A Novel Method Of Routing In All-Optical Packet Switched Networks

By

Bora MOCAN

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

MASTER OF SCIENCE

Department: Electrical and Electronics Engineering
Major: Electronics and Communication

İzmir Institute of Technology
İzmir, Turkey

August, 2002

We approve the thesis of **Bora MOCAN**

Date of Signature

.... **19.08.2002**

Assist. Prof. Dr. Mehmet Salih DİNLEYİCİ
Supervisor
Department of Electrical and Electronics Engineering

.... **19.08.2002**

Assist. Prof. Dr. H. Sami SÖZÜER
Department of Pyhsics

.... **19.08.2002**

Assist. Prof. Dr. Damla KUNTALP
Dokuz Eylül University
Department of Electrical and Electronics Engineering

.... **19.08.2002**

Prof. Dr. Ferit Acar SAVACI
Head of Department

ACKNOWLEDGEMENT

I would like to acknowledge the following people who helped me put the thesis together.

I would like to thank my supervisor, Asst. Prof. Dr. Mehmet Salih Dinleyici for his support and guidance throughout my research. He made my job much easier so that I could concentrate totally on the subject. He provided invaluable assistance and patience during the creation of the thesis and he amazed me with his abilities.

Many people at İzmir Institute of Technology have helped me to make this thesis in success. I wish to express my special thanks to Alper Taban and my roommate Özgür Oruç; they helped me greatly by taking care of many details. Also, Funda Kurtdemir, and Erdal & Berna Özbek were always guiding me with their experience. I would like to thank Olcay Kalkan and Lalehan Candemir as well for their help.

Of course, this thesis would not have been possible without the unlimited understanding and patience of my family. They have lived through the long days and nights it took to complete this project, and have always been there with their love, trust and sacrifices. I thank you all.

And finally, my soulmate Zuhal, the source of my motivation and inspiration; I can only express my feelings to you by quoting the French poet De Ronsard: *"Deux corps mais une seule âme."*

ABSTRACT

Increasing bandwidth demand, driven by Internet Protocol (IP), let the communication industry change to IP-centric networks. To satisfy the needs, optical fiber communication links provides a usable transmission bandwidth of 25,000,000 MHz. Despite the huge potential of the optical links, electronic-based networking devices (Router, switch, repeater, etc.) act as bottlenecks of the system because of the material limitations of the electronics. Optical networks appear to be the solution of choice for providing faster networking infrastructure that can meet the explosive growth of the Internet.

This thesis discusses architectures and technology issues for the design of a high performance all-optical router. In particular, it focuses on the concept of an optical router for packet switched computer networks as an edge network device, functioning as an interface between autonomous systems.

A novel architecture is proposed and simulated by means of special software. Implementation problems and the limitations of the architecture are discussed in detail component by component.

ÖZ

İnternet protokolünün (IP) etkisiyle artan bant genişliği ihtiyacı haberleşme sistemlerinde IP merkezli bir değişime yol açmıştır. Fiberoptik iletişim hatları bize bu ihtiyacı karşılayabilecek 25,000,000 MHz büyüklüğünde kullanılabilir bir bant genişliği sunmaktadır. Optik hatların bu yüksek potansiyeline rağmen, elektronik tabanlı ağ elemanları (yönlendirici, anahtar, yineleyici, vb.) malzeme yapılarında doğan etkilerden ötürü sistemi sınırlayan başlıca faktörleri oluştururlar. Optik ağ yapıları, İnternet aracılığıyla artan büyümeyi daha hızlı ağ altyapıları sayesinde karşılayabilecek bir çözüm olarak görünmektedir.

Bu tezde, yüksek performanslı tamamen-optik bir yönlendirici için gerekli mimari ve teknolojik gereksinimler üzerinde durulmuştur. Otonom sistemler arasında bir arayüz vazifesi gören ve paket anahtarlamalı bilgisayar ağlarında bir köşetaşı olan yönlendirici kavramı üzerinde özellikle yoğunlaşılmıştır.

Tasarlanan yeni bir yönlendirici mimarisi özel bir simülasyon yazılımı yardımıyla, gerçeklenebilir elemanlar kullanılarak simüle edilmiştir. Bu özel mimarinin gerekliliği, uygulanabilirliği, avantajları ve sınırlayan faktörleri de detaylı bir şekilde gösterilmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

High-performance communication networks of today have evolved from an analog switched network to digitally packet switched networks. Greater demand of the public for even greater amounts of information exchange and wider bandwidths let this evolution and the technology improvements happen. With the use of fiber cables for communication networks they are undergoing rapid developments.

In the past, the largest networks were electronic, circuit switched networks providing plain-old telephone service (POTS), and carrying mostly voice traffic. Starting with the ARPANET and the explosive growth of the Internet and the worldwide web, electronic packet switched networks have become popular and dominate the networking technology. The rapid growth of these packet networks can be attributed to the efficiency of the internet protocol (IP) in servicing bursty traffic or computer users.

At the same time, we have seen a revolution in the transport technology that is used to interconnect nodes in a network. Specifically, fiber optic transmission technology has advanced from lower rate multi-mode fiber links to single-mode amplified fiber links capable of carrying multiple 10 Gb/s channels per fiber. This capacity has increased to Tb/s range with optical multiplexing techniques. Still, the incredible bandwidth offered by optical transmission technology has only been used as a very high-speed replacement of copper cables. The routing and switching technologies used are still electronic based and electronic network devices are bottlenecks for faster networks because of their material limitations. With the advent of advanced optical devices such as optical signal processing elements, integrated tunable lasers, optical routers, and cross-connect switches, a new class of optically routed and switched wavelength division multiplexing (WDM) or optical time division multiplexing (OTDM) network is feasible. Therefore optical means for router and routing purposes in optical networks opens a new era of all-optical network.

Optical technology has been inserted at the physical layer (bottom layer) of the typical Open System Interconnection (OSI) multi-layer protocol stack. A protocol transparent all-optical routing allows straightforward extension of existing networks into the optical regime, without any modification of the higher layers. However, such an architecture does not maximally utilize the advantages offered by optical networking.

A new architecture will be proposed in the thesis, which uses practical optical devices for routing purposes, takes advantage of the unique capabilities of optical networking technologies. Tight coordination is required due to the lack of optical buffers that can temporarily store packets before processing and routing. This property is key to optical data network protocol designs and presents interesting and sometimes severe constraints on network synchronization and end-to-end routing. With the availability of buffering at routers internal to the network, higher network efficiencies in terms of throughputs and delays can be achieved with an optical time division multiplexing scheme where the medium bandwidth is available to the packet in one large channel (100 Gb/s) instead of fragmented (WDM) channels. The decision information required for switching packets in this network would be contained in the packet header and no centralized or highly coordinated scheduler is required. Network management and control could be simpler and more efficient, especially in a bursty data environment. However, the technology needed to implement a network of this type is still in the research stage and some typical networking components may not be commercially feasible at ultra-fast rates . At a minimum, optical logic gates, threshold elements, ultra-fast pulse generators and buffering at the channel rate are necessary architectural building blocks. A demonstration of this OTDM network architecture is simulated using a special software (Virtual Photonics 3.1).

In this thesis, the tradeoffs between electronic and optical routing in packet switched networks will be described. Concentration points will be mainly the architectures and the components needed to implement such a network. Techniques, algorithms, applications and future trends in the optical routing architecture will be mentioned as well. Finally, a novel architecture will be recommended as a solution for packet switched computer networks. Components of the system are developed and demonstrated using a special software. The overall performance of the system was satisfactory and their realizations with current optical network seem possible.

CHAPTER 2

ROUTING IN PACKET SWITCHED COMPUTER NETWORKS

2.1 Routing Basics

This chapter introduces the underlying concepts widely used in standard routing protocols. Topics summarized here include routing protocol components and algorithms both in electronic and optical domain. In addition, the role of routing protocols is briefly contrasted with the roles of routed network protocols.

Routing is the act of moving information across an internetwork from a source to a destination, along the way; at least one intermediate node typically is encountered. The topic of routing has been known for more than two decades, but routing achieved commercial popularity as late as the mid of 1980s. Only recently has large-scale internetworking become popular.

2.2 Routing Components

Routing involves two basic activities: determining optimal routing paths and transporting information groups (typically called *packets*) through an internetwork. In the context of the routing process, the latter of these is referred to as *switching*. Although switching is relatively straightforward, path determination can be very complex.

2.2.1 Path Determination

A metric is a standard of measurement, such as path length, that is used by routing algorithms to determine the optimal path to a destination. To aid the process of path determination, routing algorithms initialize and maintain routing tables, which contain route information. Route information varies depending on the routing algorithm used.

Routing algorithms fill routing tables with a variety of information. Destination/next hop associations tell a router that a particular destination can be found optimally by sending the packet to a particular router representing the “next hop” on the way to the final destination. When a router receives an incoming packet, it checks the destination address and attempts to associate this address with a next hop. Table 2-1 depicts a sample destination/next hop routing table.

Routing tables also can contain other information, such as data about the desirability of a path. Routers compare metrics to determine optimal routes, and these metrics differ depending on the design of the routing algorithm used. A variety of common metrics can be used as decision criteria.

Routers communicate with one another and maintain their routing tables through the transmission of a variety of messages. The routing update message is one such message that generally consists of all or a portion of a routing table. By analyzing routing updates from all other routers, a router can build a detailed picture of network topology. A link-state advertisement, another example of a message sent between routers, informs other routers of the state of the sender’s links. Link information also can be used to build a complete picture of topology to enable routers to determine optimal routes to network destinations. Routing update messages and link state advertisements are exchanged between the routers that share the same topology every 30-120 sec. The time period of this algorithm depends on the routing protocol used [1].

Table 2.1 Destination/next hop associations determine the data’s optimal path.

To reach network:	*Send to:*
27	Node A
57	Node B
17	Node C
24	Node A
52	Node A
16	Node B
26	Node A
⋮	⋮

2.2.2 Switching

Switching algorithms are relatively simple and are basically the same for most routing protocols. In most cases, a host determines that it must send a packet to another host. Having acquired a router's address by some means, the source host sends a packet addressed specifically to a router's physical (Media Access Control (MAC)-layer) address, with the protocol (network layer) address of the destination host.As it examines the packet's destination protocol address, the router determines that it either knows or does not know how to forward the packet to the next hop. If the router does not know how to forward the packet, it typically drops the packet or forwards it to the default route. If the router knows how to forward the packet, it changes the destination physical address to that of the next hop and transmits the packet. The next hop may, in fact, be the destination host. If not, the next hop is usually another router, which executes the same switching decision process. As the packet moves through the internetwork, its physical address changes, but its protocol address remains constant, as illustrated in Figure 2-1.

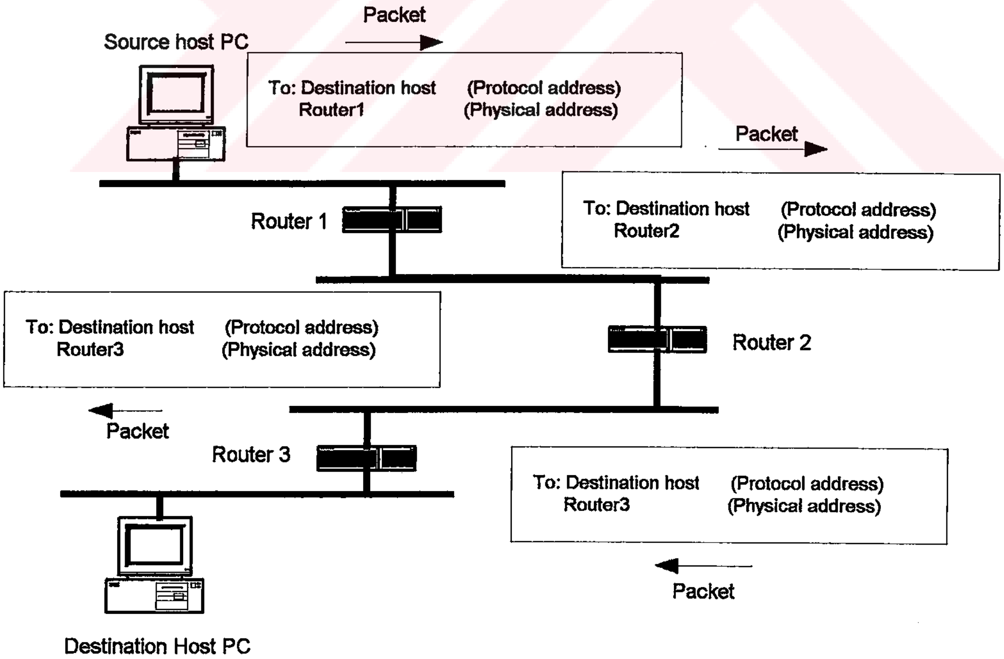

Figure 2.1 Numerous routers may come into play during the switching process.

The preceding discussion describes switching between a source and a destination end system. A routing domain generally is considered to be a portion of an internetwork under common administrative authority that is regulated by a particular set of administrative guidelines. Routing domains are also called autonomous systems. With certain protocols, routing domains can be divided into routing areas, but intra-domain routing protocols are still used for switching both within and between areas [2].

2.3 Network Protocols

Routed protocols are transported by routing protocols across an internetwork. In general, routed protocols in this context also are referred to as network protocols. These network protocols perform a variety of functions required for communication between user applications in source and destination devices, and these functions can differ widely among protocol suites. Network protocols occur at the upper four layers of the Open System Interconnection (OSI) reference model: the transport layer, the session layer, the presentation layer, and the application layer.

Confusion about the terms routed protocol and routing protocol is common. Routed protocols are protocols that are routed over an internetwork. Examples of such protocols are the Internet Protocol (IP), DECnet, AppleTalk, Novell NetWare, OSI, Banyan VINES, and Xerox Network System (XNS). Routing protocols, on the other hand, are protocols that implement routing algorithms. Put simply, routing protocols direct protocols through an internetwork. Examples of these protocols include Interior Gateway Routing Protocol (IGRP), Enhanced Interior Gateway Routing Protocol (Enhanced IGRP), Open Shortest Path First (OSPF), Exterior Gateway Protocol (EGP), Border Gateway Protocol (BGP), Intermediate System to Intermediate System (IS-IS), and Routing Information Protocol (RIP) [1,3].

2.4 Routing Algorithms

Routing algorithms can be classified based on several key characteristics. First, the particular goals of the algorithm designer affect the operation of the resulting routing protocol. Second, various types of routing algorithms exist, and each algorithm has a different impact on network and router resources. Finally, routing algorithms use a variety of metrics that affect calculation of optimal routes. The following sections analyze these routing algorithm attributes.

2.4.1 Design Goals

Routing algorithms often have one or more of the following design goals:

- Optimality
- Simplicity and low overhead
- Robustness and stability
- Rapid convergence
- Flexibility

Optimality refers to the capability of the routing algorithm to select the best route, which depends on the metrics and metric weightings used to make the calculation. One routing algorithm, for example, may use a number of hops and delays, but may weight delay more heavily in the calculation. Naturally, routing protocols must define their metric calculation algorithms strictly.

Routing algorithms also are designed to be as *simple* as possible. In other words, the routing algorithm must offer its functionality efficiently, with a *minimum of software and utilization overhead.* Efficiency is particularly important when the software implementing the routing algorithm must run on a computer with limited physical resources.

Routing algorithms must be *robust*, which means that they should perform correctly in the face of unusual or unforeseen circumstances, such as hardware failures, high load conditions, and incorrect implementations. Because routers are located at network junction points, they can cause considerable problems when they fail. The best routing algorithms are often those that have withstood the test of time and have proven *stable* under a variety of network conditions.

In addition, routing algorithms must *converge rapidly.* Convergence is the process of agreement, by all routers, on optimal routes. When a network event causes routes either to go down or become available, routers distribute routing update messages that permeate networks, stimulating recalculation of optimal routes and eventually causing all routers to agree on these routes. Routing algorithms that converge slowly can cause routing loops or network outages.

Routing algorithms should also be *flexible*, which means that they should quickly and accurately adapt to a variety of network circumstances. Assume, for example, that a network segment has gone down. As they become aware of the problem, many routing algorithms will quickly select the next-best path for all routes normally using that segment. Routing algorithms can be programmed to adapt to changes in network bandwidth, router queue size, and network delay, among other variables. [4]

2.4.2 Routing Algorithm Types

Routing algorithms can be classified by type as mentioned in Ref. [1,4,5] and also important points are given in the next section.

2.4.2.1 Static and Dynamic Routing Algorithms

Static routing algorithms are table mappings established by the network administrator prior to the beginning of routing. These mappings do not change unless the network administrator alters them. Algorithms that use static routes are simple to design and work well in environments where network traffic is relatively predictable and where network design is relatively simple.

Because static routing systems cannot react to network changes, they generally are considered unsuitable for today's large, changing networks. Most of the dominant routing algorithms in the last decade are dynamic routing algorithms, which adjust to changing network circumstances by analyzing incoming routing update messages. If the message indicates that a network change has occurred, the routing software recalculates routes and sends out new routing update messages. These messages permeate the network, stimulating routers to rerun their algorithms and change their routing tables accordingly.

Dynamic routing algorithms can be supplemented with static routes where appropriate. A router of last resort (a router to which all unroutable packets are sent), for example, can be designated to act as a repository for all unroutable packets, ensuring that all messages are at least handled in some way.

2.4.2.2 Single-Path and Multipath Routing Algorithms

Some sophisticated routing protocols support multiple paths to the same destination. Unlike single-path algorithms, these multipath algorithms permit traffic multiplexing over multiple lines. The advantages of multipath algorithms are obvious: They can provide substantially better throughput and reliability.

2.4.2.3 Flat and Hierarchical Routing Algorithms

Some routing algorithms operate in a flat space, while others use routing hierarchies. In a flat routing system, the routers are peers of all others. In a hierarchical routing system, some routers form what amounts to a routing backbone. Packets from non-backbone routers travel to the backbone routers, where they are sent through the backbone until they reach the general area of the destination. At this point, they travel from the last backbone router through one or more non-backbone routers to the final destination.

Routing systems often designate logical groups of nodes, called domains, autonomous systems, or areas. In hierarchical systems, some routers in a domain can communicate with routers in other domains, while others can communicate only with routers within their domain. In very large networks, additional hierarchical levels may exist, with routers at the highest hierarchical level forming the routing backbone.

The primary advantage of hierarchical routing is that it copies the organization of most companies and therefore supports their traffic patterns well. Most network communication occurs within small company groups (domains). Because intra-domain routers need to know only about other routers within their domain, their routing algorithms can be simplified, and, depending on the routing algorithm being used, routing update traffic can be reduced accordingly.

2.4.2.4 Host-Intelligent and Router-Intelligent Routing Algorithms

Some routing algorithms assume that the source end-node will determine the entire route. This is usually referred to as source routing. In source-routing systems, routers merely act as store-and-forward devices, mindlessly sending the packet to the next stop. Other algorithms assume that hosts know nothing about routes. In these algorithms, routers determine the path through the internetwork based on their own calculations. In the first system, the hosts have the routing intelligence. In the latter system, routers have the routing intelligence.

The trade-off between host-intelligent and router-intelligent routing is one of path optimality versus traffic overhead. Host-intelligent systems choose the better routes more often, because they typically discover all possible routes to the destination before the packet is actually sent. They then choose the best path based on that particular system's definition of "optimal." The act of determining all routes, however, often requires substantial discovery traffic and a significant amount of time.

2.4.2.5 Intradomain and Interdomain Routing Algorithms

Some routing algorithms work only within domains; others work within and between domains. The nature of these two algorithm types is different. It stands to reason, therefore, that an optimal intra-domain- routing algorithm would not necessarily be an optimal inter-domain- routing algorithm.

The routing table size for an intradomain router is typically between 200 and 3000. It depends on the specifications of the autonomous system. The use of the term Autonomous System (AS) here stresses the fact that, even when multiple Interior Gateway Protocols (IGP) and metrics are used, the administration of an AS appears to other AS's to have a single coherent interior routing plan and presents a consistent picture of what destinations are reachable through it. Based on AS path, longer prefixes are announced for local traffic engineering purposes.

2.4.2.6 Link State and Distance Vector Routing Algorithms

Link- state algorithms (also known as shortest path first algorithms) flood routing information to all nodes in the internetwork. Each router, however, sends only the portion of the routing table that describes the state of its own links. Distance- vector algorithms (also known as Bellman-Ford algorithms) call for each router to send all or some portion of its routing table, but only to its neighbors. In essence, link- state algorithms send small updates everywhere, while distance- vector algorithms send larger updates only to neighboring routers.

Because they converge more quickly, link- state algorithms are somewhat less prone to routing loops than distance- vector algorithms. On the other hand, link- state algorithms require more CPU power and memory than distance vector algorithms. Link-state algorithms, therefore, can be more expensive to implement and support. Despite their differences, both algorithm types perform well in most circumstances.

2.4.3 Routing Metrics

Routing tables contain information used by switching software to select the best route. But how, specifically, are routing tables built? What is the specific nature of the information they contain? How do routing algorithms determine that one route is preferable to others? Routing algorithms have used many different metrics to determine the best route. Sophisticated routing algorithms can base route selection on multiple metrics, combining them in a single (hybrid) metric. All the following metrics have been used:

- Path Length
- Reliability
- Delay
- Bandwidth
- Load
- Communication Cost

Path length is the most common routing metric. Some routing protocols allow network administrators to assign arbitrary costs to each network link. In this case, path length is the sum of the costs associated with each link traversed. Other routing protocols define hop count, a metric that specifies the number of passes through internetworking products, such as routers, that a packet must take en route from a source to a destination.

Reliability, in the context of routing algorithms, refers to the dependability (usually described in terms of the bit-error rate) of each network link. Some network links might go down more often than others. After a network fails, certain network links might be repaired more easily or more quickly than other links. Network administrators can take any reliability factors into account in the assignment of the reliability ratings, which are arbitrary numeric values usually assigned to network links.

Routing delay refers to the length of time required to move a packet from source to destination through the internetwork. Delay depends on many factors, including the bandwidth of intermediate network links, the port queues at each router along the way, network congestion on all intermediate network links, and the physical distance to be traveled. Because delay is a conglomeration of several important variables, it is a common and useful metric.

Bandwidth refers to the available traffic capacity of a link. All other things being equal, a 10-Mbps Ethernet link would be preferable to a 64-kbps leased line. Although bandwidth is a rating of the maximum attainable throughput on a link, routes through links with greater bandwidth do not necessarily provide better routes than routes through slower links. If, for example, a faster link is busier, the actual time required to send a packet to the destination could be greater.

Load refers to the degree to which a network resource, such as a router, is busy. Load can be calculated in a variety of ways, including CPU utilization and packets processed per second. Monitoring these parameters on a continual basis can be resource-intensive itself.

Communication cost is another important metric, especially because some companies may not care about performance as much as they care about operating expenditures. Even though line delay may be longer, they will send packets over their own lines rather than through the public lines that cost money for usage time [1].

2.5. Internet Success And Limitation

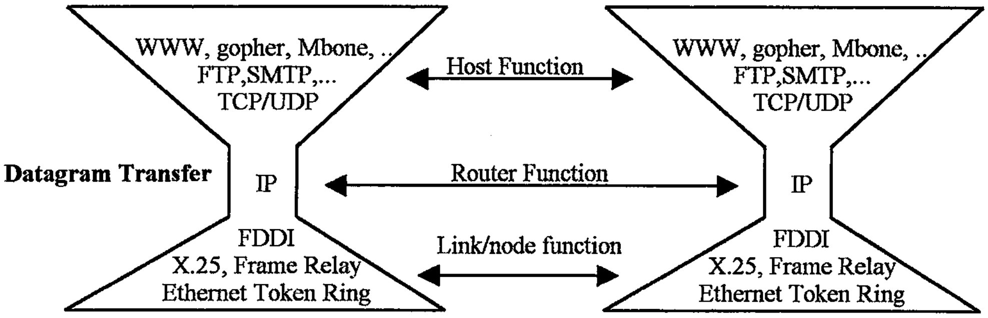

Figure 2.2 Internet Implementation of the Open Data Network Model

Internet suite of protocols is organized in a multilayered architecture resembling the seven-layer OSI model. Figure 2.2 summarizes both of these aspects. It lists the different protocols in a manner that shows their layered dependence and how those layers are related to the OSI model [6,7].

The narrow ''waist'' of the figure represents the single and IP bearer service: the end-to-end transport of IP datagrams. This service can be provided by routers capable of the basic tasks of storing packets and routing them to appropriate outgoing links after consulting a routing table. Most significantly there are no performance requirements, so that slow and old routers can coexist with new, high-performance routers. This "backward compatibility" is enormously valuable and explains why networks with widely differing performance can be interconnected. Domain names and IP addresses are assigned on a decentralized basis, so network growth is opportunistic rather than planned. The benefits of connecting to the Internet grow with its size at the same time as equipment costs (LANs, links, computers) decline because of scale economies, resulting in a doubling of the size of the Internet each year.

The brilliance of the IP design lies in its simplicity: because IP datagrams are self-contained, routers do not need or keep any state information about those datagrams. As a result, the network becomes very robust. If a router fails, datagrams in the router may be lost, but new datagrams would automatically be routed properly, with no special procedures. (By contrast, if the bearer services were connection-oriented like ATM, routers would have to maintain connection-state information, and if a router were to fail, that state information would be lost, making it very difficult to restore the connection.) Simple rules in routers can help route traffic around congested parts of the network, giving the network the capability to adapt to changes in traffic.

The third feature of the figure (its wide top) represents the rich variety of applications that the IP bearer service, together with UDP and TCP, can support. The last decade of successful, sophisticated applications like the World Wide Web has shown that UDP/IP datagram service and TCP/IP reliable, byte-stream can serve as building blocks for complex services, provided that the end hosts are sophisticated.

The most remarkable aspect of this feature is that the application software resides entirely in the end hosts and not in the routers. This means that the same basic service, implemented by simple routers, can support these sophisticated applications. Thus the network hardware and software have a much longer technical and economic life than does the end host. Indeed, in the mid 1990s, significant numbers of Internet routers are 15 to 20 years old. This also implies that parts of the Internet can experiment with new applications on advanced hosts using the real network, while other parts of the

Internet continue undisturbed to run old applications on primitive host. This ability to experiment with new applications has greatly helped the proliferation of new applications.

Thus the technical basis for the Internet's success is its reliance on simple routers to transfer individual datagrams and on advanced end hosts to run sophisticated applications. The simple infrastructure is compatible with a wide range of applications. The developers of successful applications can distribute them for fame or profit, without requiring any change from the infrastructure. The contrast with the telephone network could not be more striking. There the network "intelligence" is located in its expensive switches, while the end hosts (the telephone sets) are primitive, with little functionality. The introduction of new services requires changes in the infrastructure –changes that are slow and expensive. Hence experiments are costly and infrequent, and new services are introduced after much deliberation and planning.

The limitations of the Internet can be foreseen from the Figure 2.2. The IP bearer service cannot provide any guarantees in terms of delay or bandwidth or loss. Routers treat all packets in the same way. (This "equal service for all" is perhaps ironically, called *best-effort service.*). This is an innate feature: the absence of state information means that packets can not differentiated by their application or connection, and so routers will be unable to provide additional resources to more demanding applications.

The technical challenge is to expand the services offered by UDP/TCP and IP to provide guarantees in away that preserves the Internet's accommodation of backward compatibility and incremental change. Some recent proposals will be discussed to meet this challenge [8].

CHAPTER 3

OPTICAL TECHNIQUES FOR OPTICAL NETWORK DEVICES

Present day electronic signal processing speeds have fallen far behind the capabilities of both optical time division (OTDM) and wavelength division (WDM, DWDM) multiplexed systems. All-optical signal processing techniques and tools could meet the requirements of the technology.

Single-mode optical fibers have a usable transmission bandwidth of 25,000GHz (i.e., 25 THz) around the 1.55 μm wavelength with a very low attenuation of 0.2 dB/km. Dispersion-shifted single-mode fibers have made ultra-high-speed transmission systems and very high-capacity networks possible for communication applications. However, the use of conventional electronic processing and electrooptic/optoelectronic interfaces places limitations on the processing speed of optical transmitter and receiver. This in turn prevents to take advantage of such a huge bandwidth offered by optical fibers. To eliminate the throughput bottleneck, optical signal processing techniques should be exploited for high-capacity communication networks.

Therefore, future optical fiber networks will be able to perform signal transmission, processing, detection, and regeneration in the optical domain where the transmission bandwidth can support bit rates in excess of 100’s Gbit/s. It means that optical fiber networks using optical processing can achieve an ultrahigh throughput, which is far beyond requirements of today's telecommunications. In this chapter, a number of optical techniques, which are vital for the all-optical routing, will be introduced. Kerr-Effect threshold elements, ultra-short OTDM pulse generators, optical logic gates, Bragg grating filters and Erbium Doped Fiber Amplifiers will be discussed in detail.

3.1 Nonlinear Properties of Optical Materials

Nonlinearity is an important aspect to construct optical signal processing devices. Many optical devices rely on the nonlinear characteristics of the materials. The optics, including the processes of transmission, reflection, refraction, superposition and birefringence, fall in the category of what is called *linear optics*. Linear optics can be described by a linear wave equation and an optical disturbance propagating through an optical medium. As a consequence of this assumption, two harmonic waves in the medium obey the principle of superposition, traveling without distortion due to the medium itself or as a result of the mutual interference of the waves, regardless of the intensity of the light. Only the wavelength and the velocity of a light beam in a transparent material are required to describe its behavior.

As known, when the light intensity becomes strong enough, linear optics is not adequate to describe the situation. With the advent of the more intense and coherent light made available by the laser, the optical properties of the medium, such as its refractive index, become a function of the intensity of the light. When two or more light waves interfere within the medium, the principle of superposition no longer holds. The light waves interact with one another via the medium. These *nonlinear* phenomena require an extension of the linear theory that allows for a nonlinear response of optical materials to the electromagnetic radiation.

Nonlinear phenomena have important applications in optical signal processing. Using the nonlinear characteristic of the materials different kind of optical elements could be realized in optical domain. Threshold elements, Bragg grating applications, optical switches and optical logic gates relies on this manner.

Table 3.1 Linear And Nonlinear Processes

Linear first order: $P_1=\varepsilon_0\chi_1E$	*Nonlinear second order:* $P_2=\varepsilon_0\chi_2E^2$	*Nonlinear third order:* $P_2=\varepsilon_0\chi_3E^3$
Classical optics:	Materials lacking inversion symmetry:	Third harmonic generation
Superposition	Second harmonic generation	Four-wave mixing
Reflection	Three-wave mixing	Kerr effect
Refraction	Optical rectification	Raman scattering
Birefringence	Parametric amplification	Brillouin scattering
Absorption	Pockels effect	Optical phase conjugation

Some of the nonlinear processes itemized in Table 3.1 together with several of their applications are used in the production of modulated light beams. Any means of modifying the amplitude (AM), frequency (FM), phase, polarization, or direction of a light wave is referred as light modulation. The purpose of modulation is to render the wave capable of carrying information. Using the modulation that is accomplished by varying the refractive index of a material through the use of different electric, magnetic, optic or acoustic effects, different kind of optical signal processing elements can be designed that depends nonlinear manners [9].

The response of any dielectric material to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception. On a fundamental level, the origin of nonlinear response is related to an harmonic motion of bound electrons under the influence of an applied field. As a result, the induced polarization **P** from the electric dipoles is not linear in the electric field **E**.

The polarization of a linear medium by an electric field **E** is usually written in the form

$$P = \varepsilon_0 \chi E \qquad (3\text{-}1)$$

where χ is the susceptibility and ε_0 is the vacuum permittivity. When departures from linearity are small, it is possible to represent the modification of the susceptibility in a nonlinear medium by a power series in the form

$$\chi = \chi_1 E + \chi_2 E^2 + \chi_3 E^3 + ... \qquad (3\text{-}2)$$

When substituted into Eq. (3-1), the polarization takes the form

$$P = \varepsilon_0 (\chi_1 E + \chi_2 E^2 + \chi_3 E^3 + ...) \qquad (3\text{-}3)$$

$$P = \underbrace{P_1}_{linear} + \underbrace{(P_2 + P_3 + ...)}_{small.nonlinear.terms} \qquad (3\text{-}4)$$

where the subscripts on χ match the powers of **E** and reflect the decreasing magnitude of the higher-order terms. The linear and nonlinear susceptibility coefficients characterize the optical properties of the medium, and this relation between **P** and **E** completely characterizes the response of the optical medium to the field. The linear susceptibility χ_1 represents the dominant contribution to **P**. Its effects are included through the refractive index *n* and the attenuation coefficient α. The second order susceptibility χ_2 is responsible for such nonlinear effects as second-harmonic generation and sum-frequency generation. However, it is nonzero only for media that lack inversion symmetry at the molecular level. Since SiO_2 is a symmetric molecule, χ_2 vanish for silica glasses. As a result, optical fibers do not normally exhibit second-order nonlinear effects. Nonetheless, the electric-quadrupole and magnetic-dipole moments can generate weak second order nonlinear effects. Defect or color centers inside the fiber core can also contribute to second-harmonic generation under certain conditions.

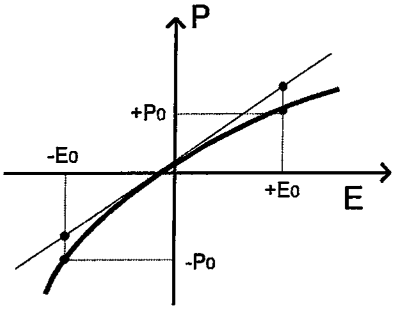

Figure 3.1 Linear and typical nonlinear response of polarization to an applied electric

Figure 3.1 shows the polarization as a function of the **E**-field for the linear case and the deviation from linearity due to this second-order term. For equal positive and negative fields the response of the optical medium is not symmetrical in the case of the nonlinear (curved line) response. In this case, the negative field $\mathbf{E_0}$ produces greater polarization than a positive field of the same magnitude [9,10].

3.2 Kerr-Effect Threshold Element

In this part of the thesis the optical signal processing functionality of periodic structures consisting of alternating layers of materials possessing Kerr nonlinearity will be analyzed. Using this model, optical building blocks, such as all-optical analog-to-digital converters, threshold elements, modulators, logic gates, optical switches etc. can be designed in the same manner. Performing signal processing operations entirely within the optical domain will give us the opportunity to design faster and flexible systems [11].

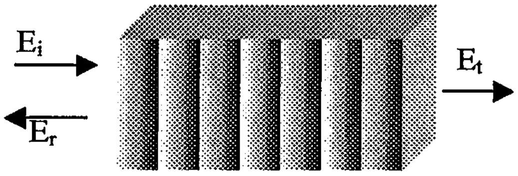

Figure 3.2 Multi-level structure of the device

The threshold device (Figure 3.2), one of the key elements, relies upon the nonlinear reflection mechanism rather than absorption of light. Thus, it is less susceptible to damage rather than absorption-based devices. The device is relatively easy to fabricate into a desired shape or to attach to any kind or form of surface [12]. Optical device uses fast Kerr-type nonlinearities of opposite sign for achieving the desired operation. The fast response of the molecular reorientation makes the Kerr-effect a prime candidate for use in quick optical shutter or optical gate [13].

The refraction index of the material used could be expressed as [14]

$$n = n_0 + n_{nl} I \tag{3-5}$$

n_0 : linear index coefficient

n_{nl} : Kerr coefficient

I : intensity of the light medium

Depending on the material chosen and optical wavelength selected the refraction index may increase or decrease with the intensity.

In the case of linear periodic structures, [15] the Bragg condition for a medium with intensity- dependent refractive indexes is itself a function of intensity.

$$(n_{01} + n_{nl1} I) d_1 + (n_{02} + n_{nl2} I) d_2 = \frac{\lambda}{2} \tag{3-6}$$

where;

n_{01} and n_{02} : linear parts of the refractive indices

n_{nl1} and n_{nl2} : Kerr nonlinear coefficients

d_1 and d_2 : layer thickness

The Bragg condition gives us spectral position λ of the center of the stop-band of a periodic grating. To achieve stable, narrowband device operation, the center of the stop-band should stay fixed in the intensity dependent medium.

$$n_{01} d_1 + n_{02} d_2 = \lambda/2 \qquad (I) \tag{3-8}$$

$$n_{nl1} d_1 + n_{nl2} d_2 = 0 \qquad (II)$$

The second condition can be satisfied if and only the Kerr-coefficients have opposite signs. Required thickness for given material pair can be found in terms of linear and nonlinear refractive indexes [16].

$$d_1 = \frac{\lambda}{2(n_{01} - n_{02}\frac{n_{nl1}}{n_{nl2}})} \quad (III) \qquad d_2 = \frac{\lambda}{2(n_{02} - n_{01}\frac{n_{nl1}}{n_{nl2}})} \quad (IV) \qquad (3\text{-}9)$$

Equations *(III, IV)* ensure the stability of the system by fixing the transmittance minimum at λ regardless of incident intensity. Formulas from *(I)* to *(IV)* are just for an ideal case. In reality the intensity will vary from layer to layer, but only between adjacent layers. In other words the approximation does not give any important failure in low-index-contrast structures. Results observed through exact methods in this work confirm that these conditions could result in a stable response.

In order to model the response of the proposed structures, the coupled mode equations are adapted to the case of a nonlinear medium and the electromagnetic field is written as a sum of forward and backward propagating waves

$$E(z) = A_1(z)e^{jkz} + A_2(z)e^{-jkz} \qquad (3\text{-}10)$$

where, A_1 and A_2 are the forward and backward propagating wave envelopes and k is the propagation constant.

The case of noncoherent radiation wherein intensity, proportional to the squared modulus of the electric field, is analyzed and approximated as $I(z) = |A_1(z)|^2 + |A_2(z)|^2$. Then, the periodic linear and nonlinear parts of the index of refraction is expanded in Fourier series.

$n_0 = (n_{01}d_1 + n_{02}d_2)/\Lambda$: average linear refractive indexes during Λ
$n_{nl0} = (n_{nl1}d_1 + n_{nl2}d_2)/\Lambda$: average nonlinear refractive indexes during Λ,
$f(z)$: Fourier expansion of the step function

Since the device response near the structural resonance, only the first order terms take part in the contra directional coupling. The higher order Fourier coefficients do not result in phase matching. Through full numerical solution of the exact equation set, it is verified, that the inclusion of these higher order terms results in no noticeable changes to the transfer curves. Coupled mode equations for a nonlinear periodic structure with negligible absorption are obtained by restricting the attention to the pertinent Fourier component, [17,18].

$$jdA_1(z)=\frac{\omega}{c}\left\{[(n_{01}-n_{02})+(n_{nl1}-n_{nl2})I(z)]\exp\left(-j\frac{\pi d_2}{\Lambda}\right)\frac{\sin\frac{\pi d_2}{\Lambda}}{\pi}A_2(z)\exp\left[i\left(\frac{2\omega n_0}{c}-\frac{\pi}{\Lambda}\right)z\right]-n_{nl0}I(z)A_1(z)\right\} \quad (3\text{-}10)$$

$$jdA_2(z)=\frac{\omega}{c}\left\{[(n_{01}-n_{02})+(n_{nl1}-n_{nl2})I(z)]\exp\left(j\frac{\pi d_2}{\Lambda}\right)\frac{\sin\frac{\pi d_2}{\Lambda}}{\pi}A_1(z)\exp\left[-i\left(\frac{2\omega n_0}{c}-\frac{\pi}{\Lambda}\right)z\right]-n_{nl0}I(z)A_2(z)\right\} \quad (3\text{-}11)$$

where ω is the frequency of the radiation and c is the speed of light in vacuum.

Two boundary conditions are specified: $(A_2(L)=0)$ (no incident on the structure from the right) and $|A(0)|^2=I_{in}$ (known intensity incident on the structure from left)

The mechanism responsible for this behavior is illustrated in Figure 3.3. The variation of the intensity and intensity dependent refractive index for different values of I_{in} across the Period N (between 0 and 1000) is plotted with material parameters; linear indexes of refraction of 1,5 and 1,52 and Kerr coefficients of 0,01 and –0,01.

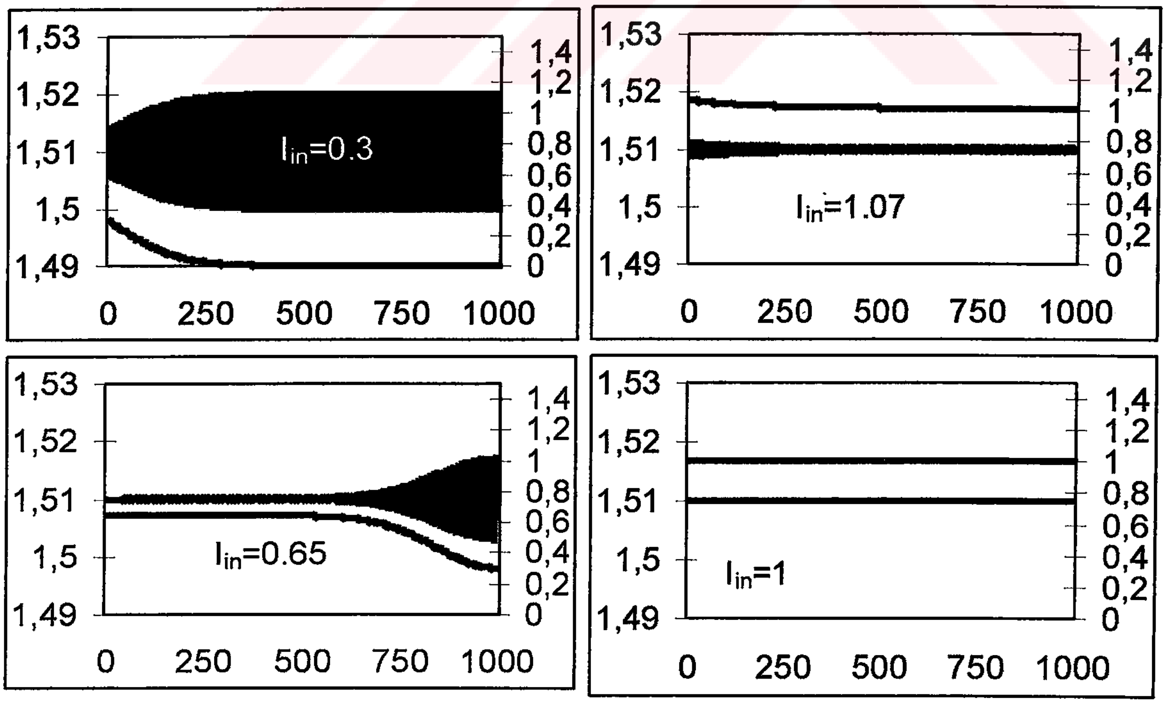

Figure 3.3 Local index and intensity across 500-period structure

Low incident intensity (I_{in}=0.3) is blocked by the strong linear grating and decays sharply to a negligible small value. As the intensity increases beyond $a(=\frac{n_{01}-n_{02}}{|n_{nl1}|+|n_{nl2}|})$ the Kerr-effect modifies the profile of refractive index variation across the whole structure (for I_{in}= 0,65). When the incident intensity reaches $\frac{n_{01}-n_{02}}{|n_{nl1}|+|n_{nl2}|}$ the grating disappears and the device starts completely transmitting. As the incident intensity is increased further (e.g. I_{in}= 1,07) the grating will be formed again and limits the intensity at a. In order to achieve a sharp characteristic the structure need to be designed at least 500 periods long.

The new parameter a is defined as $a=\frac{n_{01}-n_{02}}{|n_{nl1}|+|n_{nl2}|}$ for a given choice of materials.

The approximate piecewise-linear relation between transmitted and incident intensity is as given below;

$$I_{out}=\begin{cases} 0 & for \quad I_{in}<a/2 \\ 2a(I_{in}-1)\, for & a/2<I_{in}<a \\ a & for \quad I_{in}>a/2 \end{cases} \tag{3-12}$$

A threshold device output should be transmitted for input greater then or equal to threshold value, and should otherwise be zero. Arranging the proposed structure in series results in an increasingly steep transition. Figure 3.4 shows how the response of the hardlimiter is modified with increasing number of units [19].

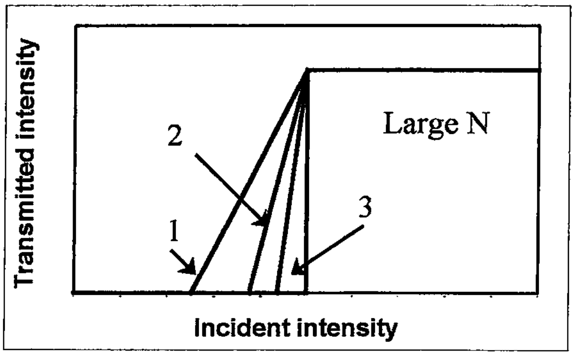

Figure 3.4 The response of the hardlimiter with increasing number of units.

$$I_{out} = \begin{cases} 0 & for \quad I_{in} < a(1 - \frac{1}{2^N}) \\ a[2^N (I_{in} - 1) + 1] & for \quad a(1 - \frac{1}{2^N}) < I_{in} < a \\ a & for \quad I_{in} > a \end{cases} \tag{3-13}$$

If the number of units is sufficiently chosen, the device will behave as an all-optical threshold device. For the intensity values of smaller then a the optical signal will be reflected and for the intensity values of greater than a it will be transmitted. The value of a depends on the linear and nonlinear indexes of material. Thus, appropriate choice of material biases the device at the desired threshold-value. Implementation of the devices considered will rely on the use of materials with large Kerr nonlinearity in order to obtain a low-intensity threshold for limiting action [20,21].

Using the structure for different threshold values and different architectures many all-optical devices can be designed for photonic network use.

3.3 Fiber Bragg Grating Filter

A critical and important component in optical fiber communication systems is fiber Bragg gratings and its applications. Fiber Bragg gratings could be used to make optical devices such as optical filters, dispersion compensators, gain equalizers, add/drop multiplexers, WDM demultiplexers etc.

A fiber Bragg grating filter can be used for pulse compression operation and also for extending an optical pulse up to the desired pulse width. The pulse is dispersed in the time domain by adjusting the filter bandwidth and the filter order. These factors will be used in the design of all-optical routing at XOR operation between header bit pulses and routing table pulse.

Several different kinds of filters can be realized by using two or more fiber Bragg gratings. For example, placing two identical Bragg gratings next to each other with controlled spacing produces Fabry-Perot filters (or interferometers) [22]. If the two gratings are placed in two arms of an all-fiber Michelson interferometer, the device acts as a band-pass filter [23]. If the two arms of the Michelson interferometer are closed by using a fiber coupler, the resulting Mach-Zender arrangement acts as a add/drop filter [24].

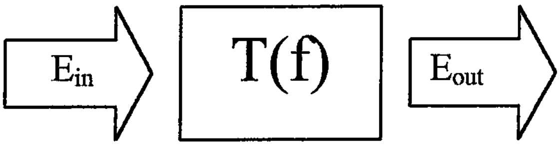

Figure 3.5 Relationship between input and output fields

$T(f) = A(f)e^{j\phi(f)}$; complex transfer function (Figure 3.5) in frequency domain characterizes an optical filter in transmission direction, where $\phi(f)$ is the phase and $A(f)$ is the amplitude function. Both of them are frequency dependent. Via using $T(f)$, a relationship between output and input fields can be satisfied as follows:

$$\begin{pmatrix} E_{x,out}(f) \\ E_{y,out}(f) \end{pmatrix} = T(f).\begin{pmatrix} E_{x,in}(f) \\ E_{y,in}(f) \end{pmatrix} \tag{3-14}$$

The transfer function of a fiber Bragg grating filter depends on grating parameters.

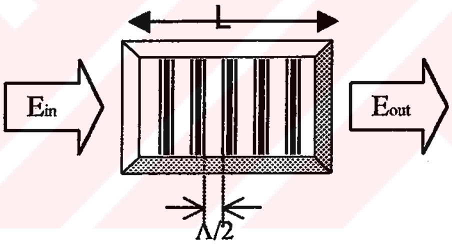

Figure 3.6 General Bragg Grating Model

A fiber Bragg grating is a periodic perturbation of the refractive index ($n_{eff} = n + \delta n_{eff}$) along the fiber length, which in general can be described [25].

$$\delta n_{eff}(z) = \overline{\delta n}_{eff}(z)\left(1 + \upsilon\cos\left[\frac{2\pi}{\Lambda}z + \phi(z)\right]\right) \tag{3-15}$$

where $\overline{\delta n}_{eff}(z)$ is the “dc” index change spatially averaged over a grating period, υ is the fringe visibility of the index change, Λ is the nominal period defining filter center frequency and $\phi(z)$ describes grating chirp. In a uniform filter, the refractive index $\delta n_{eff}(z)$ and $\phi(z)$ is constant. A transfer function of the uniform filters can be calculated analytically [26] and is given by (Figure 3.6):

$$T(f)=\frac{\kappa\sinh\sqrt{\kappa^2-\xi^2}}{\xi\sinh\sqrt{\kappa^2-\xi^2}+j\sqrt{\kappa^2-\xi^2}\cosh\sqrt{\kappa^2-\xi^2}} \tag{3-16}$$

where κ describes the coupling "strength" between the incident and reflected waves (E_{in} and E_{out}) and parameter ξ represents a normalized frequency offset from the center-frequency of the filter. κ can be found from the maximum FBG reflectivity $R_{\max}=\left|E_r/E_i\right|^2$ according to $\kappa=\arctan h\sqrt{R_{\max}}$ and is defined by the FBG length L and the refractive index perturbation as given by $\kappa=(\pi\upsilon\bar{\delta}_{neff}L)/\lambda$, where λ is the wavelength of the light wave.

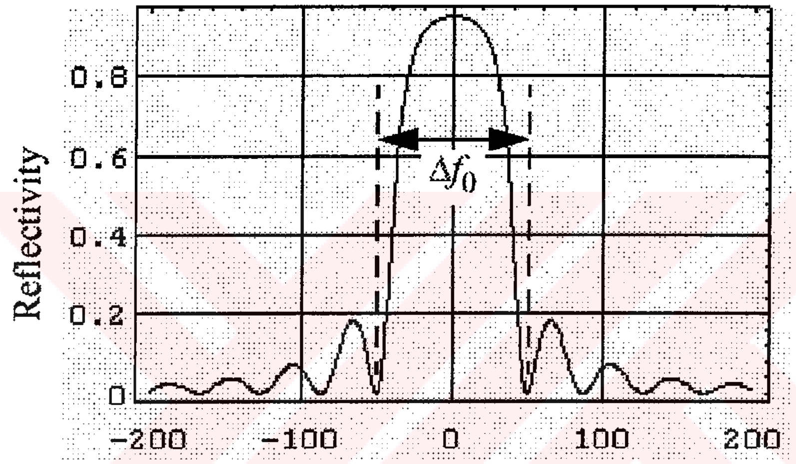

Figure 3.7 Frequency Response of a Uniform Bragg-Grating Filter [27]

The normalized detuning is defined by the frequency offset $f-f_c$ and the filter bandwidth Δf_0 as given by $\xi=2\kappa\sqrt{1+(\pi/\kappa)^2}\,\frac{f-f_c}{\Delta f_0}$. It can be seen in (Figure 3.7) that the filter bandwidth Δf_0 is defined as the frequency difference between two first zero points of the transfer function $A(f)$ [27,28].

In the simulation a uniform fiber Bragg grating filter with the transfer function in Eq. (3-16) and 1mW energized Gaussian optical pulse with 0.1 ns pulse width is used which is shown in Figure 3.8.

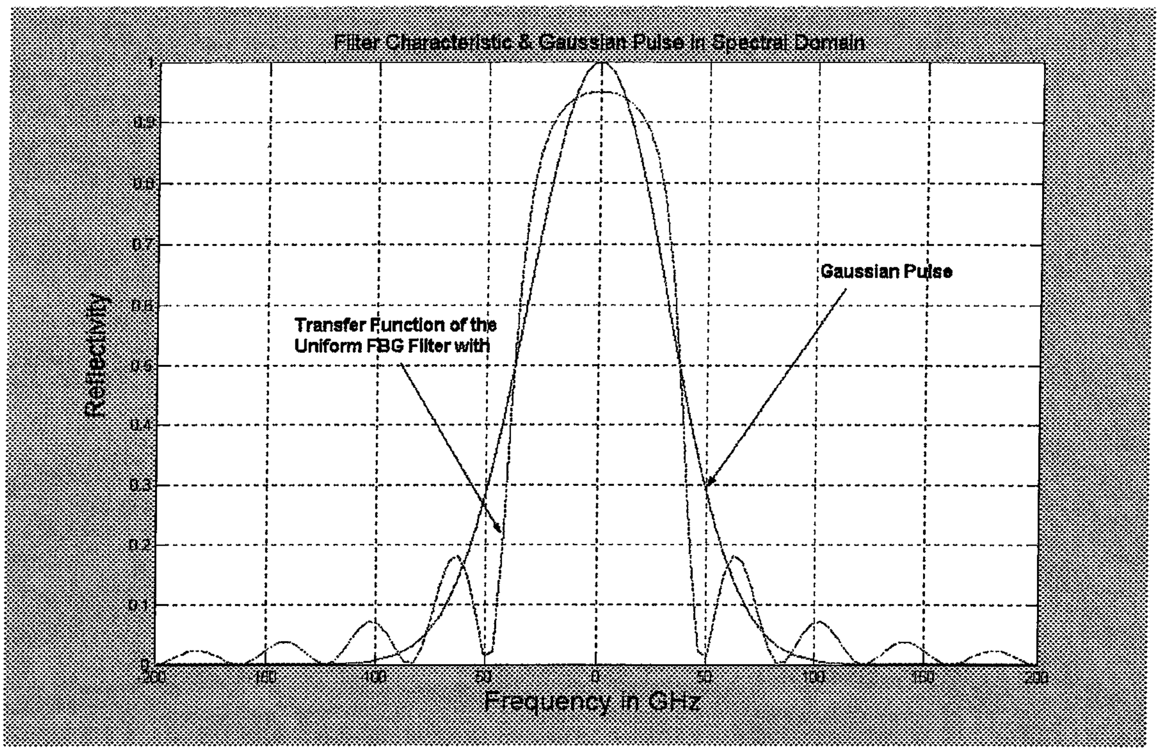

Figure 3.8 Spectral dependence of the Filter Transfer Function $|T(f)|^2$ and Gaussian Optical Pulse

Other simulation parameters are shown below:

R_{max}=0.95, κ=2.17827, Δf_0=100 GHz, f_c=0,
λ=1.55 μm, Λ=0.531 μm, ν=1, δn_{eff}=0,0004, L=2,68678 mm
Gaussian pulse power= 1 mW Gaussian pulse width (FWHM)= 0.1 ns

The power efficiency of the pulse extension unit is calculated as ≈ 96.109% for 1/32 extension rate.

The effect of the fringe visibility can change effective refractive index and grating characteristics as well. Figure 3.9 shows refractive index change functions of different apodized Bragg gratings. More efficient and more sharp transfer characteristics may be achieved using different values and apodization of fringe visibility, but only uniform effective refractive index change is used in the simulation.

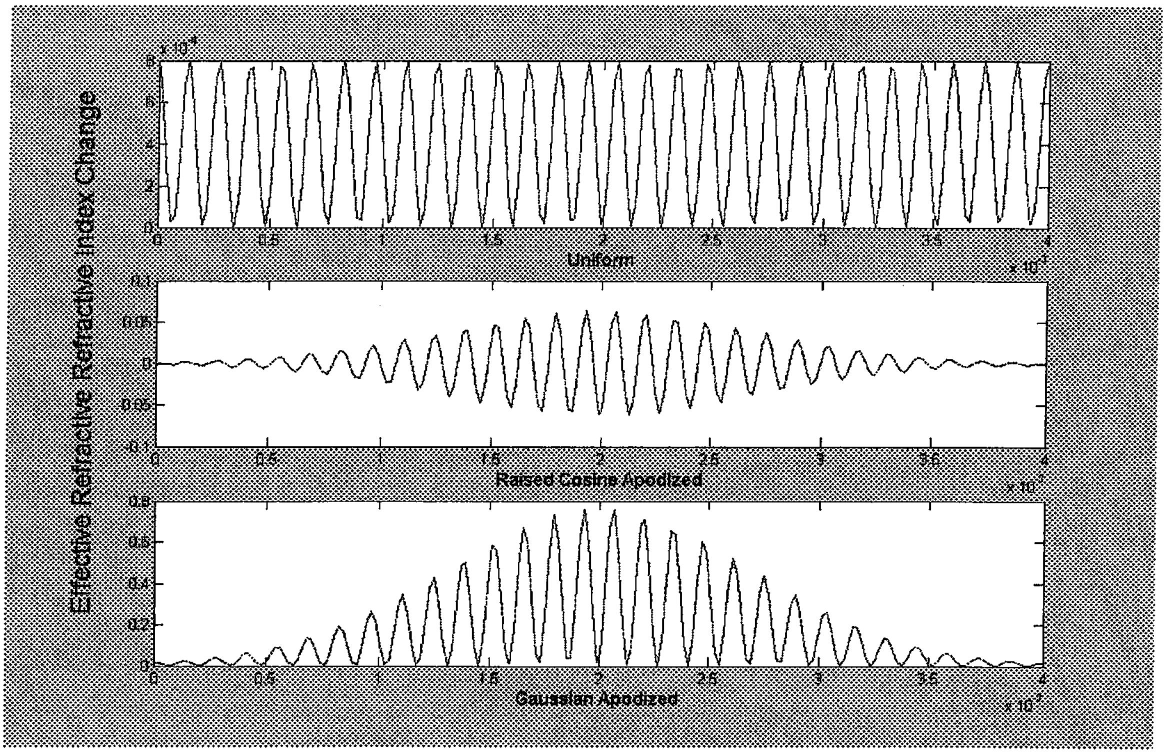

Figure 3.9 Common Types Gratings as Classified by Variation of the Induced Index Change

3.4 Ultra-Fast OTDM Signal Generation

Current limit of the electrical time division multiplexing systems is approximately 40 Gb/s. In order to efficiently use the bandwidth of the optical networks Optical Time Division Multiplexing (OTDM) technologies operating at a bit-rate over 100 Gb/s should be used. The concept of OTDM is developed to overcome the low bit-rates of electrical time division multiplexing systems. [by Tucker 1988] Since then OTDM bit-rates are significantly increased (About 1.6 dB per year) (Figure 3.10) [29].

OTDM has many advantages over any other multiplexing methods: Simple management and control (single stream vs. many wavelength channels), flexible bandwidth on demand service, packet switching of self-routing of data packets, scalability in number of users, possible use of statistical multiplexing, ability to support variable quality of service (QoS), the use of digital regeneration, buffering coding and encryption, potential to provide burst rates (over 100 Gb/s) at a signal wavelength.

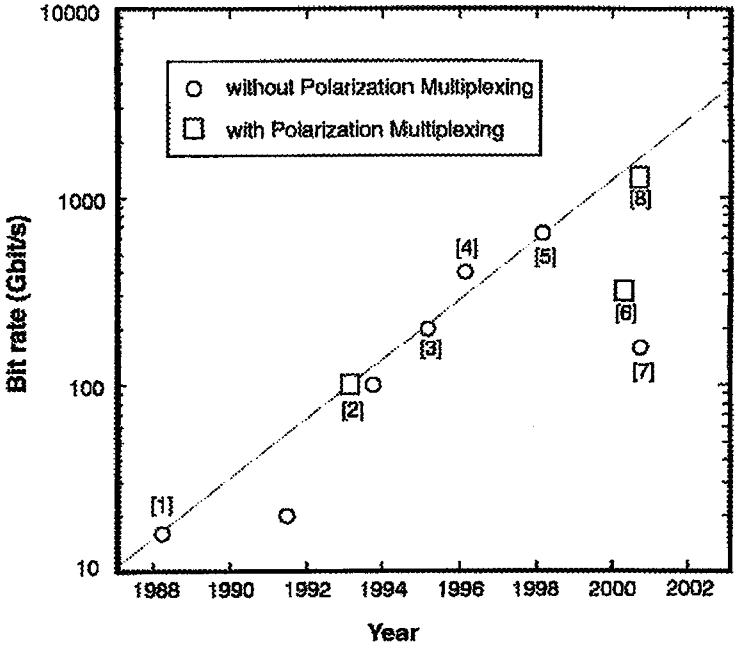

Figure 3.10 Optical transmission bit-rates achieved in experiments

To generate OTDM signals, very high quality short pulse sources are required, as well as high precision multiplexers. Furthermore, as the channel separation is performed in the time domain and not in the wavelength domain, active signal processing is a necessity to perform, e.g., demultiplexing. Short pulse lasers are used to generate OTDM signals. Optical short pulses are first modulated and then multiplexed into a higher speed signal (Figure 3.11).

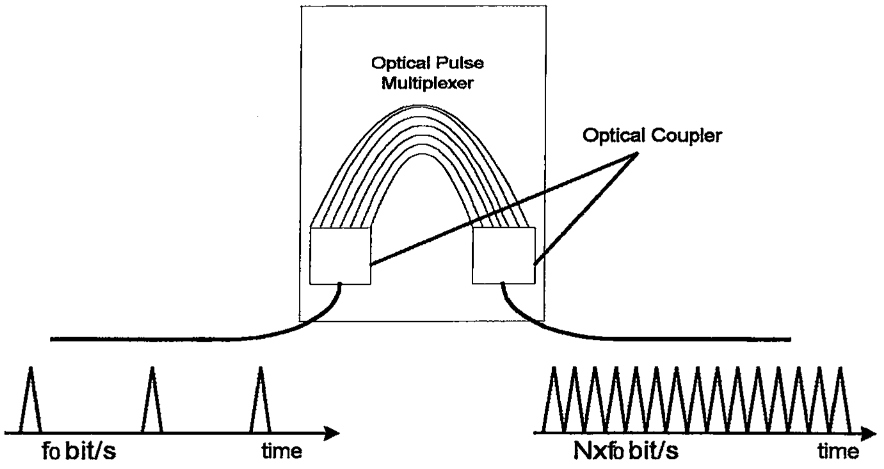

Figure 3.11 Schematic Configuration of an Optical Pulse Multiplexer

At the receiver a time domain demultiplexer is used to recover the original sub-channels. Time domain multiplexer is driven by a clock, which is extracted from the signal.

Optical pulse multiplexers, which consist of optical couplers and optical delays, were used to multiplex one modulated optical signal to a higher bit-rate OTDM signal. There are two types of optical multiplexers: parallel type and serial type. They both offer speeds over 100 Gb/s.

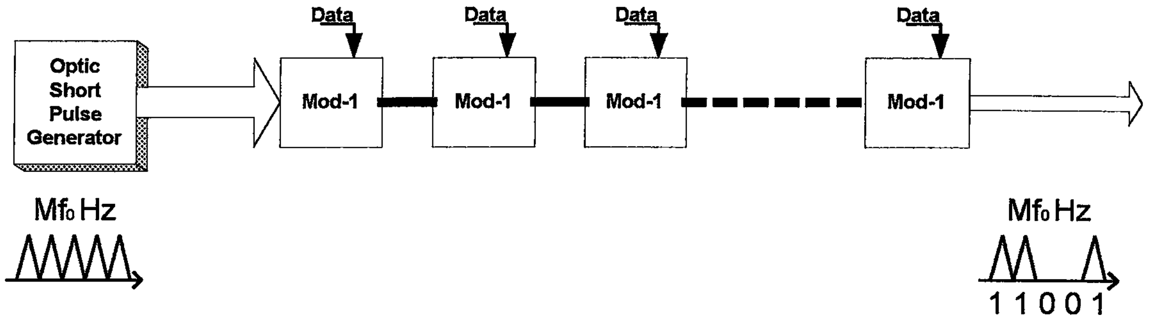

Figure 3.12 Serial Type Multiplexer

The serial type multiplexer in Figure 3.12 combines an ultra-fast optical clock pulse train with modulation pulses using a high-speed all-optical switch to generate the modulated OTDM signal. This cascade process allows all channels to be independently modulated.

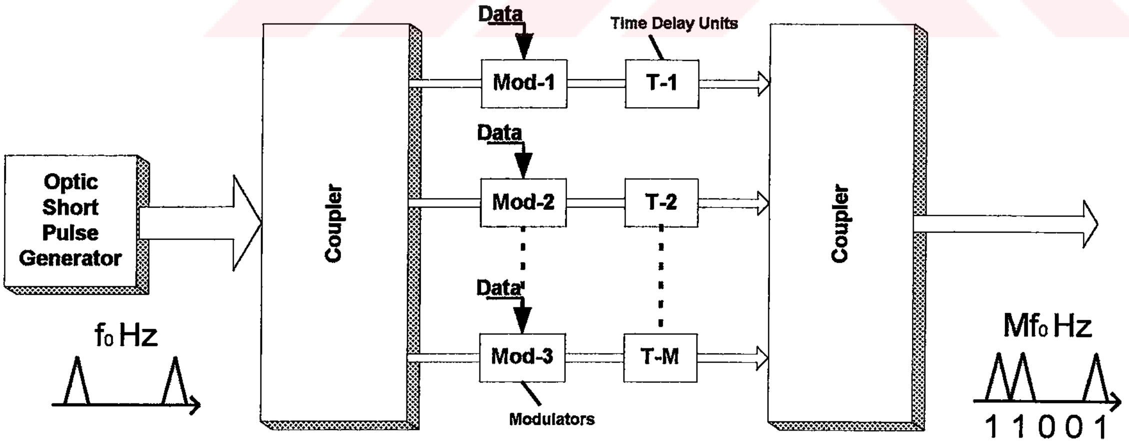

Figure 3.13 Parallel Type Multiplexer

The parallel one in Figure 3.13 consists of an optical pulse source, couplers, modulators and optical delay lines. The first coupler splits the optical pulse train into m-different channels. Each optical pulse train is modulated by an optical modulator.

Modulated signals are combined in the second coupler. The path-length of the each channel is aligned so that optical signals are optically multiplexed into higher bit-rate OTDM signals. Parallel-type multiplexing has been investigated in depth, because it is relatively easy to construct parallel type multiplexers. It uses all-passive components and no high-speed switching element is required [29]. Pulse separation problems and achievable bit rates using OTDM methods will be discussed in next section.

3.4.1 Pulse Separation Fluctuations

Thermal expansion factor of a standard fiber is about 0.05 ps/m/°C. It is a significant problem for both types of multiplexers, the reason of which is couplers and optical delay lines used. Optical path length of each channel is different from each other at least by several meters. As a result the pulse separations change because of the temperature fluctuations.

There are several methods to overcome the problem. Optical Pulse Timing Control, Integration of Optical Multiplexer Components into a compact circuit, All-optical Regularizing (combined with an optical clock) are some of them. Table 3.2 compares three different methods for suppressing the pulse separation fluctuations [30].

Table 3.2 Comparisons of Three Different Methods

Method	Temporal Resolution (max. BR)	Output Power	Configuration
Optical pulse timing control	*~0.5 ps (~200 Gbit/s)*	High	Simple
Integration of MUX	*<0.1 ps (>1 Tbit/s)*	Low	Simple
All-optical Regularization	*0 ps (unlimited)*	High	Complex

The optical pulse timing control method has a simple configuration and its implementation is easy for both type of optical MUX's, but the maximum bit rate is relatively low due to electrical noise of the receiver. This method could be used for the bit-rates of about 200 Gbit/s.

The temporal resolution of the integrated MUX is higher. This method makes 1 Tbit/s OTDM signal generation possible. The performance of it depends on the accuracy of the optical path length of the waveguide on hybrid planar lightwave circuit. Its disadvantage is the low power output because of the low conversion efficiency of

FWM in Semiconductor Optical Amplifier (SOA). (-22 to –25 dB) By utilizing optical modulator such as periodically-poled LiNBO3 waveguides it can be expected to stable and compact MUX's with higher conversion efficiency ~ (-12 dB).

For all-optical regularization, the maximum bit rate is not limited by the temporal resolution due to uniform pulse separation. However, the configuration is very complex. A nonlinear optical loop mirror and ultra-fast optical clock is needed.

The pulse separation regulation is a very critical process for reducing crosstalk in demultiplexing and jitter in retiming at the receiver end of an OTDM signal.

Stable multiplexing is possible and successfully demonstrated at Lab-environment using optical pulse timing control (up to 200 Gbit/s) or an integrated MUX (100 Gbit/s – 1Tbit/s) or all-optical regularization (over several 100 Gbit/s). It is expected that these techniques will allow us to provide ultra-high speed signals for OTDM systems [30].

3.5 Optical XOR Gate

XOR describes a logic circuit with two or more inputs and one output, which is high if one input is high. Such circuits rely on truth tables: In binary terms, two 0's or two 1's in the input yield an output of 1, while an input of 1 and 0 (or vice versa) results in 0 at the output.

An interferometer can be used to control the waves entering the logic circuit. The instrument caused the interference of two input waves, which produced a phase change between them. At the input of the logic gate, the waves either combined constructively (resulting in an output of 1) or destructively (resulting in 0).

Ultrafast Nonlinear Interferometer (UNI) gate [31,32,33], SOA assisted Sagnac Gate [34], Cross Polarization in SOA [35], Photorefractive Fanning Effect [36], Series of Self-Pumped Phase Conjugators [37], Mach-Zehnder Interferometer (MZI) [38] and Nonlinear Interference Filters [39] could be used to design optical XOR gates.

3.5.1 All-Optical XOR using MZI and SOA

A schematic diagram at the Mach-Zehnder interferometer and an illustration detailing the principle of the operation as an XOR gate are shown in Figure 3.14. As the

Fiber indicates two input data streams A and B, respectively are coupled into part 1 and 2 of the MZI, while a continuous wave (CW) is coupled into part 3. In the MZI data signals are launched into the SOAs where they modulate the carrier density and thereby also the refractive index. This causes phase modulation (ϕ) of the CW light propagating in the SOAs according to the bit pattern of the input data signals. At the output of the interferometer the CW light from the two SOAs interfere either constructively or destructively depending on the cosine to the phase difference between the lights from the two SOA. Thus the output is controlled by the input data signals. That corresponds to the logical XOR of the two input signals [32].

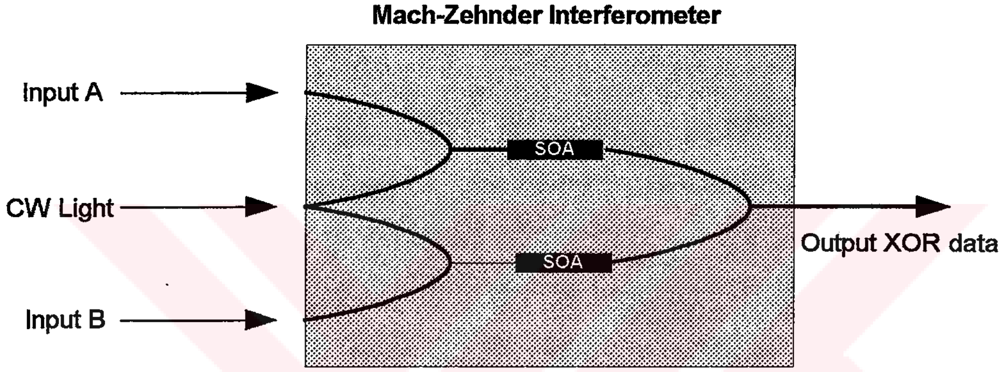

Figure 3.14 Schematic Diagram of MZI

All optical XOR functionality has been demonstrated experimentally using an integrated SOA-based Mach-Zehnder interferometer (SOA-MZI) at 20 Gb/s. The performance of the XOR results has been analyzed by solving the rate equation of the SOA numerically. The high speed operation is limited by the carrier lifetime in the SOA. In order to solve the limitations imposed by carrier lifetime a differential scheme for XOR operation has been experimentally investigated. This scheme is potentially capable of XOR operation to > 100 Gb/s [38].

In trials, XOR has been successful at 10 Gb/s, 20 Gb/s, 40 Gb/s and 100 Gb/s but companies such as Cisco Systems Inc., Juniper Networks Inc. and Hyperchip Inc. are developing commercial routers to transmit data at speeds of greater than 1 Pb/s, up to 1000 times faster than today's most advanced systems. These next-generation routers will operate in all-optical networks. XOR offers a way to implement all-optical label swapping with a limited increase in cost and complexity [40].

3.5.2 All optical XOR with UNI-Gate

The concept of operation of the UNI Gate relies on polarization rotation of the incoming clock signal in the presence of a control pulse in SOA. The clock pulse splits into two orthogonal polarization components, which are relatively delayed in a length of birefringent Polarization Maintaining (PM) fiber before entering into the SOA. The length of the PM fiber is determined to insert a temporal displacement between the two polarization components equal to half the pulse repetition period. It corresponds to 6.25 m for 1.6 ps 40 GHz pulse.

For logic operation the control pulse is temporally synchronized with one of the two orthogonal polarizations of the clock. This causes a local, time-dependent refractive index change in the SOA, which in turn imparts a phase change only on synchronized polarization component of the clock pulse. For dual logic such as XOR, the phase of each polarization state must be accessed and changed independently with the two control signals in the SOA.

40 Gbit/s operation is realized using 1.55 mm long InGaAsP-InP ridge waveguide SOA at 1.55 μm signal wavelength with 6.25 m of PM fiber and it has been shown that the system has been capable of logical operations at 100 Gbps [31].

3.5.3 All-Optical XOR in a SOA-Assisted Fiber Sagnac Gate

The gate operates by measuring the differential phase change between the two counter-propagating clock pulses. This phase change is imposed on them by their nonlinear interaction with the temporally synchronized control pulses A, B in the SOA and is due to the rapid carrier depletion in the presence of one or two control pulses.

Crucial of the operation of the device is the position of the SOA with respect to the center of the loop. This has to be asymmetrically placed so that the two counter-propagating clock pulses can experience a differential phase change as only one of them interacts with the control pulse in the SOA. In the absence of any control pulses the gate is reflective and the clock pulses exit through the same port that they enter. When either pulse A or B is present, the gate becomes transmissive and if both A and B are present it becomes reflective again.

The SOA-assisted Sagnac interferometer gate was constructed using a 3-dB polarization preserving coupler into the ports of which the optical clock signal is injected. The logical inputs A and B are inserted in the loop via two optical fiber polarization beam splitters/combiners PBS1 and PBS2. Two control input beam experiments at 20 GHz are performed with the SOA-assisted gate and it is proved that it is possible for the interferometer to pass to the second interference fringe simply by introducing twice as much energy/pulse as for the first [34]. Experiments are currently in progress to extend the operation of the device to higher rates.

3.6 Optical Buffer System

One difficulty in the implementation of photonic packet switching systems is the lack of optical random access memory (RAM). Unfortunately, optical RAM suitable for photonic packet switching has not yet been found. The alternative is to use optical fiber delay-lines incorporating other optical components such as optical gate switches, optical couplers and amplifiers to realize photonic packet buffering.

3.6.1 Optical Buffer Memories

At present, the most reliable and effective way to store packets in a photonic switch relies on optical buffers based on sets of fiber delay-lines, with lengths equivalent to multiple of a packet (or cell) duration τ_c.

Generally, optical buffers can be classified into recirculation-type (or loop-type) and travelling-type (Figure 3.14).

3.6.1.1 Recirculation Buffer

The main advantages of this configuration is the minimum amount of optical hardware; on the other hand the optical amplifier inside the loop, necessary to compensate for the loss of the coupler, introduces optical noise which eventually limits the maximum buffering time.

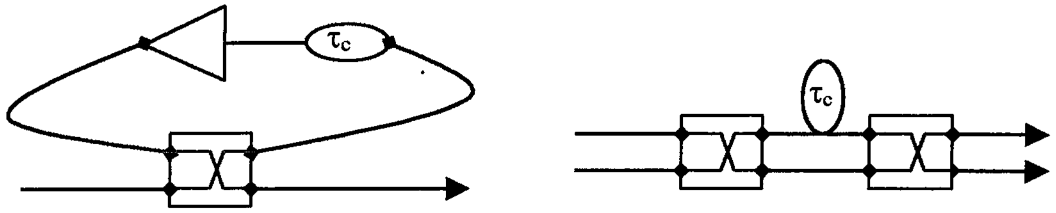

Figure 3.14 Recirculating Type (left) and Travelling Type (right) Buffer

3.6.1.2 Travelling-type Buffer

The parallel configuration presents low insertion loss and a simple control, at the expense of a large amount hardware, while the serial binary arrangement allows reaching high buffering time with a relatively small amount of components, at the expense of higher insertion loss.

Controllability, buffer capacity, delay-line length, loss in the delay path the number of device and expandability are the main issues in optical buffer systems that should be taken care-off.

As an improvement, Wavelength Division Multiplexing (WDM) is a very effective way to increase the capacity of an optical buffer without increasing the amount of hardware. Using multiwavelength buffer system with fiber gratings has the following advantages: Easy management due to integration of the control part, high-speed wavelength path routing part with passive devices and high capacity [40].

3.7 Fiber Amplifiers

Optical fibers attenuate light during propagation like any other material. In the case of silica fibers, the attenuation constant α is quite small, particularly in the wavelength range 1.0-1.6 μm where it is typically less than 1 dB/km with the minimum value of about 0.2 dB/km occurring near 1.55 μm. In fact, in most experiments related to nonlinear fiber optics, fiber loss can simply be ignored since propagation distances are typically below 1 km. An important exception occurs in the case of long-haul fiber-optic communication systems where transmission distances are ~100 km and exceed thousands of kilometers for undersea lightwave systems. Another need for amplification occurs at optical nodes, where the signal should be distributed to many different channels such as LAN applications. In practice, to overcome the loss limitations by periodic generation of the optical signal at repeaters, an optical signal is converted into the electric domain by using a receiver and then regenerated by using a transmitter. Such regenerators become quite complex and expensive, especially for multichannel lightwave systems [42].

Several kinds of optical amplifiers were studied and developed during the 1980s. Semiconductor laser amplifiers were used initially, but the interest shifted toward fiber-based amplifiers because of practical issues related to coupling losses, polarization sensitivity, and interchannel crosstalk. Fiber Raman amplifiers require high pump powers (~0.5-1 W) that are not readily available from semiconductor lasers. Fiber-Brillouin amplifiers can operate at low pump powers, but have bandwidths too small to be useful as in-line amplifiers in communication networks. A new kind of fiber, based on silica fibers doped with rare-earth ions, was developed in the late 1980s and turned out to be most suitable for lightwave system revolutionizing the field of optical communications. Many laboratory experiments have shown its potential applications in actual lightwave systems. EDFAs (Erbium Doped Fiber Amplifiers) became available commercially in 1990. EDFAs are expected to play an important role in the design of soliton communication systems where they will be used to amplify optical solitons.

The technique of doping silica fibers with rare-earth elements was not a new technology, but their use became practical only, after the techniques for fabrication and characterization of low-loss, rare-earth-doped fibers were perfected. Amplifier characteristics such as the operating wavelength and the gain bandwidth are determined by dopants rather than by the fiber, which plays the role of a host medium.

Many rare-earth ions, such as erbium, holmium, neodymium, samarium, thulium, and ytterbium, can be used to make fiber amplifiers operating at different wavelengths covering a wide range from visible to infrared (up to ~3 μm). EDFAs have attracted the most attention among them simply because they operate near 1.55 μm, the wavelength region in which the loss of silica fibers is minimum, and are therefore ideal for 1.55 μm fiberoptic communication systems [10].

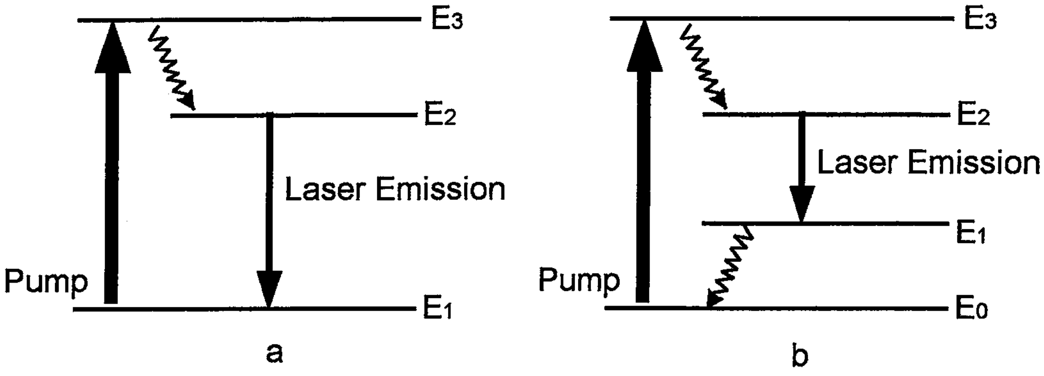

Figure 3.15 Schematic illustrations of (a) 3-level and (b) 4-level pumping schemes.

Optical amplifiers amplify incident light through stimulated emission, the same mechanism used by lasers. Indeed, an optical amplifier is just a laser without feedback. Its main ingredient is the optical gain realized when the amplifier is pumped (optically in the case of doped fibers) to achieve population inversion. Depending on the energy levels of the dopant, pumping schemes can be classified as a three- or four-level scheme. Figure 3.15 shows two kinds of pumping schemes. In both cases dopants are excited to a higher energy state through absorption of pump photons and then relax rapidly to a lower-energy state through absorption of pump photons and then relax rapidly to lower-energy exited state (Level 2). Wavy arrows indicate fast relaxation of the level population through nonradiative processes. The stored energy is then used to amplify a signal beam through stimulated emission. The main difference between 3-level and 4-level pumping schemes is related to the energy state occupied by the dopant after each stimulated emission. This difference affects the amplifier characteristics significantly. Erbium-doped fiber amplifiers discussed make use of a three-level pumping scheme.

EDFAs are typically capable of gains of 30 dB or more and output power of 17 dB or more. While the signal gain by a gain medium of erbium ions is inherently wavelength dependent, it can be corrected with gain flattering filters especially for multi-wavelength applications. An erbium doped optical amplifier has a noise figure of 3.6 dB. Noise figure is a crucial parameter for optical amplifiers because this effect is cumulative and is an ultimate limiting factor in the number of amplifiers that can be concatenated and, therefore, the length of a fiber link without electronic signal regeneration [10,43].

EDFAs are designed for use in high bit rate and long haul transmission with saving the expensive regenerators. The amplification of EDFA is independent of the signal format and network protocol.

EDFAs can be used as Boost-amplifier to amplify optical transmitter output power, In-line-amplifier to amplify the weak signal in the fiber, Pre-amplifier to improve the sensitivity of optical receiver, WDM EDFA to amplify multi-wavelength signals or Analog EDFA to amplify CATV signals [42].

3.7 All-Optical Clock Recovery

In transmission networks, pulse degradation through active or passive devices, or just through long fiber transmissions have to be compensated to avoid errors of the transmitted data. For that, regeneration techniques will become key-elements in the future network designs. 3R techniques (reshaping, retiming, reamplification) are based on two fundamental parts: the all-optical clock recovery (CR) and the decision gate.

A very important part is the CR unit, which guarantees the three R's: right timing, optical power and the shape of the regenerated data. The decision gate is needed to determine whether the incoming bit is "1" or "0". It also has to modulate the clock pulses with the information bits to form the regenerated data (Figure 3.16).

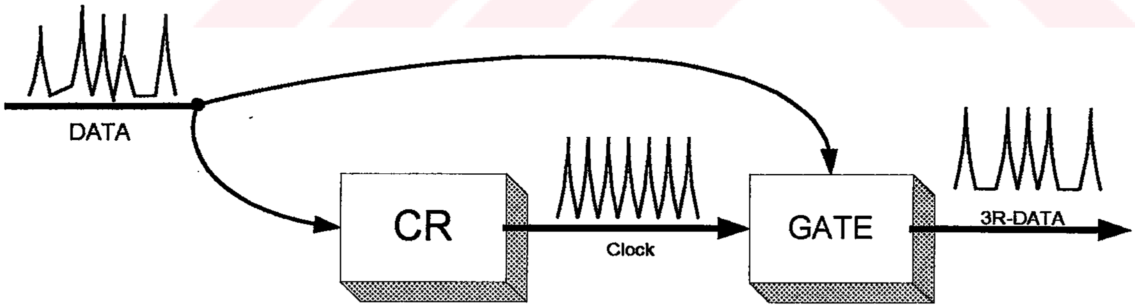

Figure 3.16 Principle of all-optical regeneration (3R) with clock recovery

As all-optical CR unit a mode-locked laser can be used, which will be optically, modulated through the incoming data pulses that force the laser to pulse at its fundamental repetition rate.

As decision gate monolithically integrated Mach-Zehnder interferometers (MZI) can be used with semiconductor optical amplifiers (SOA) in its arms. Due to its transfer function, incoming power levels can be clearly referred to “1”s or “0”s [44].

CHAPTER 4

ALL OPTICAL ROUTING AND SWITCHING

4.1. Towards to Optical Internets

Over a period of last few years, the Internet has become the dominant protocol for all new network services. The Internet is increasingly used for all forms of media and for commercially networking. As a result, Internet Protocol (IP) has become widespread in packet-based networks, because of its simple and efficient network interface.

- Tim Berners- Lee develops the World Wide Web. CERN releases the first Web server in 1991.
- 1992: the number of hosts breaks 1,000,000.
- The www supports a growth rate of 342% in service traffic in its 3rd year, 1993.
- OC-48, 2.5 Gbps links in 1997.
- 100 Mbps Ethernet in 1998.
- 40 x WDM, 100 Gbps links in 1999.
- 1 Gbps Ethernet in 1999.
- 100-1000 x WDM (DWDM) in 2001 [8].

The amount of IP traffic growing exponentially (246%, averaged over last decade) and will be soon a giant to all other types of traffic. With the increasing importance of the Internet there is an increasing pressure to optimize the network infrastructure. Optical communication links offer bandwidths at Tbps range, but electronic network devices at the critical network nodes (switching and routing points) are the bottlenecks of the whole process. An electronic network device cannot provide speed higher than 40 Gbps. The challenge is to design a network that combines the strengths of both IP and optical technologies. The application of photonic technologies to packet and routing offer the potential of very large switching and routing capacity in the terabit per second range.

4.2. Advantages of Optical Nodes

The merging packet switching and routing with photonic technologies opens up the possibility of packet switching in transparent optical media by optically transparent self-routing networks, in which optical packets pass through photonic network elements in a transparent fashion, without undergoing any optical to electrical and electrical to optical conversions. The attraction of such a network is that there is no electronic processing in the data path and the data can ideally pass through the switch without any limitation on bit rate. Also, wavelength-division multiplexing (WDM and DWDM) and optical time division multiplexing (OTDM) can be readily exploited. Thus very large throughput becomes feasible. An important application is in the development of photonic local area and metropolitan networks with a highly improved throughput (100 Gbit/s Ethernet) [45].

Optical IP routing and switching is a key to future expansion of data and other Internet related services to overcome the bottlenecks of the system. Electronic algorithms offer great potential but are ultimately limited in data and throughput by the processing capacity of electronic devices. As a solution, electronic packet switches and routers should be replaced with optical ones in which signals remain in optical form.

The wide bandwidth of photonic components, combined with the flexibility of optical multiplexing techniques (WDM, DWDM and OTDM) and optical routing and the high speed capabilities of optical devices such as optical gates, switches, optical wavelength converters, fast tunable lasers, optical hardlimiters and optical filters provides the potential of photonic packet switched networks with throughput in the terabit range. The application of photonic technologies to packet switching and routing will result in high capacity nodes.

Table 4.1 Electronic vs. optical switching

Configuration	**Number of switch elements required at 320x10 Gbps**	**Number of switch elements required at 640x10 Gbps**	**Number of switch elements required at 1280x40 Gbps**
622 Mbps electrical switching* $O(N\log N)$, $O(N^2)$	106,522 4,096,000	238,642 16,384,000	2,113,932 262,144,000
2.5 Gbps electrical switching* $O(N\log N)$, $O(N^2)$	26,632 1,024,000	59,662 4,096,000	528,480 65,536,000
Optical switching** elements, guides	768 98304	3072 393,216	3072 786,432

* Assumes 2x2 switch elements, N^2 expansion maximum, $N\log_2 N$ expansion minimum

** Assumes 1xN switch elements, one N^2 expansion, then one N expansion

High-capacity photonic nodes will be attractive as alternatives to very large electronic switch nodes, even when the individual channels operate at data rates that are compatible with electronic capabilities. Table 4.1 shows the number of switch elements required for a various configuration both for optical and electrical elements. Above this, the copper cables needed to connect a 50 Tbps router would weigh more than 1000 tons [46].

4.3 Hybrid Architectures

Key design issues and different approaches of photonic packet switching and routing will be discussed in the rest of the chapter. The discussion will focus on photonic approaches to packet routing including optical buffering, packet header recognition, and packet switching and packet synchronization. Figure 4.1 shows the general schematic diagram of a hybrid photonic routing algorithm.

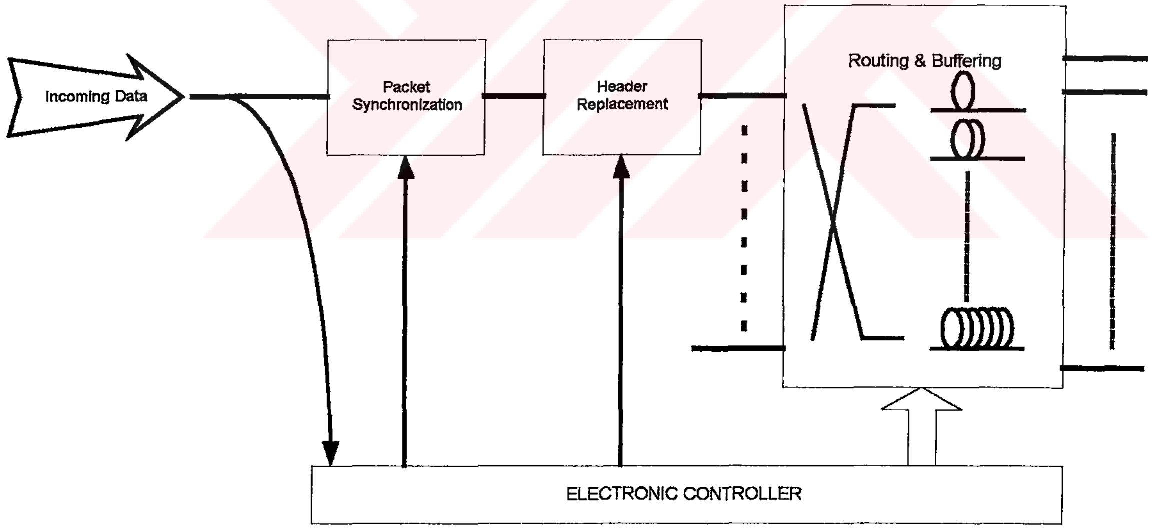

Figure 4.1 Schematic of general hybrid photonic packet routing

4.3.1 Electro-Optic Routing

There have been a number of recent proposals [47] and experimental demonstrations of hybrid photonic packet switching and routing techniques in university and industrial laboratories. The switching and/or routing components in these demonstrations have generally been optical. However, electronic and optoelectronic components remain attractive alternatives to photonic devices in functions such as address processing, switching and buffering controls. Large photonic packet switches will probably rely on electronics for control functions (electro-optic switches), while the packet routing and buffering is being carried out by photonic means.

This approach provides very large capacity through the transparency of the photonic devices, combined with the functionality and processing power of electronic control circuits. Header processing is an important problem in hybrid algorithms. As the header has to be processed at each switch node, it is desirable that the header has a relatively low fixed bit rate suitable for electronic processing (say, less than 10 Gb/s); while the payload could have a variety of bit rates ranging from 10 Gb/s to 100's of Gb/s [48].

The lack of optical equivalents to electronic random access memories and electronic processing capabilities has resulted in hybrid optoelectronic implementation of photonic packet switched systems. Photonic implementation of packet header recognition and synchronization is another key in the realization of truly optical transparent packet switching systems. Some of the techniques will be discussed in detail later in the thesis.

4.3.2 MEMS Optical Switches

The core of the packet switch is the switch fabric. There have been numerous schemes proposed to construct an N x M optical switch in the past few years. The fabrication of even a small switch unit, such as a 1 x 2 or 2 x 2 switch block, involves many physical issues. Conventional mechanical switches suffer from large size, large element mass, and slow switching time. Guided-wave solid-state switches impose limited cascadability, high crosstalk, and large size. Meanwhile, micro-electro-mechanical-systems (MEMS) technology is beginning to impact many areas of science and industry. It has shown a bright future of achieving high-quality and high-port-count optical switching. MEMS devices are built in a similar manner. Various layers of different materials are deposited and patterned to produce complicated, multilayer, three-dimensional structures. Most MEMS switches make use of movable torsion mirrors to redirect the propagation direction of light and achieve the switching functionality. They can provide low loss and low crosstalk while remaining compact in size and providing good economy [49].

4.3.3 Multi-Protocol Lambda Switching

For the control of all kinds of Optical Cross Connects (OXCs), the Multi-Protocol Lambda Switching (MPLambdaS) approach was proposed by IETF [50]. According to this approach, the MPLambdaS traffic engineering control plane is used as the control plane of the OXCs. This concept originated from the observation that an MPLambdaS capable IP router, which is called Label Switching Router (LSR), and an OXC have many similar functional characteristics. First of all, they both decouple the control plane from the data plane. From a data plane perspective, an LSR switches packets according to the label that they carry.

An OXC uses a switching matrix to connect an optical signal from an input fiber to an output fiber. From a control plane perspective, an LSR bases its functionality on a table that maintains relations between incoming label/port and outgoing label/port. An OXC bases its functionality on a switching matrix that maintains relations between incoming wavelength/fiber and outgoing wavelength/fiber. It must be pointed that in the case of the OXC, the table that maintains the relations is not a software entity but it is implemented in a more straightforward way, e.g. by appropriately configuring the MEMs of the optical switching fabric. More specifically, LSRs manipulate packets that bear an explicit label and OXCs manipulate wavelengths that bear the label implicitly; the wavelength itself is the label.

The MPLambdaS control plane has been already used in ATM and Frame Relay networks. The fact that OXCs manipulate wavelengths is because optical packet processing is infeasible with existing optical technology. There are predictions that optical packet processing will be feasible in about ten years time [50]. The MPLambdaS approach seems to have a strong industry momentum. There are already many manufacturers that have announced the development of OXCs that use the MPLambdaS traffic engineering control plane. The main advantage of the MPLambdaS approach is that it offers a framework for real-time optical path establishment. In addition it uses already existing and deployed protocols while it simplifies network management because this can be performed in a unified way in both the data and the optical domain.

Furthermore, it offers a functionality framework that can accommodate future expectations concerning the way networks will work and the way services will be provided to clients [51].

4.4. Key Building Blocks of an All-Optical Node

Figure 4.1 shows the schematic diagram of a general optical node. As shown in this diagram key functions affecting the operation include (a) packet routing, (b) packet buffering, (c) packet header replacement, and (d) packet synchronization and timing recovery. Truly photonic switches require photonic implementations of all these functions. Packets generally have affixed duration and consist of a header and a payload. The header contains routing information and other control information. The use of fixed length packets can significantly simplify the implementation of packet contention resolution and buffering, packet routing, as well as packet synchronization. Routing of 32 byte fixed size packets with 4-bit headers is simulated using the novel architecture. So the use of simple optical delay lines could be possible for buffering operation (Figure 4.2).

Packet header recognition is an important operation in packet switched computer networks because it carries the important information about the packet destination address. To satisfy the packet propagation transparency, it is necessary that the header recognition be carried out photonically. High-energy separator bits, codewords, synchronization signals, packet labeling or different wavelengths for header bits can be used to simplify the operation.

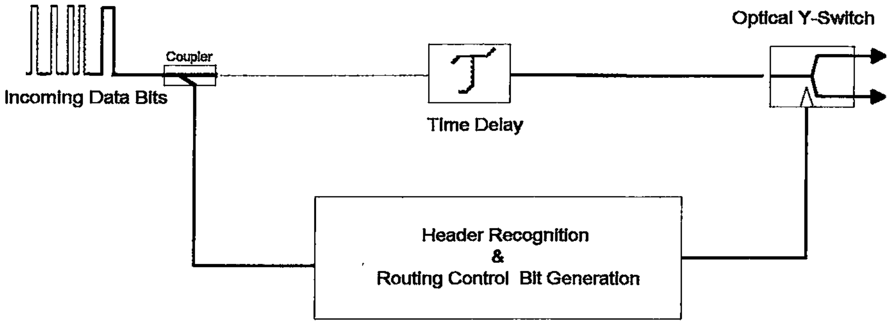

Figure 4.2 Schematic of general optical node

As shown in Figure 4.2, buffering of photonic packets somewhere within the switch fabric is essential to prevent packet contention. Each packet should be held in buffering element until the path decision is made. The difficulty in implementing fully functional photonic equivalents to the electronic random access memory (RAM) makes clocked optical buffering and synchronization difficult. One possible approach to the photonic buffering problem is to use fiber delay lines either in recirculating or traveling configurations. Deflection routing may offer an attractive approach to circumvent packet contention in distributed systems, in which the order of packet arrivals cannot be guaranteed.

Optical signal processing remains to have an important role in such functions as address recognition, switching and buffering controls. To achieve satisfactory performance, significant efforts are required in developing key devices and components.

4.5. Techniques and Architectures of Optical Routing and Switching

During the development of optical packet switched networks, the most prominent and early project was the ACTS KEOPS [52,53] Project which addressed the analysis and demonstration of optical transparent packet switching within all-optical network architectures by means of network and system studies, and laboratory demonstrations based on components developed in the project. Since the KEOPS node architecture uses wavelength conversion to achieve switching, it can apply optical buffering or optical buffering plus wavelength conversion for contention resolution. WASPNET [54] is another research collaboration between three British universities. The project involves determining the management, system, and device ramifications of an optical packet network applying wavelength conversion plus buffering for contention resolution. In addition to the above projects, there are several other projects ongoing across the globe. In the future, optical tag switching, micro-electro-mechanical systems (MEMS) [55], photonic slot routing, and optical burst switching, among others, will likely play an important part in the architecture and system of photonic packet switched networks.

4.5.1. Deflection Routing

Optical buffering was inspired by its conventional electronic network counterparts. In a network deploying optical buffers, each guaranteed to arrive at its destination along the shortest possible path, and for a given connectivity the expected number of hops is minimized. Especially in unslotted (asynchronous) networks buffer elements implement amount of hardware and complex electronic controls. Another issue that arises with optical buffers is that the optical signal suffers from power loss in the delay lines, and optical amplifiers are often used. The accumulated noise from the cascaded amplifiers can severely limit the network size at very high bit rates, unless expensive signal regeneration is applied. In deflection routing, as the name implies, contention is resolved as follows: if two or more packets need to use the same output link to achieve minimum distance routing, only one will be routed along the desired link, while others are forwarded on paths which may lead to greater than minimum distance routing. Hence, for each source-destination pair the number of hops taken by a packet is no longer fixed. Deflection routing does not necessarily exclude the use of optical buffers. The most simplification can be obtained with hot-potato routing, which is a special case of deflection routing, where buffers are not provided at all.

Deflection routing plays a prominent role in many optical network architectures, since it can be implemented with no optical buffering. Asynchronous (unslotted) deflection routing combined with limited buffering can help avoid complex synchronization schemes and provide decent performance with careful design. In general, deflection routing presents more choices to the network designer, while many problems, such as packet reordering and the impact of deflection degree, remain to be more thoroughly studied [49].

4.5.2. Optical Tag Switching

The current Internet Protocol requires a complicated IP header to be processed on a hop-by-hop basis. This involves hundreds of lines of software processing, which could impose a bottleneck in the future as fiber link speeds approach terabits per second. Tag switching, as an alternative approach, has been proposed to simplify the packet forwarding process. It assigns a short fixed-length label containing routing information, a so-called tag, to multiprotocol (i.e., IP, ATM, frame relay, etc.) packets for transport across interconnected subnetworks.

A tag switched network consists of;

- Tag edge routers, which are located at the boundaries of the Internet and apply tags to packets
- Tag switches, which switch tagged packets based on the tags
- Tag distribution protocol, which is used to distribute tag information between nodes

The tag switches use the routing table generated by routing protocols to assign and distribute tag information via the tag distribution protocol, while they also receive tag information and build a forwarding table for local switching. When a tag edge router receives a packet for forwarding across the network, it analyzes the network layer header, performs applicable network layer services, selects a route for the packet, and applies a tag to the packet. Then it forwards the packet to the next-hop tag switch. The tag switch receives the tagged packet and switches the packet based on the tag, without reanalyzing the network layer header. The packet reaches the tag edge router at the exit point of the network, where the tag is removed and the packet delivered [49].

4.5.3. All-Optical Label Swapping

In fiber-based optical networks, next generation optical IP routing will require technologies to support packet routing and forwarding operations at Terabit wire rates that are compatible with wavelength division multiplexed (WDM) transmission and routing. Up to 50 % of IP traffic consists of packets smaller than 522 bytes and 50 % of these packets are in the 40–44 byte range. New low-latency packet forwarding and routing technologies will be required that can handle wire-rate routing of the smallest packets at rates in excess of Gigapackets/s. These technologies should support new streamlined IP routing protocols such as Multiprotocol Label Swapping (MPLS) that simplify route lookup and separate the routing and forwarding functions [56].

All-Optical Label Swapping (AOLS) implements the packet-by-packet routing and forwarding functions of MPLS directly in the optical layer. This is in contrast to next generation commercial optical networks, that will use MPLS to set up optical circuits over which flows of electronic packets are routed. For future optical networks, it will be desirable to perform optical routing layer functions independent of the IP packet length and payload bit rate. AOLS approaches should interface seamlessly to both

WDM and TDM systems. This leads to the concept of using optical labels to "encapsulate" the IP packet in the optical layer. The optical label format is chosen to best match the optical routing and forwarding technology and to satisfy other constraints in the optical layer.

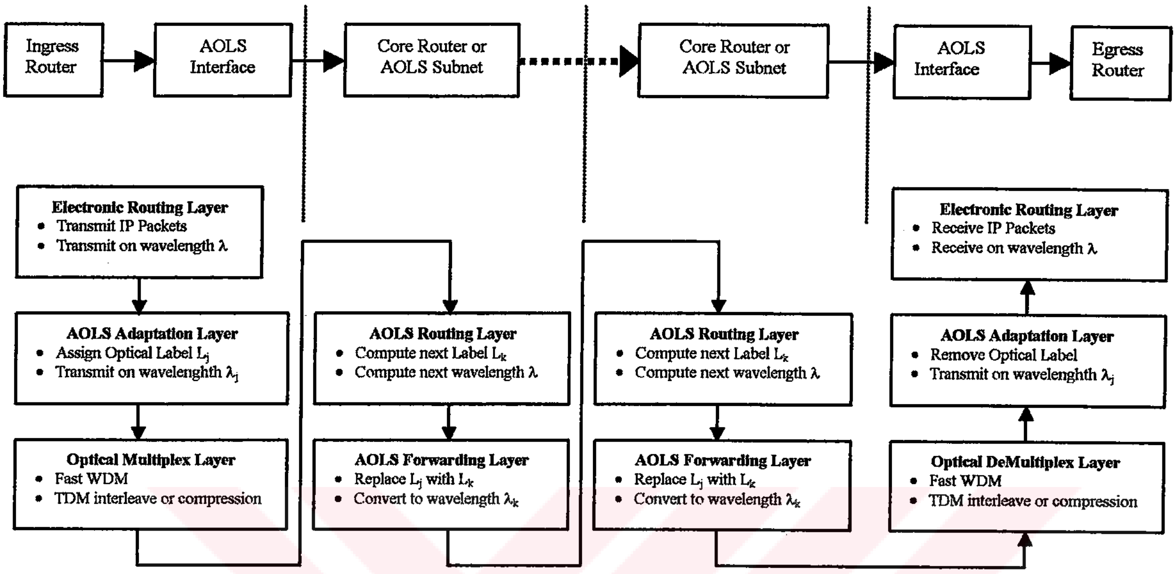

Figure 4.3 Layered routing and forwarding hierarchy and associated network element connection diagram for an AOLS network

An AOLS optical packet core network is illustrated in Figure 4.3. IP packets enter the core network at an ingress router and travel multiple hops through the core, exiting at an egress router. Packets are handled within the network by core AOLS routers or AOLS subnets. Fiber links and the packet-switched network hierarchy connect the network elements. IP packets are generated at the electronic routing layer and processed in an adaptation layer that "encapsulates" IP packets with an optical label without modifying the original packet structure. If necessary, the adaptation layer shifts the packet and label to a new wavelength specified by local routing tables. An optical multiplexing layer multiplexes labeled packets onto a shared fiber medium. Several optical multiplexing approaches may be used including insertion directly onto an available WDM channel, packet compression through optical time division multiplexing or time interleaving through optical time division multiplexing. This technique is not limited to IP packets and other packet or cell structures like ATM may also be routed.

Once inside the core network, core routers or AOLS subnets perform routing and forwarding functions. The routing function computes a new label and wavelength from an internal routing table given the current label, current wavelength, and fiber port. The routing tables at egress and core routers are generated by converting IP addresses into smaller pairs of labels and wavelengths and distributing them across the network much in the same way that multi-protocol label switching (MPLS) is used in today's IP networks. The forwarding function involves swapping the original label with the new label and physically converting the labeled packet to the new wavelength. Other switching or buffering mechanisms (space, time, etc.) are also configured in the forwarding process. The reverse process of optical demultiplexing, adaptation and electronic routing are performed at the egress node [56,57].

4.5.4. Photonic Slot Routing

A WDM network offers wavelength conversion as one more dimension of switching. On the other hand, taking advantage of this feature requires fast control and wavelength-selective devices, which can dramatically increase the network cost. Photonic slot routing (PSR) was proposed as an alternative to using WDM only as a way to multiply network capacity, thus reducing node complexity and cost, and facilitating network scalability. According to this concept, packets transmitted in the same time slot (photonic slot) on all wavelengths are switched jointly. The switching node is only required to handle each slot as a whole, without having to access and switch packets on different wavelengths individually. At each node, packets destined for a specific node are transmitted on the available wavelength in the slots assigned to that particular node. If a slot is not assigned, it can be assigned by the first packet transmitted in that slot under a certain fairness control protocol: Contention can be resolved using switched delay lines. The Photonic Slot Routing approach is a solution of wavelength selective switching and problem of finding effective access protocols at the source nodes [49].

4.5.5 Optical Burst Switching

Optical burst switching was proposed as another way of implementing packet switching optically to avoid potential electronic bottlenecks. The basic unit of data to be transmitted is a burst, which consists of multiple packets. The data burst is sent after a control packet reserves necessary resources on the intermediate nodes without waiting for acknowledgment from the destination node (as in the virtual circuit setup process in ATM). Optical burst switching could achieve high bandwidth utilization with lower average processing and synchronization overhead than pure packet switching since it does not require packet-by-packet operation. It is also possible to implement quality of service (QoS) by manipulating the offset time between the control packet and the data burst [58].

CHAPTER 5

A NOVEL ROUTING ARCHITECTURE FOR ALL-OPTICAL PACKET SWITCHED COMPUTER NETWORKS

In this chapter, a novel all-optical routing architecture for packet switched computer networks will be proposed. Main components of the system are optical buffering, header recognition, pulse extension, routing table pulse generation, optical XOR gates and threshold elements as shown Figure 5.1. Header recognition and parallel to serial conversion of header bits is the first step of the procedure. XOR operation between routing table and extended header pulses is the core operation of the system. Afterwards a control bit for the switching operation is generated by a novel method. Delaying original data packets is realized with choosing appropriate buffering technique that holds the data packets for a time interval during the whole decision process for the given network protocol. Finally, generated control bit signal sets the optical switch that depending which route the data packet takes.

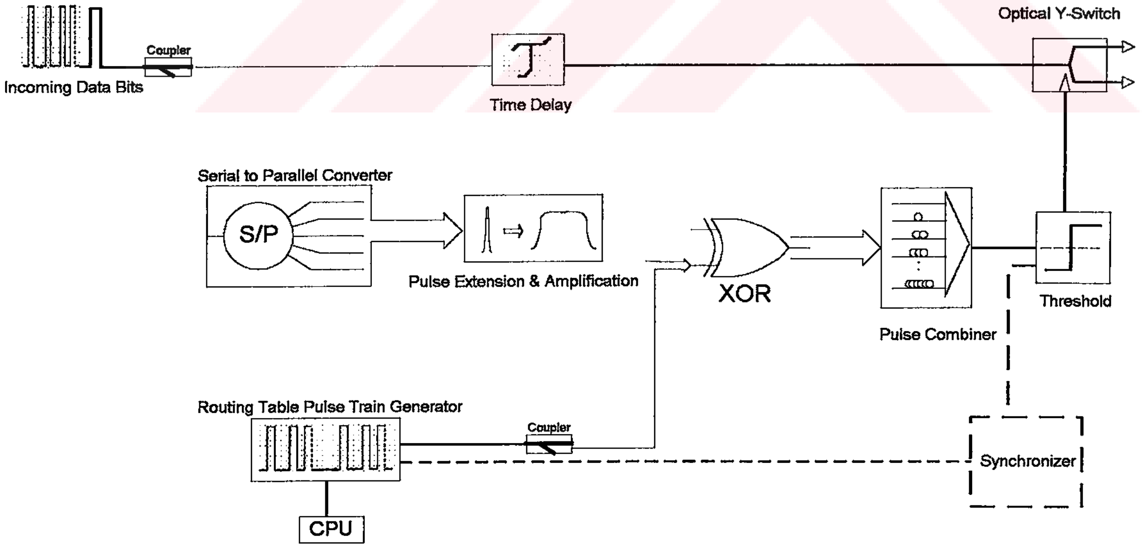

Figure 5.1 Main Components of the All-optical Routing Architecture

5.1 Header Recognition

In packet switched networks communication between the source and destination network devices is performed using data packets. Every packet includes a part named header, which convey destination address of the packet. At every node of a network topology the destination address is checked and the packet is sent to an appropriate port of a network device of the system. Various routing algorithms may be designed for this purpose.

Header bits can be separated from the data bits using different techniques. High-energized separator bits, synchronization pulses, codewords, different wavelengths or fixed time slots are some of this techniques. In the simulation, fixed length data packets and address bits are used, but the adaptation of the system to other header types (like MPLS and DWDM) is possible as well. 4-bit destination address header plus 32-byte of data is sent to the input of the system as integrated data packets. To extract address bits from the packets a synchronization signal is used. This signal can be fed to the system externally or, using the data separator bits it may be generated from the data packet. Recovering a clock signal from the original datagrams is another alternative that may be used to produce a synchronization signal.

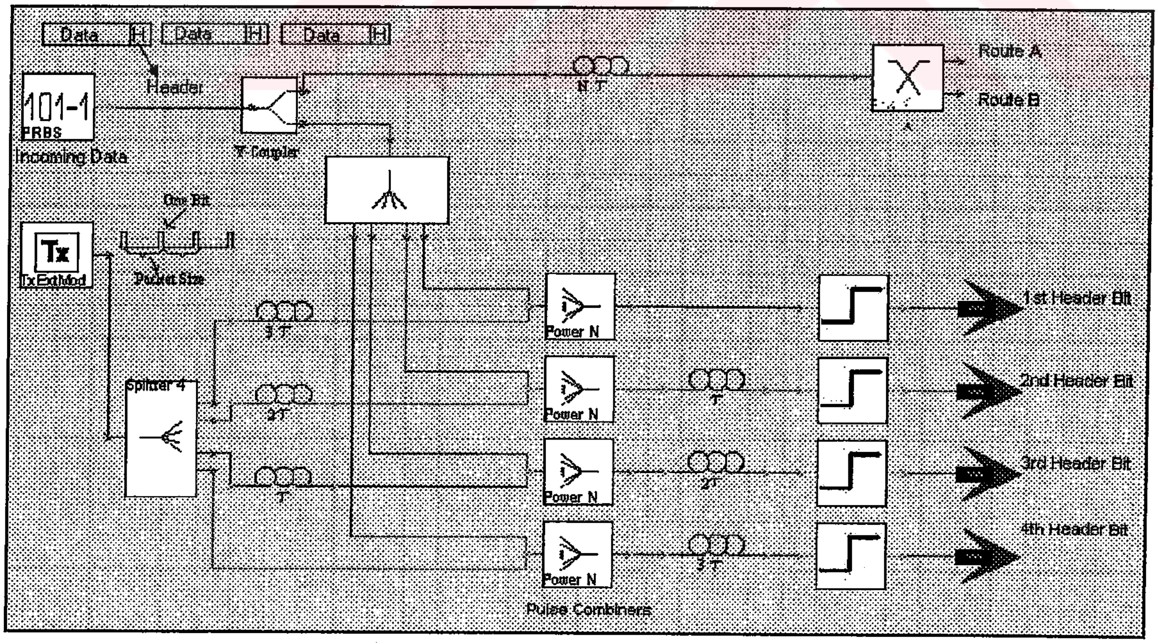

Figure 5.2 Parallel to Serial Conversion of Optical Header Bits

First step of the operation is to decompose a small amount of the signal power with a Y-coupler. This splitted data will be processed in the routing operation. The main data is sent to a fixed time optical buffer or delay line –a simple fiberoptic cable- which holds the packet during the whole operation. The initial 4-bits of each data packet are taken for header bits in the simulation. A synchronization signal and the coupled information signals (Y-coupled data packets) are summed using a pulse combiner (Coupler). If the time delays are adjusted appropriately, each synchronization pulse matches an address bit consecutively. After the pulse combining operation, a threshold device [12,19] is used to obtain the header bits in parallel. The threshold value should be set at the point that allows a logical AND operation between the address bits and synchronization pulse. The output of each threshold device gives us the header bits in parallel. All optical header recognition and serial to parallel conversion unit is simulated as in Figure 5.2.

5.2 Pulse Extension

The next step of the algorithm is to extend every bits of parallel address sequence in the time domain. The aim of the pulse extension is to prepare the header

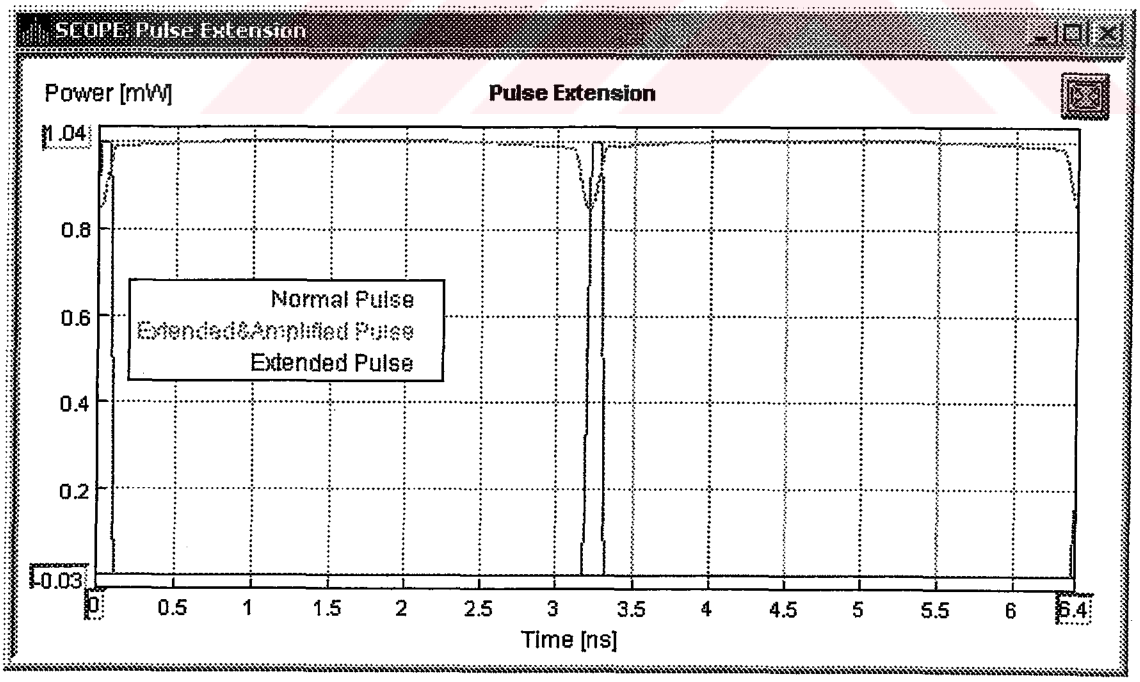

Figure 5.3 Extension of a 0.1 ns Optical Pulse

information bits for XOR operation [32] with routing table pulse train. Routing table is a sequence of pulse trains, which is all address bits in series form. In the routing procedure, routing table and each address bit should be XORed together. Uniform Bragg grating filter is used to extend the pulse up to the desired width. The pulse is dispersed in the time domain by adjusting the filter bandwidth and the filter order. Signal amplification is needed as well because of the power lost during the extension step. Simulation results of a pulse extension and amplification of a 0.1 ns and 1 mW optical pulse is shown in the Figure 5.3.

As an alternative the combination of fiber Bragg grating and EDFA can be used for the pulse extension amplification phase. If the bandwidth of the EDFA is appropriately selected, it can do both the extension and amplification step of the procedure. Optical materials with longer relaxation times could be an another alternative solution to the problem. Triggering of this sort of optical materials or semiconductor laser diodes in on-off keying approach may be a solution too.

5.3 Routing Table Pulse Train Generator

Applications like large capacity OTDM systems, optical soliton transmission and ultra-fast data processing requires generation of ultra-short ultra-fast optical pulses. Compact, reliable and high quality optical pulse sources are the most important parts of a pulse generator.

The mode locked laser diode (MLLD) is preferred in many applications for its excellent features over any other optical pulse sources. MLLD has very high repetition frequency exceeding several tens of GHz, very short pulse width ranging picoseconds till subpicoseconds and small frequency chirping. Mode locked laser diodes can increase data capacity of OTDM systems and communication applications. By applying special pulse timing control methods and MLLD architectures in parallel approach high-speed ultra-short pulse generations at THz region is feasible [19,20].

In this novel architecture, pulse train generators should be as fast as possible (10 Gbit/s – 10 Tbit/s) to speed up the whole process. The speed of the pulse train generator has an effect on the routing table size and the optical buffer length. The relationship will be shown later in this thesis.

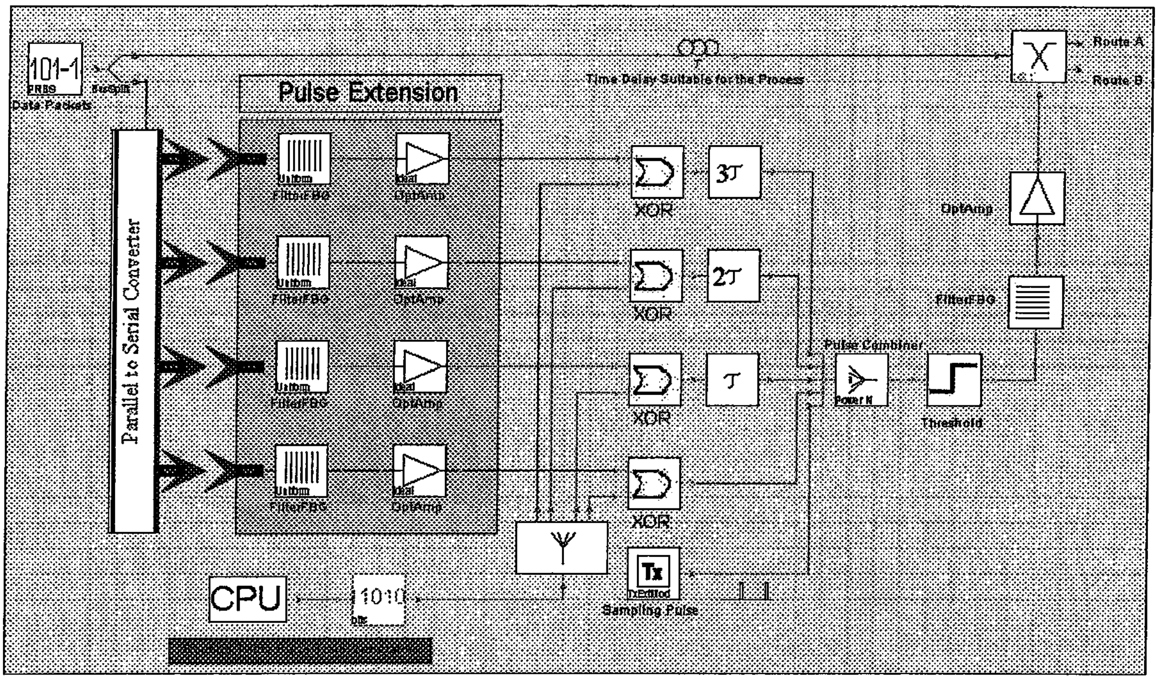

Figure 5.4 All-Optical Routing Architecture.

Routing table pulse train and parallel header bits are sent to an optical XOR gate. XOR operation is used for searching the address information in the routing table. An ultra-fast pulse source generates pulse trains. This generator is driven by a simple processor (CPU). CPU keeps routing table and updates it using one of the known routing algorithms (Link State Algorithms or Distance Vector Algorithms) as needed. Depending on the routing algorithm protocol used, the routing tables are updated in the time interval between 30 sec. and 120 sec. This algorithm has an acceptable speed for electronics and it does not limit the process.

In the simulation shown in Figure 5.4 a 100 Gbit/s pulse generator is used to generate the required routing table pulse train. In the 4-bit destination address scheme there are 16 possible addresses. Five of them are used as routing table for the Route A. When an address of a data packet is in this routing table, it takes the Route A, if not it will be sent to the default port of the router Route B. Five addresses are used to generate a 20-bit long routing table. It is generated by the pulse train generator as repeated pulse trains to make it available for the next coming address bits [59].

5.4 XOR Operation

Extended pulses obtained from the header bits are XOR-ed with the strings of the routing table. If bits of an address word match exactly to an address in the routing table, a series of optical logic 1's will occur at the XOR outputs. The number of optical 1's should be equal to the number of address bits for a full match. The synchronization between XOR outputs is satisfied with time delay elements (one bit each, in the time domain). As an alternative, time delay operation may be applied to the routing table pulse trains at the pulse splitter output. The delay operation of the routing table pulse train gives us the opportunity to get rid of the other synchronization delay elements at the architecture. All of these synchronized bits are collected with a pulse combiner and applied to a suitable threshold device. Threshold devices used in this architecture work with nonlinear Kerr-effect principle as mentioned in Chapter 3 and it is easy to adjust the threshold value to logic 1 level by the order of the operation and by changing refractive indexes and the number of layers of the materials. An optical pulse is added to the pulse combiner at an appropriate frequency to sample address bits at the right time interval. This sampled address bit is necessary for synchronizing the address word and to avoid inter byte matching errors.

5.5 Simulation Results

Photonic Transmission Design Suite, Photonic Module, Optical Design Module and Optical Networking Module of the software Virtual Photonics 3.1 are used for simulating the architecture. This design software includes many optical tools. Optical pulse generators, modulators, couplers, delay elements, interferometers, pulse splitters, pulse combiners, optical switches, Bragg grating filters, fiber amplifiers and many different types of optical devices were already available with the software. But devices like optical threshold element and XOR logic gate, which are not involved in the software, were designed using signal processing tools. Kerr effect principle [12] is used to model the threshold element mathematically and the analysis results of Ref. [31] and [32] are used to realize the XOR gate. In the simulation, there was no synchronization problem between the elements, but in implementation of the architecture some stability and synchronization problems may occur. Optical devices and fiberoptic cable lengths should be adjusted carefully to avoid some possible problems.

R.T. Pulse Train		0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	0	0	0	0
1st Bit	0	τ	τ	τ	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1
2nd Bit	0	τ	τ	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1	1
3rd Bit	1	τ	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	0	0	0
4th Bit	1	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1

Table 5.1 The XOR Operation of the Matching Address Bits

R.T. Pulse Train		0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	0	0	0	0
1st Bit	0	τ	τ	τ	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1
2nd Bit	0	τ	τ	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1	1
3rd Bit	0	τ	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1	1	1
4th Bit	0	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1	1	1	1

Table 5.2 The XOR Operation of the Matching Address Bits

R.T. Pulse Train		0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	0	0	0	0
1st Bit	1	τ	τ	τ	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	0
2nd Bit	1	τ	τ	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	0	0
3rd Bit	0	τ	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1	1	1
4th Bit	0	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	1	1	1	1

Table 5.3 The XOR Operation of the Mismatching Address Bits

In the example (Table 5.1, 5.2 and 5.3) the routing table includes five of the sixteen addresses that will be routed to the Route A. For each of these addresses an optical control bit has to be generated for the optical switch [60]. The control bit will trigger the optical switch and let the packet transmitted through the correct path, Route A. In Table 5.1 the destination address of the packet is 0011. The routing table includes this address. Therefore, a series of 1's will be generated at the XOR output. However, in the second case (Table 5.2) destination address is chosen as 0000. This address will not to be properly processed since the routing table includes this address and also the shifted versions of the address bits. As a result, there will be four sets of the series of 1's at the XOR output. At this point, the sampling pulse takes the charge and solves the problem by choosing the proper set of the XOR outputs. Since the correct set of optical 1's occur at the integer multiples of each 4 time slots, adding a sampling signal to the pulse combiner and thresholding the sum with appropriate threshold value helps us to collect the right control bits. The marked sets in the tables correspond to the right sets to be sampled. Figure 5.5 and Figure 5.6 show the simulation results in detail. A 6 mW threshold device becomes sufficient for generating optical switch control bit.

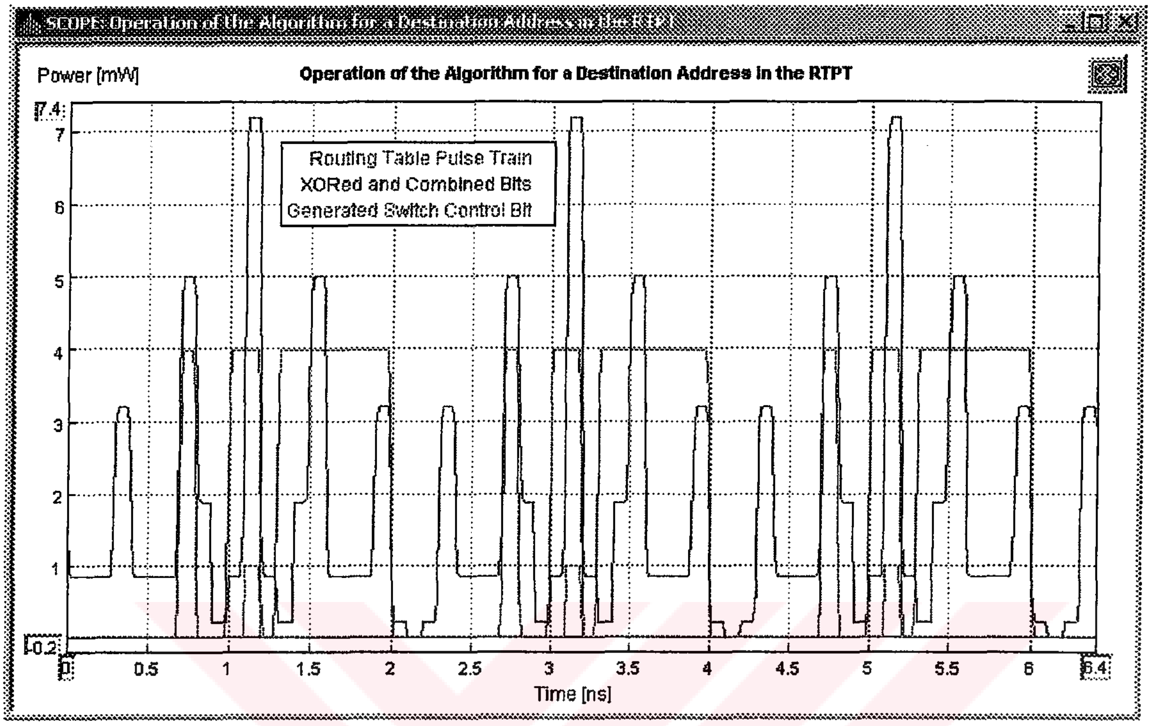

Figure 5.5 Generation of the Routing Control Bit for Matching Address Bits

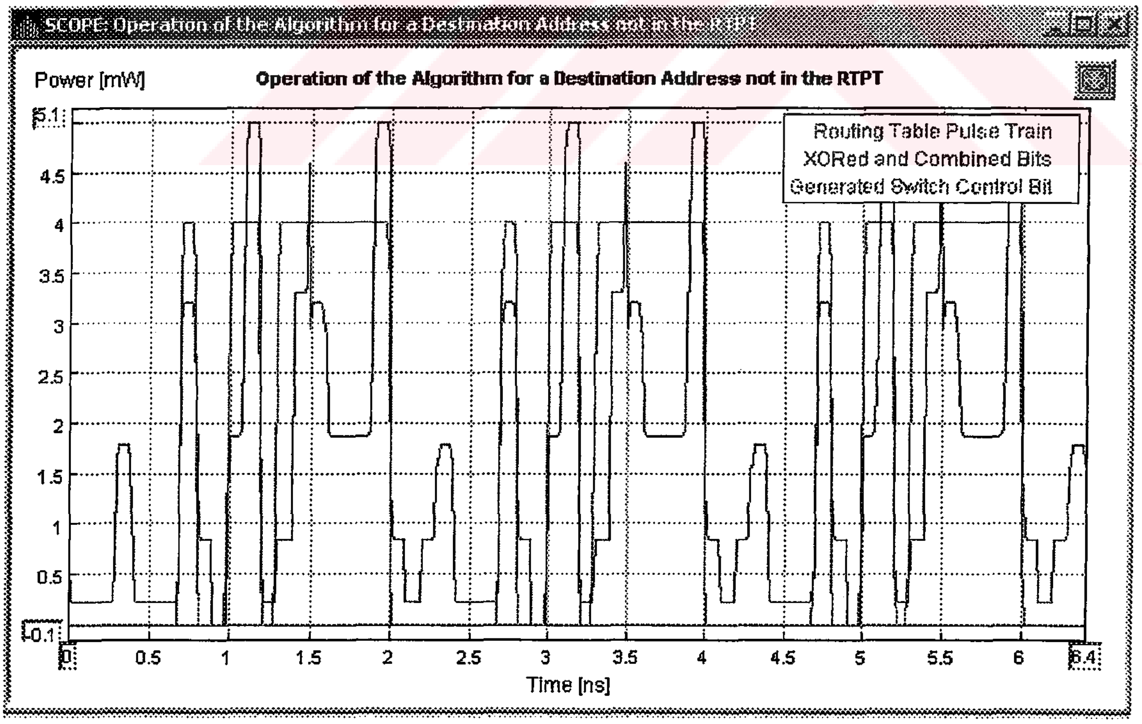

Figure 5.6 Generation of the Routing Control Bit for Mismatching Address Bits

A critical point in this issue is of the size of the routing table. It depends on the size of the packet and header, packet bit rate, routing table generation rate and the total time delay applied to the packet. The parameter N used in the formula is the integer multiple number of the optical buffer length in terms of packet propagation speed.

$$\text{Routing Table Size} \approx N \times (\text{Packet Size}) \times (\text{Routing Table Generation Rate}) / (\text{Header Size} \times \text{Packet Rate}) \qquad (5\text{-}1)$$

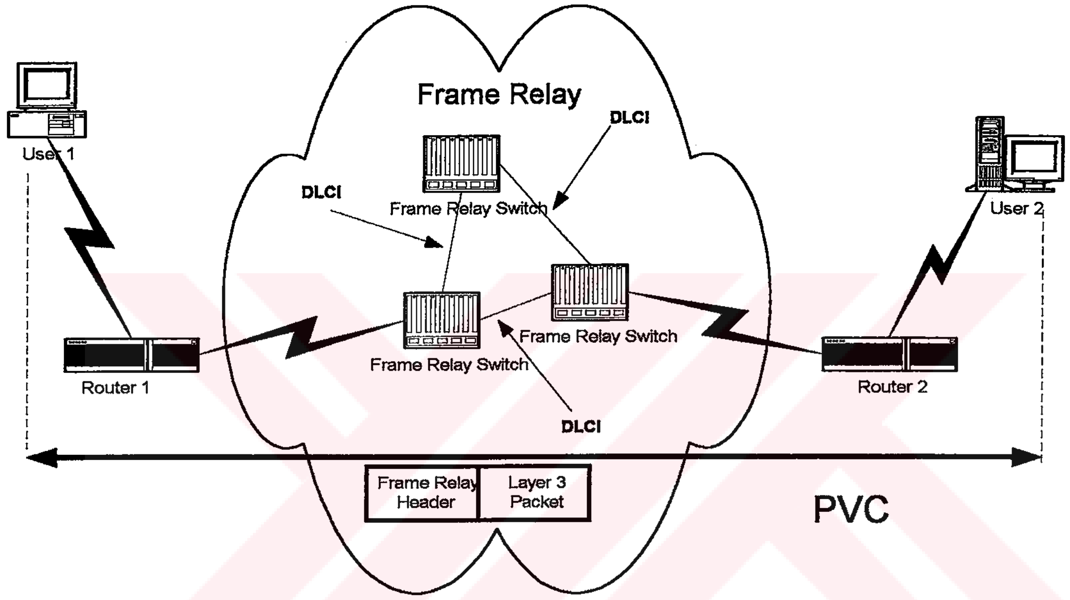

Figure 5.7 General Structure of Frame Relay Networks

As an application, the routing table size is calculated for a frame relay network (Figure 5.7). Frame Relay is a connection-oriented data transport data service for public switched networks. Frame Relay has a 2-byte header that contains address information for routing, congestion control information, for notification and enforcement and a C/R bit whose usage is application-specific. Frame Relay is a packet-switched data network designed to be simpler and faster than X.25 (ITU-T standard that defines how connections between user and carrier are maintained for remote terminal access and computer communications in Public Data Networks. X.25 specifies a data link layer protocol, and a network layer protocol.). Frame Relay has none of the reliability features or the complexity of X.25. The simplicity of Frame

Relay is due to the vastly improved error rates thanks to fiber-optic transmission systems. Frame Relay defines the connection between a customer and a carrier. The customer is typically a router, and the carrier is a Frame Relay switch [1].

Permanent Virtual Circuits (PVC) are used for connections in a frame relay network. PVC is assigned between two users when they describe a frame relay service. A PVC is identified at the network interface by 12-bit data link connection identifier (DLCI). DLCIs specify and distinguish separate connections across an access link therefore, they can be used to route (multiplex) several connections [1].

For a 522 byte data packet, 10 Gb/s Packet Bit Rate, 100 Gb/s Routing Table Pulse Train Generation Rate and N=3 (Time Delay is equal to triple packet length) the routing table size is 10440. This number is sufficient for a network device. Especially, core routers of autonomous systems require faster routing operation and smaller routing tables.

The main advantage of the architecture is its protocol transparency. The main data packets are routed and sent to another hop without any data conversion. The original datagrams remain unchanged during the end of the process.

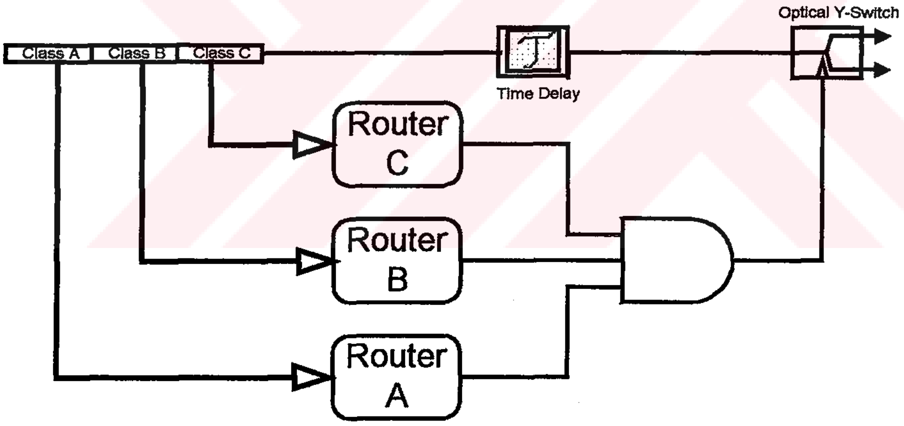

Figure 5.8 A Parallel Approach for Network Protocols with Classified Addresses

The proposed routing architecture may work in a parallel manner for reaching faster switching and routing operations, and keeping smaller routing tables. Figure 5.8 shows a parallel approach for classified network addresses. The system consists of these all-optical routers mentioned above. Each router has its own routing table for the given address class (Class A, Class B, Class C). They process the unique set of address classes and generate switch control bits. After a logical operation between these bits a final control bit is generated to route the data packets. Figure 5.9 shows another algorithm for classified network protocols with multiple outputs.

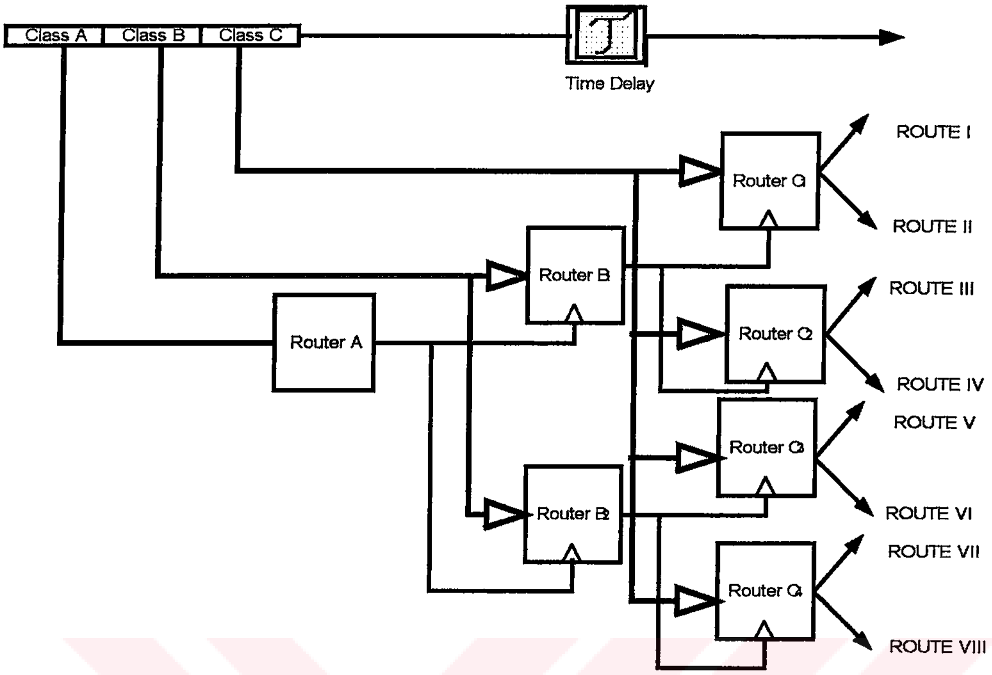

Figure 5.9 An Algorithm for Classified Network Protocols with Multiple Outputs

CHAPTER 6

CONCLUSIONS

Optical communication links have brought a huge impact on networking. Nowadays they are capable of carrying information at Terabits per second using DWDM or OTDM Technology. At these high-speeds, electronic network devices limit the system. The all-optical router can overcome the bottleneck of optoelectronic conversions and meet the demands in high-speed networks.

There are too many architectures and systems proposed for future photonic packet switched networks. There are many issues involves routing, synchronization, contention resolution, header format/updating, switch fabrics, physical impairment of the devices, network control, protocol, and so on. Some of the important aspects were covered in this thesis.

Optical packet switching is promising because it offers much higher capacity and data transparency. It is important for network designers to reduce the number of protocol layers being used in today's networks, while preserving the functionality and making use of the current optical technology. The Novel All-Optical Routing Architecture, proposed in this thesis, provides both protocol transparency and routing operation at data link layer. Routing at data link layer is an important aspect to overcome the limitations of the multi-layer protocol stacks.

Today, service providers (Telecom companies) have been using different kinds of networking technologies and protocols to build a network infrastructure. Multi-layered network architectures use fiberoptic cables and multiplexing techniques for efficient usage of bandwidth (WDM, OTDM, DWDM). Typically there are four layers in the current data network architecture: IP, Asynchronous Transfer Mode (ATM), Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) and WDM (DWDM and OTDM as well). Any one layer of the multi-layered hierarchy can effect the performance, because the limitation in one of the layers effects the entire network.

SONET/SDH provides efficient bandwidth utilization and security applications but it does not allow intelligent routing. ATM has advantages like, providing multi-service integration, quality of service (QoS) and statistical multiplexing but it suffers in data transportation because of its overhead traffic (%23 of the ATM traffic). The solution is the routing of the IP packets at the data link layer (IP over WDM) in the autonomous systems and using alternative routing techniques like Multi Protocol Label Switching (MPLS) and Photonic Slot Routing. Using all-optical backbone (core) routers is the key point of such a structure. The proposed architecture could be used as the core router in autonomous systems and Intranets. By improving the performance and by using appropriate network protocols it may be suitable both the ingress and egress routers.

The architecture is very flexible and can be implemented into the different kinds of networking protocols. It is a protocol transparent architecture. The main data packets are routed and sent to another network node without any data conversion. The original data packets remain unchanged during the end of the routing process.

The proposed architecture is designed using realizable optical networking elements. The operation principle of each element is explained in the thesis. Most of the elements are currently in use and devices like optical threshold elements, Bragg grating pulse extenders and optical XOR gates are deeply discussed in the text. Pre-results in the laboratory environment, which are mentioned in the text, of the devices are affirmative as given in references.

In the simulation, data packets having 100 Gbit/s bit rate and 4-bit header is routed successfully into the desired path. The speed of the routing algorithm is limited with the speed of the XOR element. If the XOR element could be updated, the proposed architecture can be designed for operation at higher bit rates. Parallel and serial approaches of the architecture are also possible. Classified network address like IP addresses can be routed in parallel all optical routers to speed up the whole process.

Most optical signal processing tools suffers from synchronization and stability problems because of the high data rates. Synchronization of the data bits may be another problem of the architecture. The optical cable lengths for delay elements or active buffers should be adjusted carefully to minimize the time jitter problem.

Routing table size is a critical factor for most applications. Routing with address prefixes or parallel approach for classified addresses can decrease the required routing table size. In a typical core router the routing table holds 200 to 3000 addresses. Routing table size of the proposed architecture might be big enough for core routers as defined by Eq. (5-1)

The simulation software used was only the trial version of Virtual Photonics 3.1 (VPI). It was limited by two months of use. Thus, some design parameters as noise or losses could not be included in the thesis. Only default noise and loss parameters were taken into account. Future work may be simulating the proposed architecture with different parameters and with more network traffic. Implementation to different types of routing techniques (like MPLS) may be another interesting application of it.

As a result, next generation computer networks will rely on optical networking tools and they require faster architectures at network nodes for optimization of the performance. Proposed all optical routing architecture is an efficient alternative for backbone routers or local area network (>100 Gb/s) applications. Certainly,

"The future will be bright,
with more light".

REFERENCES

[1] Wendell Odom, *Cisco CCNA Exam #640-507 Certification Guide,* Cisco Press, Indianapolis, 2000.

[2] Merilee Ford, H. Kim Lew, Steve Spanier, Tim Stevenson, *Internetworking Technology Overview*, Cisco Connection Training multimedia CD-ROM, June 1999.

[3] Catherine Paquet and Diane Teare, *Building Scalable Cisco Networks,* Cisco Press, Indianapolis, November 2000.

[4] Antonio Rodriquez-Moral, Paul Bonenfant, Stefano Baroni, Ren Wu, Optical Data Networking: Protocols Technologies and Architecture for Next Generation Optical Transport Networks and Optical Internetworks, *Journal of Lightwave Technology,* Vol. 18, No. 12, December 2000.

[5] Karen Webb, *Building Cisco Multilayer Switched Networks,* Cisco Press, Indianapolis, 2000.

[6] Catherine Paquet, *Building Cisco Remote Access Networks,* Cisco Press, Indianapolis, 1999.

[7] Andrew S. Tanenbaum, *Computer Networks,* Prentice-Hall, New Jersey, 1996.

[8] Jean Walrand, Pravin Varaiya, *High-Performance Communication Networks,* Morgan Kaufman P., California, 2000.

[9] Frank L. Pedrotti, S.J. Leno S. Pedrotti, *Introduction to Optics,* Prentice Hall, New Jersey, 1993.

[10] Govind P. Agrawal, *Nonlinear Fiber Optics 2nd ed.*, Academic Press, California, 1995.

[11] Dmitry Pelinovsky, Stable All-Optical Limiting in Nonlinear Periodic Structures Analysis, Hamilton, Ontario, Canada, February 2001.

[12] Lukasz Brozozowski, Edward H. Sargent, All-optical analog-to-digital converter for photonic networks using multilevel signaling, Transparent Optical Networks, 2000 2nd International Conference on Page(s): 203-206, 2000.

[13] Lukasz Brozozowski, Edward H. Sargent, Stability of periodic nonlinear optical structures for limiting and logic, *web page,* Toronto, Canada, September 2000.

[14] Bahaa E. A. Saleh, Malvin Carl Teich, *Fundamentals of Photonics,* Wiley&Sons, Canada, 1991.

[15] Henderson, G.N.; Gaylord, T.K.; Glytsis, E.N., Diffraction of ballistic electrons by semiconductor gratings: Rigorous analysis, approximate analyses, and device design, *Quantum Electronics, IEEE Journal of*, Volume: 29 Issue: 1 , pp. 121 –135, Jan. 1993.

[16] Lukasz Brzozowski, Edward H. Sargent, Nonlinear Disordered Media for Broad-Band Optical Limiting, *Journal of Quantum Electronics,* Vol. 36, No. 11, November 2000.

[17] A. W. Synder, J. D. Love, *Optical Waveguide Theory,* Chapman & Hall, London, 1983.

[18] A. Yariv, P. Yeh, *Optical waves in Crystals,* New York, Wiley & Sons, 1984

[19] Lukasz Brzozowski, Edward H. Sargent, All-optical Analog-to-Digital Converters, Hardlimiters, and Logic Gates, *Journal of Lightwave Technology,* Vol. 19, No. 1, January 2001.

[20] Erik Johnson, All-Optical Time-Domain IP Routers Using Optical Limiters, *web page,* Canada, March 2000.

[21] Lukasz Brzozowski, Edward H. Sargent, Nonlinear Distributed Feedback Structures for Optical Sensor Protection, April 2000.

[22] W. W. Morey et al., *Optical Fiber Commun. Conf.,* San Jose, California, Paper WA2, 1992.

[23] W. W. Morey et al., *Optical Fiber Commun. Conf.,* San Jose, California, Paper PDP-20, 1991.

[24] R. Kashyap, G. D. Maxwell, B. J. Ainslie, *IEEE Photonics Technol. Letters,* 5, 191, 1993.

[25] K. O. Hill, G. Meltz, Fiber Bragg Grating Technology Fundamentals, and Overview, *Journal of Lightwave Tech.* Vol. 15, PP 1263-1276, 1997.

[26] C.R. Giles, Lightwave applications of FBG's, *Journal of Lightwave Tech.* Vol. 15, PP 1391-1404, August 1997.

[27] Virtual Photonics 3.1 Simulation Software Users Manual, Photonics Module.

[28] T. Erdoğan, Fiber Grating Spectra, *Journal of Lightwave Technology,* Vol. 15, PP 1277-1295, August 1997.

[29] Hidehiko Takara, High-Sped optical time-division-multiplexed signal generation, *Optical and Quantum Electronics,* 32:795-810, 2001.

[30] S. Arahira, Y. Katoh, Generation and stabilization of ultrafast optical pulse trains with MLLD, *Optical Quantum Electronics,* 33.691-707, 2001.

[31] Theophilopoulos, G.; Yiannopoulos, K.; Kalyvas, M.; Bintjas, C.; Kalogerakis, G.; Avramopoulos, H.; Occhi, L.; Schares, L.; Guekos, G.; Hansmann, S.; Dall'Ara, R, 40

GHz all-optical XOR with UNI gate, *Optical Fiber Communication Conference and Exhibit, 2001*. OFC 2001 , Volume: 1 Page(s): MB2/1 -MB2/3 vol.1, 2001.

[32] Fjelde, T.; Wolfson, D.; Kloch, A.; Dagens, B.; Coquelin, A.; Guillemot, I.; Gaborit, F.; Poingt, F.; Renaud, M., Demonstration of 20 Gbit/s all-optical logic XOR in integrated SOA-based interferometric wavelength converter, *Electronics Letters*, Volume: 36 Issue: 22 , Page(s): 1863 –1864, 26 Oct. 2000.

[33] Bintjas, C.; Kalyvas, M.; Theophilopoulos, G.; Stathopoulos, T.; Avramopoulos, H.; Occhi, L.; Schares, L.; Guekos, G.; Hansmann, S.; Dall'Ara, R., 20 Gb/s all-optical XOR with UNI gate, IEEE Photonics Technology Letters , Volume: 12 Issue: 7 Page(s): 834 -836, July 2000 .

[34] Houbavlis, T.; Zoiros, K.; Vlachos, K.; Papakyriakopoulos, T.; Avramopoulos, H.; Girardin, F.; Guekos, G.; Dall'Ara, R.; Hansmann, S.; Burkhard, H., All-optical XOR in a semiconductor optical amplifier-assisted fiber Sagnac gate, IEEE Photonics Technology Letters , Volume: 11 Issue: 3 , Page(s): 334 –336, March 1999 .

[35] K.L. Hall, K.A. Rauschenbach, S.G. Finn and J.D. Moores, 100 Gb/s Multiacces Networks, http://www.ll.mit.edu/, 2001.

[36] Hon-Fai Yau, Hsiao-Yi Lee, Nai-Jen Cheng, Incoherent All-Optical NAND-NOR-and XOR-Gate using Photorefractive Fanning Effect, *Applied Physics B*, V.68, pp. 1055-1059, 1999.

[37] Hsiao-Yi Lee, Hon-Fai Yau, Nai-Jen Cheng, Incoherent optical XOR logic gate and image subtractor with series self-pumped phase conjugators, *Optical Engineering*, V. 37(7), pp 2156-2161, 1998.

[38] Chen Hongmin, Zhu Guanghao, Dutta Niloy, All-Optical XOR Demonstration, *web page*, June 2001.

[39] P. J. Cullen, W. Blau, J. K. Vij, Operation of an All-optical XOR gate and set-reset flip-flop using nonlinear interference filters, *Optical Engineering*, Vol. 28, No. 12, December 1989.

[40] Perry J. Grenbaum, XOR: A Logical Choice for All-Optical Networks, *Photonics Spectra*, November 2001.

[41] Mike J. O. Mahony, Dimitra Simeonidou, David K. Hunter, Anna Tzanakaki, The Application of Optical Packet Switching in Future Communication Networks, *IEEE Communications Magazine*, pp. 128-135, March 2001.

[42] Govind P. Agrawal, *Fiber-Optic Communication Systems*, John Wiley & Sons, New York, 1992.

[43] J. M. Senior, *Optical Fiber Communication, Principles and Practice 2^nd^ ed.*, Cambridge Univ. Press, Cambridge, 1992

[44] St. Fischer M. Dülk, H. Melchior, All-Optical Signal Regenaration, *Institute of Quantum Electronics*, www.iqe.ethz.ch/me+oe/, Switzerland, 1998.

[45] Tom McDermott, The Marriage of Optical Switching and Electronic Routing, *Lightwave*, pp 72-80, May 2002

[46] Vincent W. S. Chan, Katherina L. Hall, Eytan Modiano, Kristin A. Rauschenbaum, Architectures and Technologies for High-Speed Optical Data Networks, *Journal of Lightwave Technology*, Vol.16, No.12, December 1998.

[47] M. Erdal Özbek, Optical Routing in Packet Switched Networks, Master Thesis, İzmir Institute of Technology, August 2001.

[48] D. Cotter, J. K. Lucek, K. Smith, D.C. Rogers, D. Nesset, P. Gunnig, Self-routing of 100 Gb/s packets using 6 Bit keyword address recognition, *Electronics Letter*, vol. 31, No. 25, December 1995.

[49] Shun Yao, Biswanath Mukherjee, Advances in Photonic Packet Switching: An Overview, *IEEE Communication Magazine*, February 2000.

[50] D. O. Awduche, Y. Rekhter, J. Drake, R. Coltun, Multi-Protocol Lambda Switching: Combining MPLS Traffic Engineering Control With Optical Crossconnects, IETF draft work in progress, April 2001.

[51] Stelios Sartzetakis, Leonidas Georgiadis, Adaptive Routing Algorithm for Lambda Switching Networks, IEEE/ACM Transactions on Networking 2002.

[52] David K. Hunter, Ivan Andonovic, Approaches to Optical Internet Packet Switching, *IEEE Communications Magazine*, September 2000.

[53] Publications from ACTS KEOPS Project, www.cordis.lu/infowin/acts/rus/projects /pubs/ ac043.htm

[54] M. J. O'Mahony, UK; K. M. Guild, D. K. Hunter, I. Andonovic, I. H. White, R. V. Penty, An Optical Packet Switched Network (WASPNET)-Concept and Realisation, *Optical Network Magazine*, November 2001.

[55] Wood, D., Microstereolithography and other fabrication techniques for 3D MEMS, *Engineering Science and Education Journal*, Volume: 11 Issue: 2 Page(s): 65 -65, April 2002.

[56] Daniel J. Blumental, Bengt-Erik Olsson, Giammarco Rossi, All-Optical Label Swapping Networks and Technologies, *Journal of Lightwave Technology*, Vol. 18, No. 12, December 2000.

[57] Parasak Chokesatean, Titintorn Yaemnoi, Wonganan Sukcharoenkana, Yun Zhang, Will GMPLS replace ATM and SONET/SDH in the next few years?, *web page.*

[58] Rodney S. Tucker, Wen De Zhong, Photonic Packet Switching: An Overview, *IEICE Trans. Electron.*, Vol. E82-C, No. 2, February 1999.

[59] Bora Mocan, M. Salih Dinleyici, All Optical Switching and Routing, Information Technology Conference (Bilgitek), Mayıs 2002.

[60] Pattavina, A., Martinelli, M., Maier, G., Boffi P., Techniques and Technologies Towards All-Optical Switching, *Optical Networks Magazine*, pp. 75-93, April 2000.

[61] M. Salih Dinleyici, Bora MOCAN, Optical Signal Processing Tools for Photonic Networks, Signal Processing and Applications (SIU 2002), June 2002.