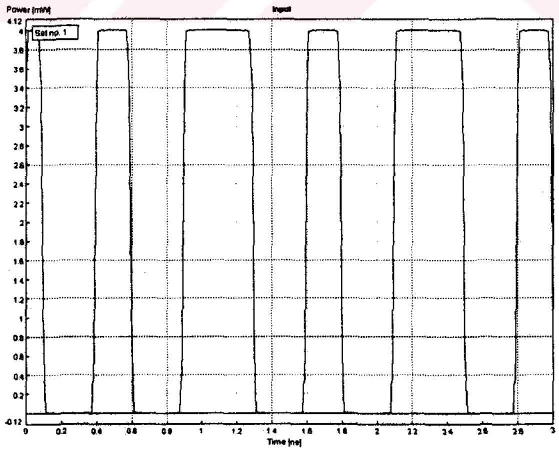


Figure 5.17 Input 8,12,7 (binary 1000, 1100, 0111)

As given in Figure 5.17, a more complicated example is simulated. This time 8,12 and 7 are given as inputs periodically and results of each step are visualized. The paralleled bits take the value 1 mW according to the input bits as shown in Figure 5.18.

Bit 0 Bit 1

Bit 2 Bit 3

Figure 5.18 Input 8,12,7: Bit 0,1,2 and 3

Then, conversion from binary to decimal value is realized for each input signal duration time. Discrete values are converted to continuous waveform where 8,12 and 7 mW signal values come consecutive as given in Figure 5.19.

Figure 5.19 Input 8,12,7: Sum

As to show the outputs of the selector unit, outputs 8,12 and 7 are visualized. 1 mW output power is detected in each of these outputs as expected and shown in Figure 5.20.

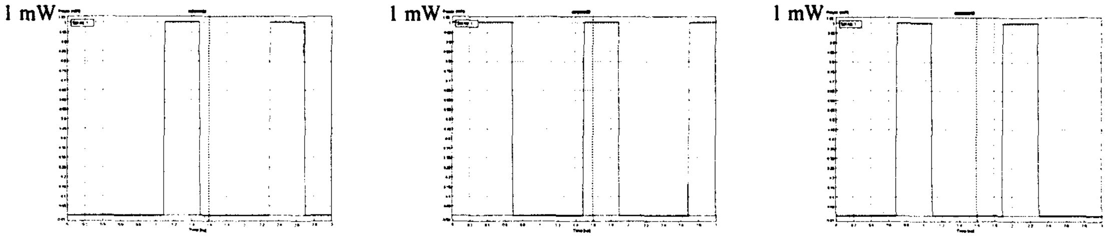
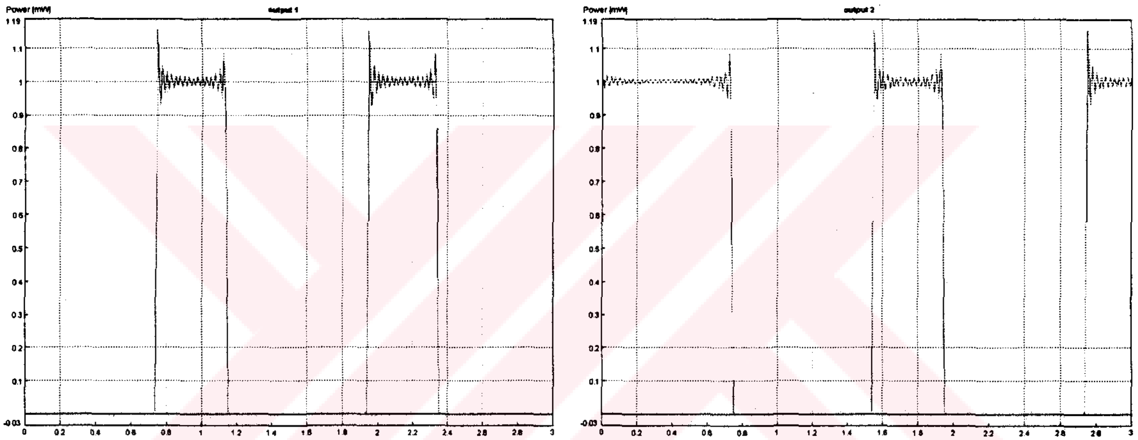


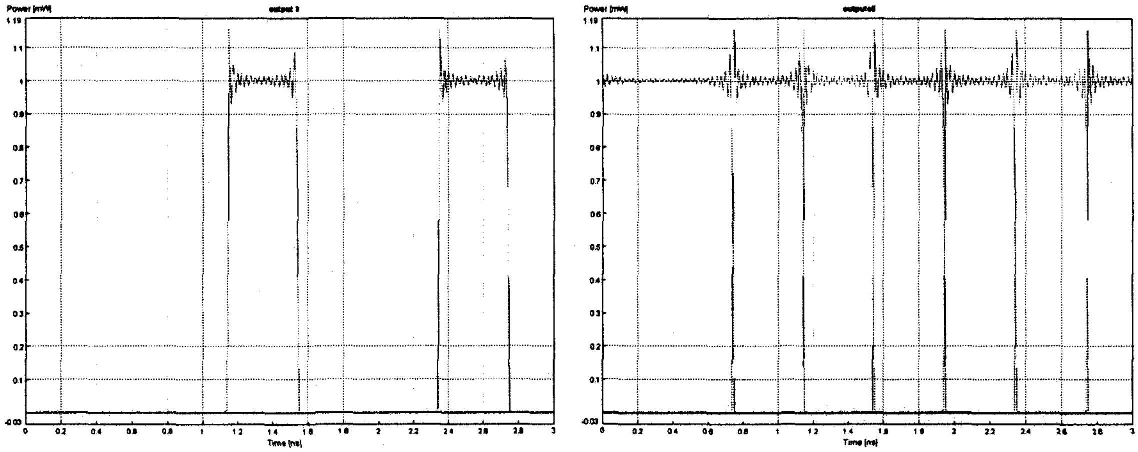
Figure 5.20 Input 8,12,7: Assigned 8,12,7

After selecting 8,12 and 7, the grating modules accomplish the routing process. Input 8 is routed to output 2, input 12 is routed to output 1 and input 7 is routed to output 3 as designed and given in Table 5.1.



Output 1

Output 2



Output 3

Output 1,2,3

Figure 5.21 Input 8,12,7: Outputs 1,2,3 individually and together

As it is stated before, transmission speed is an important function to be taken care. Thus, the overall transmission delay of the system has to be known. The packet and the routing information gathered from the header should arrive to the output switch at the same time. Therefore, the packet may have to be delayed until the processing of header is accomplished and the routing decision is done. This delay is realized and measured by using a fiber delay line which its length is adjusted according to the proper time delay. For this aim, a fiber delay line is introduced as shown in Figure 5.22 and its output is combined in an "and" gate with the outputs of the router. This "and" process corresponds to the jobs done by the driver and the optical switch, given in the switch architecture (Figure 5.1) selecting the output route.

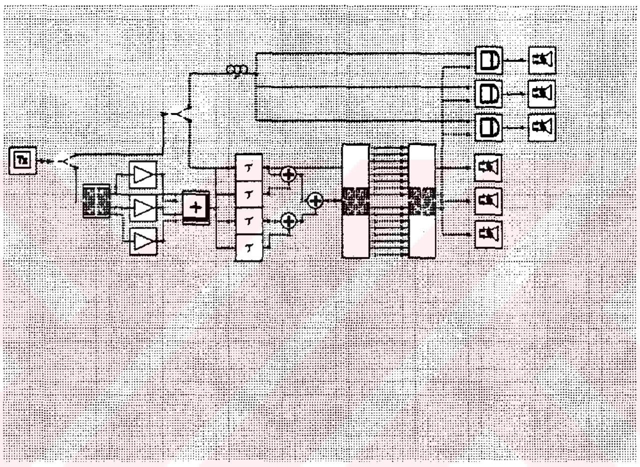


Figure 5.22 Delay measurement

The outputs of each "and" is given in Figure 5.23 where Figure 5.24 shows them together.

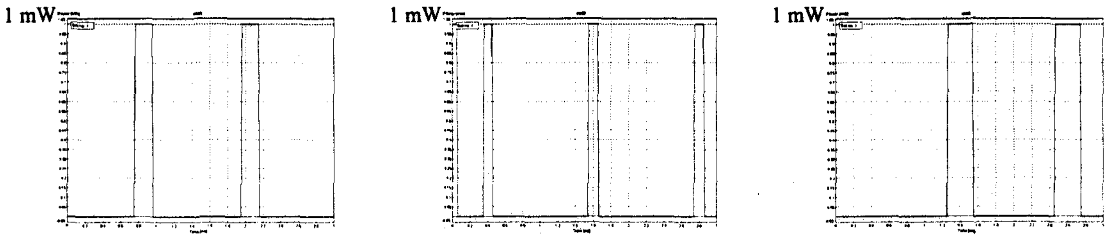


Figure 5.23 The outputs of "and" gate showing 8,12 and 7 individually

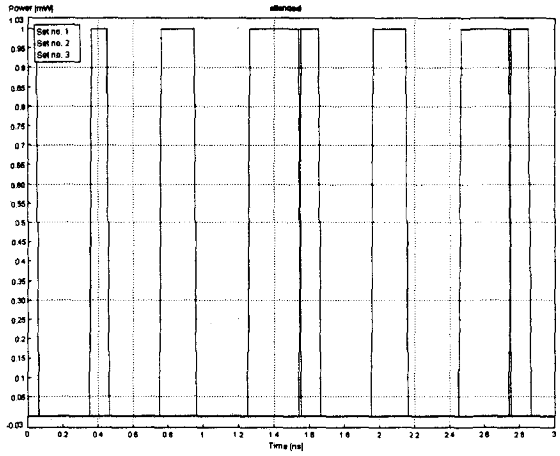
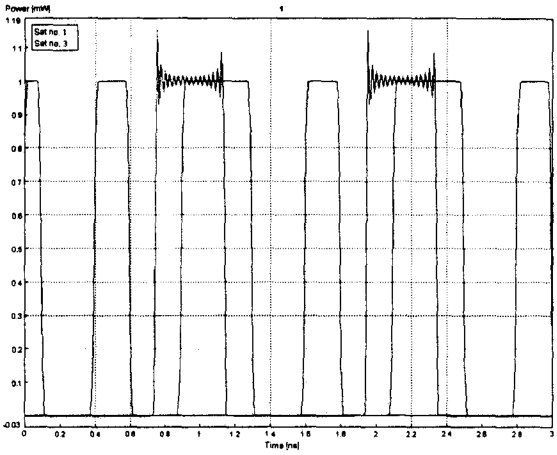


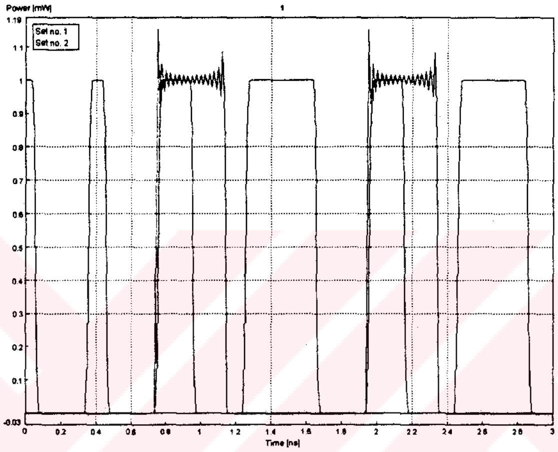
Figure 5.24 The output showing 8,12 and 7 together

The time delay can be seen by the following figures: without delay line and with delay line. When delay line is not used, the measured time delay for this input sequence is 0,36 ns. Then, fiber delay line length is set for 0,36 ns delay, the output is seen to be in phase with the input as in the Figure 5.25, shown for input 12 (binary 1100).

As a result, whatever the input is, the outputs of the router will show the corresponding route depending on the routing knowledge embedded in the grating modules. These modules can be controlled not only electronically but also optically as to change the routing algorithm or the routing table, so that any modification can be applicable. Also, it seems possible to have some iterative approaches such as optical neural networks where updating can be done dynamically.



Without delay line



With delay line set to 0,36 ns

Figure 5.25 The time delay comparison

CHAPTER 6

CONCLUSION

The necessity of switching and routing to take place in optical domain becomes more and more desirable in today's ever-growing ultra fast packet switched networks. There are various schemes proposed for faster switching/routing of data in achieving all-optical aim. In this thesis another scheme that can be used for optical routing is proposed.

In the thesis, a fiber Bragg grating based switching/routing scheme is presented for packet switched networks. The Photonic Transmission Design Suite (PTDS) software of Virtual Photonics is used for simulating the network. While using the software, several problems are encountered and several difficulties are overcome. Most simulation parameters such as noise, apodisation and chirp are used in their default values as well as the general parameters of the software. Some of the modules are combined to obtain the necessary bigger modules (called galaxies) as in serial-to-parallel converter, adder and the selector unit where proper outputs are assigned according to inputs. In each module, the signal types (optical, electrical, integer, float, etc.) are carefully inspected and conversions are done successfully when necessary.

The manipulation of gratings done by the semiconductor laser sources that are actually real-time controlled, could not be shown. This is due to the impossibility of controlling the Tx laser sources with simulation tool, magic. Consequently, refractive index is modified using continuous-wave laser sources inside grating blocks thus controlling of the gratings and the updating of routing information is not so clear.

Other important issues should be discussed are time and power. The signal power used through the system is normalized to 1 mW level after each module and set to be in phase. Moreover, time delays are followed carefully to prevent wrong routing of data. Four bits of information made it easy to follow synchronization, while simulation is done in a periodic manner, as inputs are introduced and outputs are visualized as periodic signals.

Since the scheme is designed for four bits of information, number of modules, elements and connections used in simulation are not limited. It is obvious that for largescale routing scheme, not only the number of elements or modules but also the connectivity between elements has to be considered. For the proposed scheme, 16 probable addresses can be routed. Thus the selector unit requires 16 nodes to assign one at a time. However when the system is generalized for routing depending on 32 bit IP addresses, then the quantity of nodes and connections will become a problem. To solve this problem, the scheme can be scaled to 8 bits where each one of the four 8 bits is used independently for subnetting IP addresses to classes. Classless routing can also be applied using different number of bits in the proposed scheme. On the other hand, integrated optics technologies can be used where usage and cost are important parameters for manufacturing side of view.

As a conclusion, with gratings controlling all possible routes, routing of data is simplified to classifying of header bits. It is foreseen that an iterative approach can be used and an optical neural network using the analogy between "weights" and "gratings" can realize this classification. Therefore, an optical neural classifier/router can be formed where routing depending on header bits will be based on the structure (number of neurons and layers, threshold function, training algorithm, etc.) of this neural network. Routing information update can be done in optical domain; thus all-optical packet switching can be achieved.

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