Advanced Optical Components for Next Generation Photonic Networks

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ABSTRACT

Future networks will require very high throughput, carrying dominantly data-centric traffic. The role of Photonic Networks employing all-optical systems will become increasingly important in providing scalable bandwidth, agile reconfigurability, and low-power consumptions in the future. In particular, the self-similar nature of data traffic indicates that packet switching and burst switching will be beneficial in the Next Generation Photonic Networks. While the natural conclusion is to pursue Photonic Packet Switching and Photonic Burst Switching systems, there are significant challenges in realizing such a system due to practical limitations in optical component technologies. Lack of a viable all-optical memory technology will continue to drive us towards exploring rapid reconfigurability in the wavelength domain. We will introduce and discuss the advanced optical component technologies behind the Photonic Packet Routing system designed and demonstrated at UC Davis. The system is capable of packet switching and burst switching, as well as circuit switching with 600 psec switching speed and scalability to 42 petabit/sec aggregated switching capacity. By utilizing a combination of rapidly tunable wavelength conversion and a uniform-loss cyclic frequency (ULCF) arrayed waveguide grating router (AWGR), the system is capable of rapidly switching the packets in wavelength, time, and space domains. The label swapping module inside the Photonic Packet Routing system containing a Mach-Zehnder wavelength converter and a narrow-band fiber Bragg-grating achieves all-optical label swapping with optical 2R (potentially 3R) regeneration while maintaining optical transparency for the data payload. By utilizing the advanced optical component technologies, the Photonic Packet Routing system successfully demonstrated error-free, cascaded, multi-hop photonic packet switching and routing with optical-label swapping. This paper will review the advanced optical component technologies and their role in the Next Generation Photonic Networks.

Keywords: MutliProtocol Label Switching (MPLS), Optical-Label Switching, optical-packet switching, arrayed waveguide grating, wavelength conversion, subcarrier multiplexing (SCM)

1. Introduction

1. The phenomenal growth in the Internet traffic is continuing its trend even during severe economic downturns. Three decades ago, the aggregate Internet traffic was less than 100 bit/sec nation-wide. Today, the total aggregate Internet traffic in the United States exceeds 1 Terabit/sec, and is expected to grow beyond 1 Petabit/sec by year 2010 [1]. Naturally, network service providers and researchers have been looking into new solutions for scalable and cost-effective networks. In the past several years, the first-generation optical networking exploiting dense wavelength-division-multiplexing (DWDM) has been actively deployed to support high-capacity traffic on point-to-point links. On a single strand of fiber, it is possible to support transport of more than 10 Tb/sec aggregate data rate. While such traffic growths and capacity increases are impressive on their own, more important issues are how such traffic can be switched and routed, and what performance levels can be achieved. The second-generation optical networking with a MPLS (Multi-Protocol-Label Switching) control plane offers an exciting new opportunity to combine data networking and optical networking with dynamic optical-reconfiguration capabilities. The third-generation optical-networking, optical-packet switching can achieve dynamic reconfiguration on a packet-by-packet basis in the optical domain, and it provides an attractive solution for realizing true integration of optical and data networking.

Active and Passive Optical Components for WDM Communications III, Achyut K. Dutta, Abdul Ahad S. Awwal, Niloy K. Dutta, Kazuo Fujiura, Proceedings of SPIE Vol. 5246 (2003)

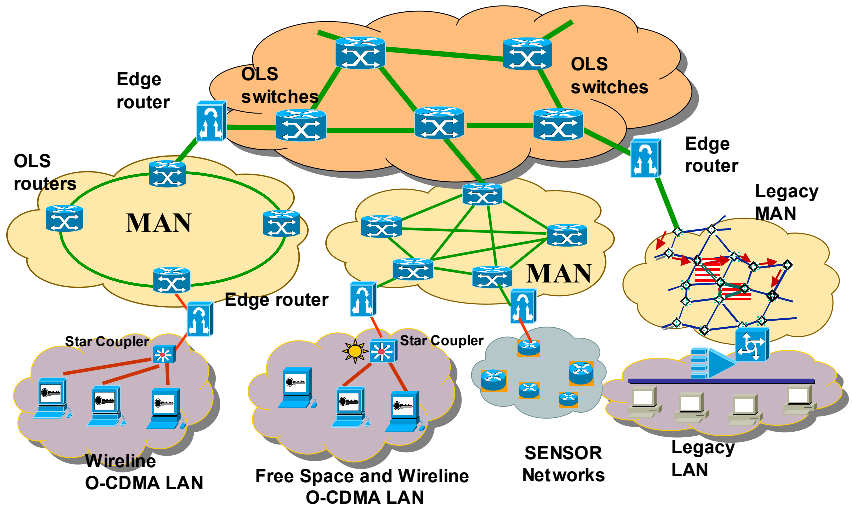


Fig. I.1. Hierarchical architecture view of next generation networks including the wide area, the metro, and the access networks.

Innovations towards future networks will explore transport, switching, and signal processing technologies in time, space, and wavelength domains as well as in the code domain. Traditional networks have primarily considered only the time domain technologies, while recent all-optical networks have exploited wavelength and space domain switching technologies. Emerging optical burst switching and packet switching networks are expected to explore rapid switching in time, space, and wavelength domains. In addition, code-division multiplexing explores a new hybrid domain typically consisting of time, space, and wavelength domains. Agile switching and conversion technologies within and between these domains can realize a new functionality not previously achievable. For instance, a combination of rapidly tunable wavelength converters and arrayed wavelength grating routers realize a rapidly switching fabric for optical packet switching applications. Considering that previous architectures based on space switching technologies using semiconductor amplifiers or $LiNbO_3$ provided scalability and speed limitations, the example switching fabric which we will discuss in a later section is capable of scaling to 42 Petabit/second aggregate switching capacity with subnanosecond switching speeds. Further, this technology can be integrated to provide improvement in the power efficiency and reduction in the required footprint by more than three orders of magnitude compared to the current state of the art.

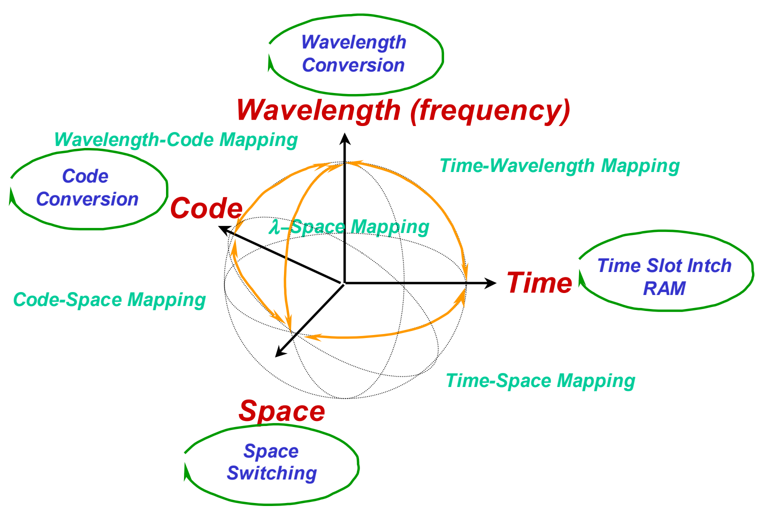


Fig. I.2. Available physical domains for transport, switching, and processing in photonic networks.

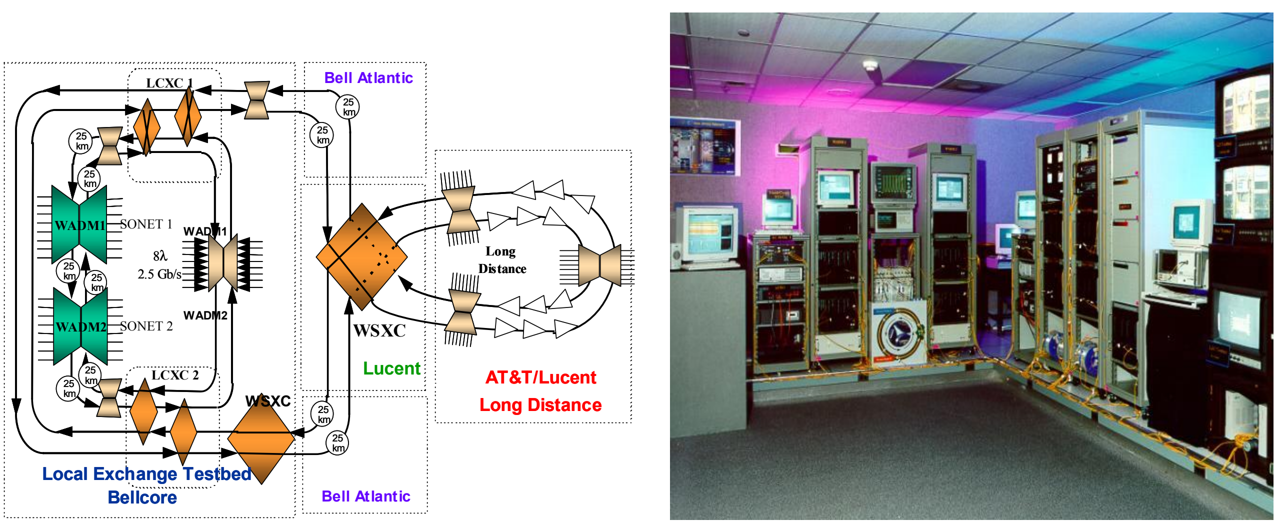
The optical component technologies may provide switching, transport, and processing functions in the above physical domains in optics. Examples of such components are tunable wavelength lasers, wavelength converters, arrayed-waveguide-grating-routers, optical memory, etc. This paper will review advanced optical component technologies for next generation photonic networks. Following this introduction, Section II reviews advanced photonic networks, Section III discusses optical systems, Section IV covers advanced optical component technologies, and, finally, Section V provides a summary.

2. Next Generation Networks

This section provides a very brief summary and description of next generation networks. We will discuss three examples: reconfigurable optical circuit switching networks, optical packet switching networks, and optical CDMA networks.

2.1. Reconfigurable Optical Circuit and Optical Burst Switching Networks

Reconfigurable all-optical networks have been widely studied in the mid 1990's especially following the work by the DARPA (Defense Advanced Research Project Agency) sponsored MONET (Multi-wavelength Optical Networking) project. In particular, the notion of wavelength routing allowed the concept of transparent optical networking in which the all-optical components such as fibers and switches supported signals of diverse formats and protocols. There are three levels of transparency. Digital transparency supports any digital signal of any bit rate typically limited by the slowest component in the network. Amplitude transparency supports any amplitude modulated signals including analog signals. Finally, strict transparency supports any signal of any format and protocol including frequency modulated signals. In the mid-1990's, there was a strong emphasis on transparent networking primarily because of the interoperability and the military application considerations, however, there were also significant challenges. Instead of electronic switches and routers, the all-optical network included network elements such as wavelength add-drop multiplexers (WADMs), wavelength selective cross-connects (WSXCs), wavelength interchanging cross-connects (WIXCs), multiwavelength amplifiers (WAMPS), etc. The MONET team has demonstrated the first reconfigurable all-optical networks. Fig II.1. shows (a) the first rec first reconfigurable all-optical network topology used for the demonstration by the MONET team, and (b) the photo of the Bellcore (now Telcordia) MONET testbed. While the switching time of each crossconnect (WSXC, LCXC) and add-drop multiplexers (WADM) is on the order of a few milliseconds, it took several seconds for each circuit to be set up or to be torn down. This is still much faster than the current state of the art. Optical burst switching uses essentially use the same hardware, but will send signaling header prior to the data burst so that the switching can occur just in time when the data burst arrives at the switching node. Since each switching node requires additional time, this offset time increases as the number of node increases.



(a) (b)

Fig. II.1. (a) The first reconfigurable all-optical network topology used for the demonstration by the MONET team, and (b) the photo of the Bellcore (now Telcordia) MONET testbed.

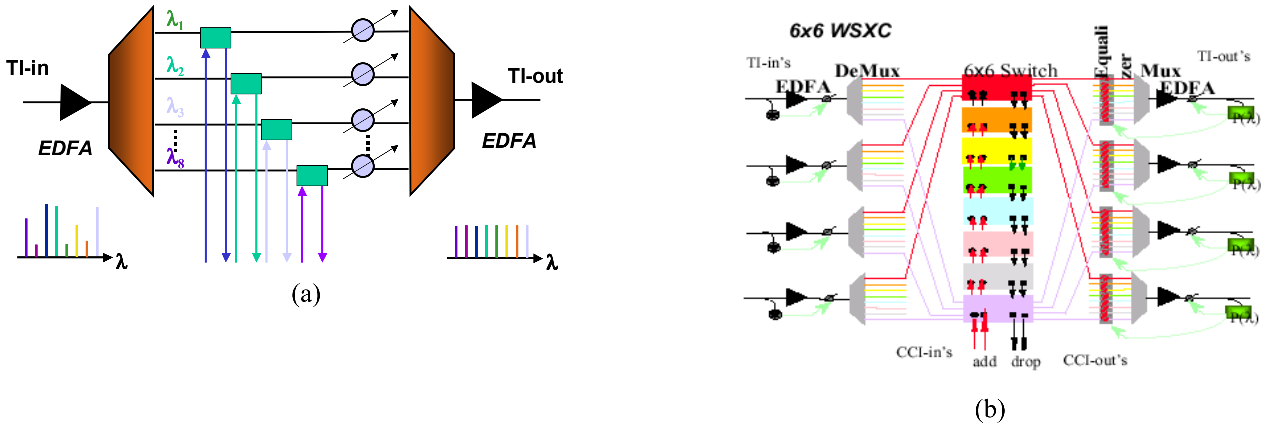


Fig. II.2. A schematic of the core functioning blocks of (a) a wavelength add drop multiplexer and (b) a wavelength selective cross connect.

2.2. Optical Packet Switching Networks (Optical Label Switching example)

The key features of optical-packet switching differ from traditional packet-switching in that it benefits from an additional domain available for contention resolution in the wavelength domain and that it lacks viable optical memory technologies necessary for time-domain contention resolution. It is important for optical-routing systems to exploit the advantages in the wavelength domain and to compensate for lack of flexibilities in the time domain. This additional wavelength domain and the natural parallelism of optics provide potentials for impressive switching capacity in an all-optical switching fabric. Moreover, the wavelength domain provides an additional dimension for output arbitration, and it is possible to design a hierarchical arbitrator which scales much better than traditional arbitrators.

Ideally, the optical-packet switching system should support the most natural form of packet-over-optical transport. Variable length IP packets as well as circuit traffic should be accommodated on optical wavelengths. In addition, it is preferred that such packets can arrive at nodes asynchronously without requiring synchronization in the network. Finally, a rich set of existing routing protocols can be adopted and extended for optical-packet routing so that backward compatibility and interoperability with legacy networks are feasible.

Here, we discuss optical label based packet switching networks and systems. The key underlying networking concept behind optical-label switching (OLS) is an efficient and transparent packet forwarding method using an optical-label switching mechanism which can co-exist with legacy WDM technology on the same fiber. Fig. II.3. depicts the underlying concept for a fast connection setup and Fig. II.4. illustrates an example of a Next Generation Internet Network Element (NGI NE), an OLSR. New signaling information is added in the form of an optical signaling label, which is carried in-band within each wavelength in the multi-wavelength transport environment. The optical-label containing routing and control information such as the source, the destination, the priority, and the length of the packet, will propagate through the network along with the data payload. Each optical-label switching router will sense this optical-label, look-up the forwarding table, and take necessary steps to forward the packet. During this processing and switching time, the packet is delayed by the optical fiber loop at the transport-input interface before entering the switch fabric. The goal is to reduce the need to manage the delay between the optical signaling label and the data payload if the optical-router itself provides the optical delay necessary for the short time required for setting the switch states within each network element. If the packet is to be routed to a wavelength/path where there is already another packet being routed, the optical-label switching router (OLSR) will seek routing by an alternate wavelength, by buffering, or by an alternate path. This space, time, and wavelength domain contention resolution is a key to implementing optical-routers without heavily relying on time-buffers as conventional electronic routers do.

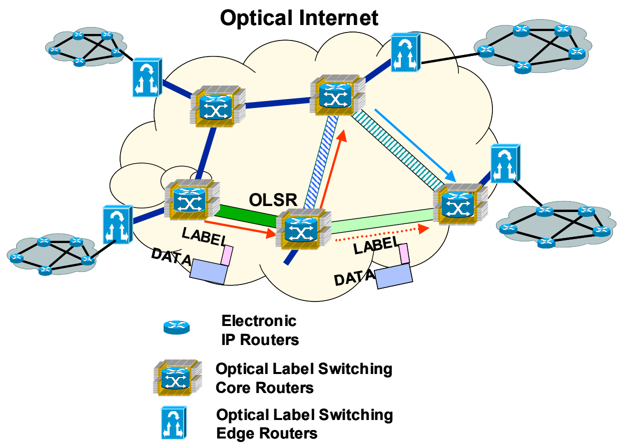


Fig II.3. Fast connection setup using the optical label for the accompanying data payload. The Next Generation Network Network Element (NGN NE), Optical Label Switching Router (OLSR) , quickly reads the label and forward the packet. If the preferred path is not available on the preferred wavelength at the time, the OLSR will forward the packet using an alternative wavelength, path, or time.

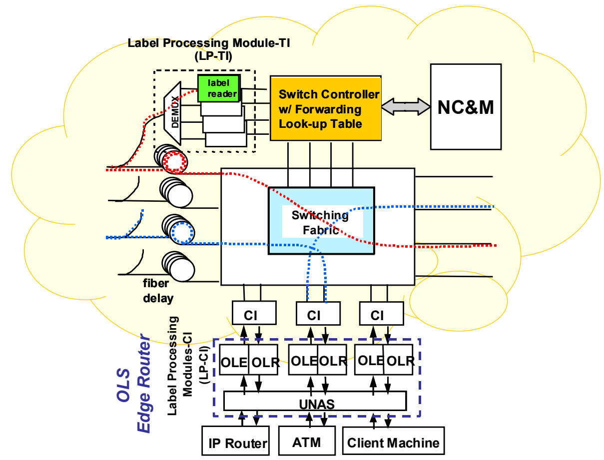


Fig. II.4 An Optical Label Switching Router (OLSR) demonstrated at UCDavis with an Edge Router with Label-Processing modules to achieve optical label switching for IP, ATM or client-specific traffic. Label-Processing Module at Transport Interface detects the signaling header, and Label-Processing Module at the Client Layer includes Optical Label Encoder (OLE) and Optical Label Remover (OLR) to encode and remove the optical label.

The OLSRs are enhanced with two types of label-processing (LP) modules to efficiently handle bursty traffic. The first type of modules (LP-CI) interface between the client interfaces (CI) of OLSRs and the client machines (*e.g.* IP routers) to encode optical signaling labels onto the packets added into the network, and to remove optical signaling label from the packets dropping out of the network. Between the LP-CI and the client machine is a Universal Network Access System (UNAS) that computes the optical label content from IP headers, ATM cell labels, etc, with the help of Network Control and Management (NC&M). UNAS can interface with client machines of any protocols and can aggregate the packets if so desired. In the language of data networking and MPLS, the combination of a CI, a LP-CI and a UNAS is considered as an 'Edge Router', whereas the rest of the optical-router is considered as a 'Label Switching Router (LSR)'. This edge router can be either all-optical or optoelectronic, but its flexible buffering and grooming capabilities can facilitate handling of diverse traffic patterns [31-34]. From this respect, optoelectronic routers can be more useful than the all-optical version especially because the capacity and the connectivity requirements are reasonably low compared to the core part of the OLSR. The second type of label-processing modules (LP-TI) tap a small fraction of the optical signal from the Input Transport Interfaces (TI), detects signaling label information, and relays the appropriate commands to the switch fabric in the OLSR after looking up the forwarding table. The fiber delay is placed at the TI so that the packet including the label and the payload reaches the switch fabric after the switching occurs. This fiber delay will be specific to the delay associated with the combined time delay of label detection, table look-up, and switching. The UC Davis OLSR prototype achieves this in 250 nsec with a 50 m fiber delay. Alternately, the power tap in LP-TI can be replaced by a frequency selective tap in order to separate the optical-label from the data payload to facilitate label-swapping. Refs [16, 35] experimentally demonstrate all optical label-swapping using fiber-Bragg grating based frequency selective filtering to separate the optical-label. On the other hand, label-swapping adds cost and complexity to OLSRs.

The optical switching fabric consists of an array of tunable wavelength converters (T-WC), wavelength routers (*e.g.* arrayed-waveguide-grating), and an array of fixed wavelength converters (F-WC). Fig. II.5. shows a schematic of the optical switching fabric. By tuning the output wavelength of the T-WC, the switching fabric achieves non-blocking connectivity from any wavelength of any input port to any wavelength of any output port. Combined with the fiber delay line in Fig II.4., the switching fabric can achieve wavelength, time, and space domain contention resolution. OLSR requires no optical-to-electrical, or electrical-to-optical conversion of the data payload at the core, and the data plane is end-to-end transparent to protocol and format of the data payload. Further, optical-label switching accommodates data packets of any length, flows of an arbitrary number of packets, a burst of a long datagram, and even a circuit-connection. The highest degree of interoperability is possible in OLS.

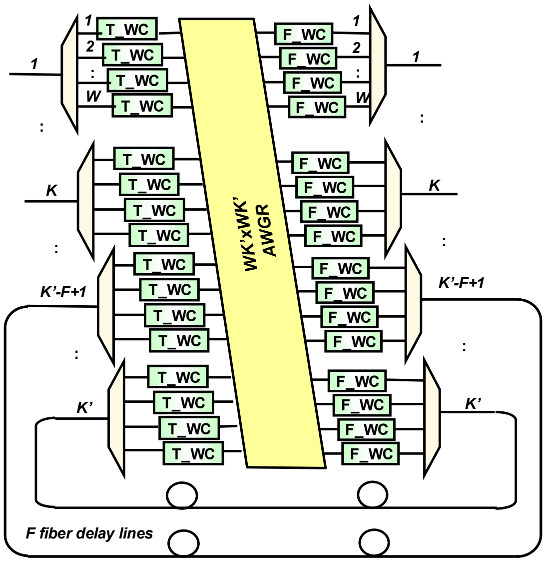


Fig. II.5. Optical Switching Fabric capable of switching in wavelength, time, and space domains.

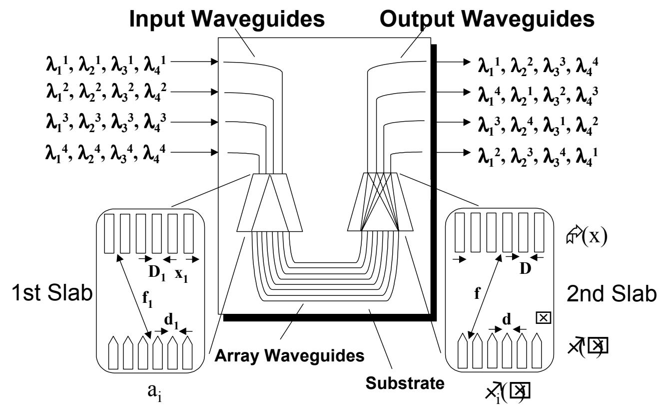


Fig. II.6 A schematic of an arrayed wavelength grating Router (AWGR) for the optical switching fabric. The AWGR achieves a well-known wavelength routing characteristics where differing wavelengths from differing input ports (left) will appear cyclically at the output ports (right).

Fig. II.5. shows an overall architecture of the optical switch fabric. The Arrayed Waveguide Grating Router (AWGR)-based switch fabric has uniquely attractive features in all categories. The AWGR-based switch fabric consists of tunable wavelength converters (*T_WCs*), AWGR, and fixed wavelength converters (*F_WCs*). The basic architecture of Fig 7 achieves nonblocking switching in wavelength and space (fiber) domains by tuning of the output wavelength of the first stage tunable wavelength converter *T_WC* to an appropriate wavelength so that the desired connection between the input wavelength of the input port to the output wavelength of the output port is established. It also achieves limited time-domain switching by utilizing *F* number of loop back delay lines. Fig. II.6. illustrates the well-known wavelength routing characterisitics of the AWGR, where the *i*-th wavelength from the *j*-th input port ($\lambda_i^{\,j}$) can appear cyclically at the output port. The second stage fixed wavelength converter *F_WC* is necessary for converting this wavelength to the wavelength desired at the output of the switch fabric. The architecture is strictly nonblocking for wavelength-space domains in that it allows any wavelength of any input port to be connected to any output wavelength of any port regardless of the previously established connections. By tuning the wavelength of the *T_WC* very rapidly, the switching fabric achieves very fast reconfiguration necessary for packet or burst switching. The wavelength tuning also corresponds to reconfiguration of a circuit (lightpath), hence the switch fabric is capable of accommodating packet, burst, and circuit switching.

2.3. Optical Code Division Multiplexing Access (O-CDMA) Networks

Code-Division Multiplexing Access (CDMA) has many attractive features not available in WDM or TDM networks. With the success of commercial wireless CDMA networks, optical-CDMA networks hope to provide flexible bandwidth access to many subscribers without relying on complicated WDM or TDM gears but using codes. Additional benefits are data-format-independent physical layer security, low probability of detection, interception, and jamming, decentralized network control, uncoordinated access to networks, contention–free networks, fine channel granularity, flexible bandwidth management, and protocol independent and topology independent networks. Optical CDMA must overcome a number of key challenges unmatched in RF-CDMAs. These challenges typically arise because of hardware and implementation constraints in optical communications, in particular the optical carrier frequency which is four orders of magnitude higher than the RF carrier frequency. UC Davis' optical-CDMA technology architecture finds its basis in the seminal paper by Profs. A. M. Weiner, J. P. Heritage, and J. A. Salehi, who demonstrated [4] the first ultrafast optical pulse based coherent O-CDMA method. Fig. II.7. shows the schematic of the experiment. This method, unlike typical 'spread spectrum' techniques, uses a spectral modulation of a broad bandwidth pulse to spread the pulse in time ('spread time'). Spectral modulation can be achieved by varying the phase of each wavelength element of a broadband transmission signal [5]. Figure II.D.1. gives a simple graphical implementation.

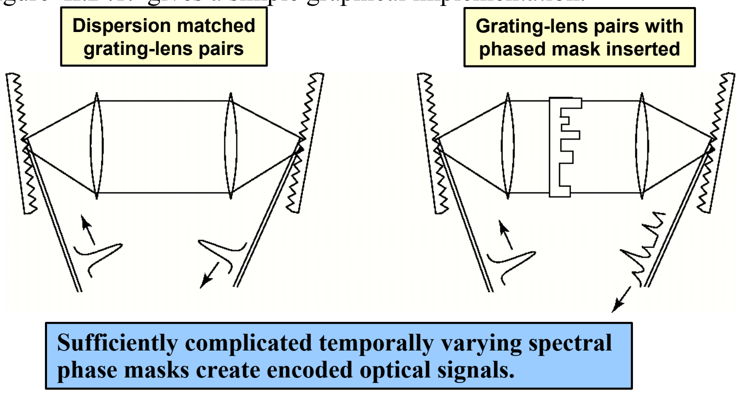


Figure II.7. A short pulse of light containing a broad coherent spectral content can be dispersed using a diffraction grating and a lens. At the Fourier plane, a phase mask can be inserted creating different phase delays for each spectral slice of the pulse thereby encoding the pulse and spreading it in time

Figure II.8. illustrates the basic principle of the encoding and decoding process of the Weiner-Heritage O-CDMA technique. When the transmitter and the receiver have the matched (conjugate) codes, the sharp optical pulse is reconstructed. When mismatched, the output is a noise burst that is spread in time. It is important to note that both outputs have identical integrated energy values. Utilizing low speed detection will achieve little contrast between the two cases. Typical detection methods included synchronous thresholding techniques, optical-Kerr nonlinear loop mirror[6, 7], or second-harmonic generation schemes [8] that are polarization sensitive, bulky, and power hungry. The UC Davis' team will utilize polarization independent, low power (10 fJoule), compact, and monolithically integrated InP based detection schemes.

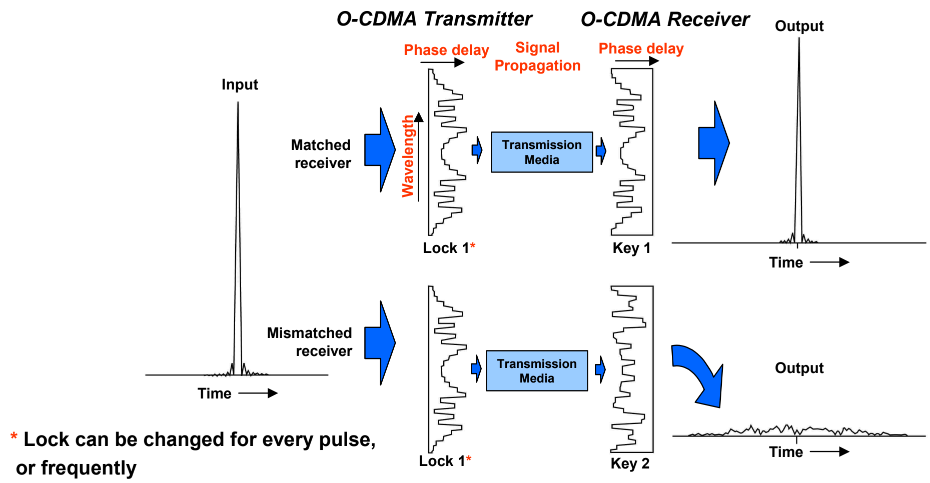


Figure II.8. A short pulse encoding and decoding process. The matched key and lock combination reproduces the sharp optical pulse at the output, whereas the mismatch will produce a noise burst that is spread in time.

The O-CDMA networks will bring a substantial impact if the O-CDMA terminals are integrated to a very small size, typically of the size of a hand-held radio or a cell phone. Significant efforts are currently in progress at UCDavis and Lawrence Livermore National Laboratory to achieve this goal. Fig. II.9. illustrates the ultimate O-CDMA system on a chip using monolithic integration of a ultrafast mode-locked laser, a thresh hold detector, photodiode, and encoder/decoder using arrayed-waveguide-gratings and phase modulators. They constitute the O-CDMA transmitter and receiver on a chip of size approximately 4 cm x 1 cm x 1 cm.

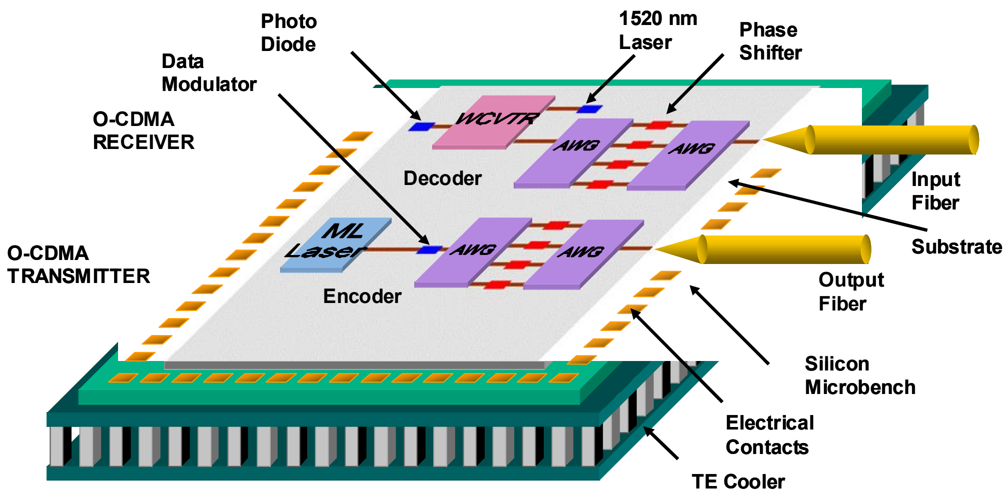


Fig. II.9. Schematic drawing of the monolithic InP O-CDMA transceivers on a chip. The transceiver module will be approximately 4 cm x 1 cm x 1 cm.

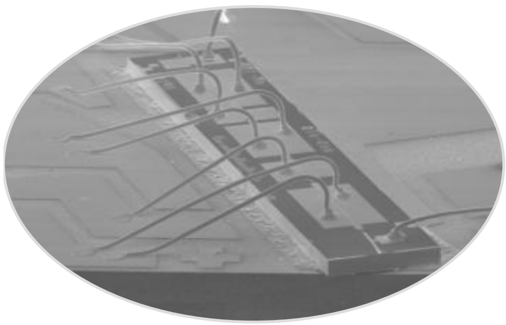
3. Key component technologies

3.1. Agility in time, space, wavelength, and code domains

The key component technology of the next generation will pursue agile switching and processing in time, space, wavelength, and code domains. For instance, tunable lasers, tunable wavelength converters, time-slot-interchangers, optical-label swapping modules, optical code-to-label converters, and all-optical random access memories are examples of advanced components for next generation photonic networks.

3.2. Tunable wavelength lasers

Tunable wavelength lasers provide new switching capabilities not considered in traditional electrical communication methods. It also resolves inventory problems of multi-wavelength lasers. A number of tunable laser schemes are possible including optomechanical tunable lasers. One promising approach for a tunable laser is to utilize tunability in distributed Bragg reflectors. In particular, the tuning in the DBR wavelengths using the current injection allow relatively fast (<10 nsec) tuning. Several DBR laser structures can be used to increase the tuning range to 40 nm to cover the entire C-band wavelength range. The laser has a front reflector and a rear reflector, in addition to the gain and phase sections. The reflectors contain a large number (~10) of short DBR sections separated by blanked sampling periods. Spatial Fourier transform shows that the sampled grating has a comb-like reflection spectrum. By using different sampling periods for the front reflector and the rear reflector, broad wavelength tuning is achieved by shifting the alignment between the wavelength combs of the front and rear reflectors, similar to the Vernier effect. One advantage of the SG-DBR laser is that the fabrication process is very similar to the conventional 3-section DBR laser. Another approach to broad wavelength tuning is the Superstructure Grating DBR (SSG-DBR) laser developed by NTT [Ref. D2, D3]. The SSG-DBR laser shown is similar to the SG-DBR laser, except that the blank sections between the sampled gratings are filled with gratings having a different grating pitch. Wavelength tuning over 40 nm and less than 2 ns wavelength switching can be achieved using the SSG-DBR laser design. A third broadly tunable laser technology was developed by ADC-Altitun using a combined Grating-Assisted Co-directional Coupler and SG-DBR design. Although broader than 40 nm wavelength tuning and switching times between 0.5 ns and 5 ns have been demonstrated, the more complex waveguide structure used for this laser make it more difficult for integration with other waveguide devices on the data plane chip. An important performance parameter for tunable lasers is the switching time from one wavelength to another wavelength. When DBR lasers are electrically tuned by current injection into the Bragg sections, wavelength switching is dominated by the carrier lifetime. Depending on the separation between the 2 switching wavelengths, switching times are typically between 0.5 ns to 5 ns. Fig III.1 shows (a) SEM photo, (b) a schematic, and (c) tuning wavelength plots of the sampled grating DBR tunable laser with an integrated modulator and the amplifier.



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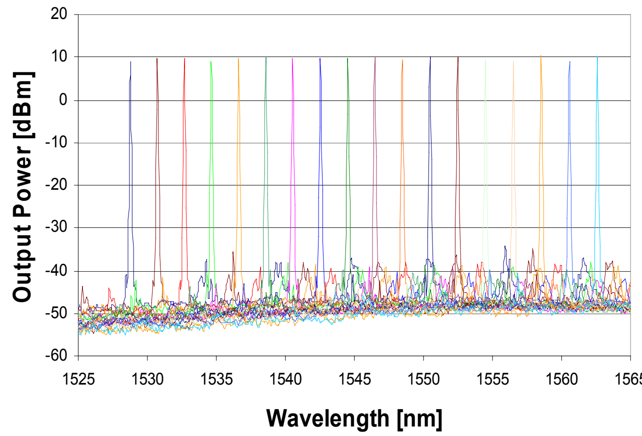

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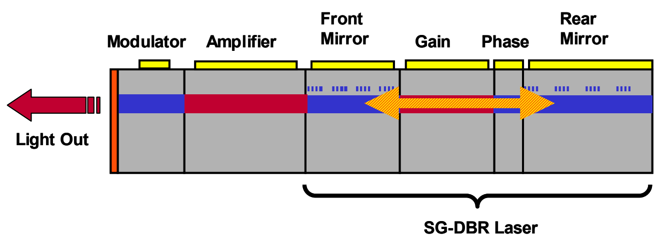
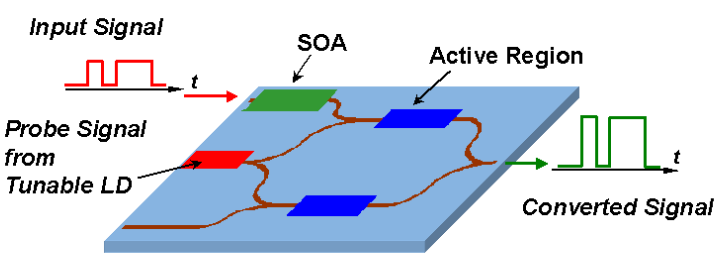


(b)

Fig. III.1. Sampled grating DBR laser with integrated amplifiers and modulators designed and fabricated by Agility Communications, Inc.

3.3. Wavelength Converters and Optical Regenerators



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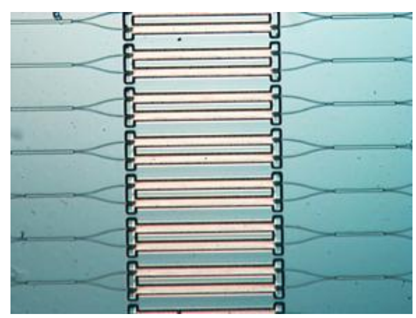


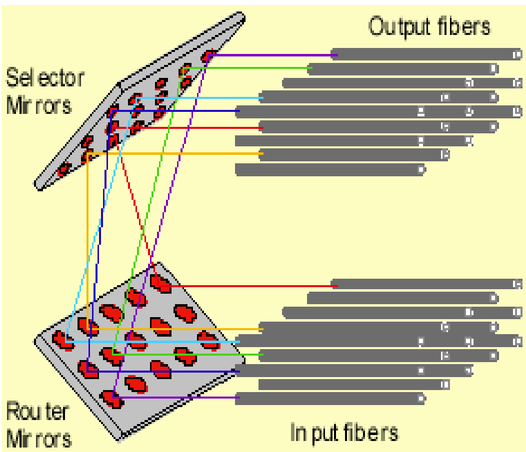
(b)

Fig. III.2 (a) A schematic of Mach-Zehnder wavelength converter to be investigated for the project integrated with a tunable laser. (b) An array of wavelength converters recently fabricated by the author. Multi-mode-interference 2 by 2 couplers, S bend waveguides and semiconductor waveguides are incorporated in the wavelength converters.

Wavelength converters are also very important component for the future. Optical gating wavelength converters include cross-gain (XPM), cross-phase (XPM), and cross-absorption (XAM) modulation effects, and can provide 2R and 3R optical regeneration functions. They are important since optoelectronic wavelength converters and regenerators can consume higher wall-plug power and space while restricting signal format. In particular, all-optical components can undergo large scale integration without worrying about the RF interference of optoelectronic components. Wavemixing wavelength converters include four wave mixing (FWM) and difference frequency generation (DFG) wavelength converters. This category of wavelength converters provide the highest degree of transparency and offer simultaneous multi-channel wavelength conversion capability. Fig III.2. (a) is an example of XPM wavelength converter with integrated tunable laser to achieve tunable wavelength conversion with regeneration., and (b) is an array of XPM wavelength converters fabricated by the author.

3.4. Micro-Optical Switches

Micro-Optical switches provide unsurpassed performance in terms of low loss, low polarization related signal degradations, and high-degrees of integration. Recent applications included high port-count optical switching fabric for optical crossconnects.



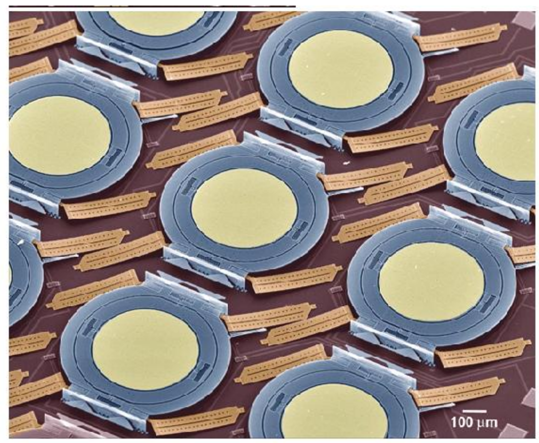
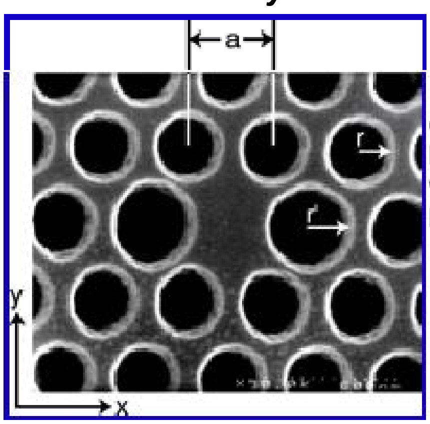
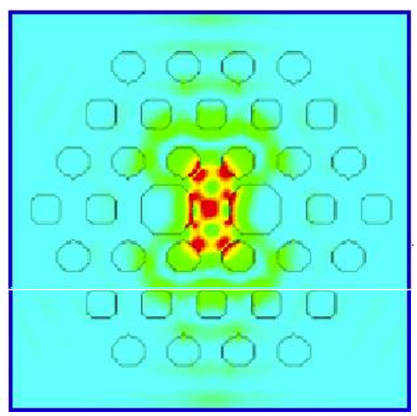


Fig. III.3 (a) A schematic of 3D optical switching fabric and (b) micro mirror array fabricated by Lucent.

3.5. Photonic Crystal Devices



(a)

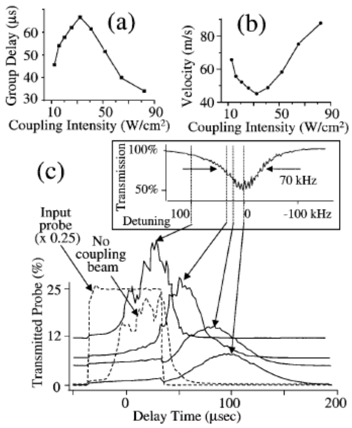


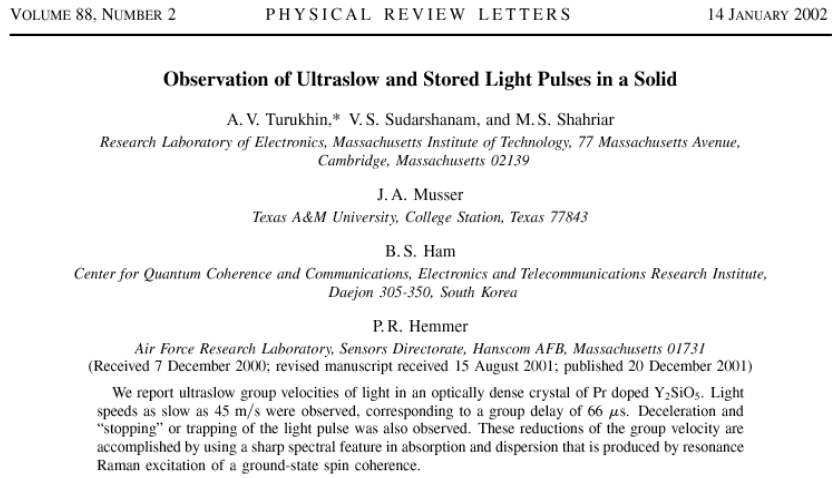
(b)

Fig. III.4 2 dimensional photonic crystal (a) fabricated and (b) simulated. {From 2 }

Crystalline structure of refractive index modulation provides unprecedented modification of optical properties such as dispersion, propagation, and spontaneous emission of light. Photonic crystal based optical fibers and semiconductor lasers are widely being studied by a large number of groups.

3.6. *Slow Light Devices*

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Observation of Ultraslow and Stored Light Pulses in a Solid

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We report ultraslow group velocities of light in an optically dense crystal of Pr doped Y_2SiO_5. Light speeds as slow as 45 m/s were observed, corresponding to a group delay of 66 μs. Deceleration and "stopping" or trapping of the light pulse was also observed. These reductions of the group velocity are accomplished by using a sharp spectral feature in absorption and dispersion that is produced by resonance Raman excitation of a ground-state spin coherence.

Perhaps the final frontier of optical component technology may explore controlling of speed of light, in particular, slow-light effects to realize optical random access memory or optical storage devices. Recent demonstrations in realizing 10 million times3 slowing of speed of light by electro-magnetic induced transparency in solid materials cast hopes for viable components based on such a technology.

3.7. *Microsystem Integration*

Finally, the large scale integration of such advanced photonic devices will play a vital role in future photonic networks by providing low cost, low loss, high reliability, and high performance.

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