Ultrafast technologies for photonic networks

Paul R. Prucnal, Varghese Baby, Lei Xu, Ivan Glesk*
EE Dept., Princeton University, Princeton, NJ 08544 E-mail: vbaby@princeton.edu

Considerable progress has been in the last decade in the fields of photonic networks and ultra-fast optics. The past few years has seen the widespread use of wavelength division multiplexing (WDM) to provide enormous point-to-point capacity in the backbone and metro area networks. Remarkable progress in electronics, in terms of both costs and performance speeds, has to some extent alleviated the 'electronic bottleneck'. Developments in fiber-optics such as novel fiber types and Raman amplification have opened up additional wavelength regions of operation resulting in great expansion of usable fiber bandwidth. There exist unique opportunities for ultrafast technologies – a subject of much interest in the last decade and reaching a point of maturity - to complement these advances and spark the next generation networks.

In our talk, we will mention two networking environments very different from WDM - (1) optical time division multiplexing (OTDM) and (2) optical code division multiple access (OCDMA). We will look at the potential of both these scenarios for different applications, focusing in particular on the latter as an approach that provides maximum flexibility to utilize the immense bandwidth of the optical fiber. We will also describe various ultra-fast technologies that have been developed e.g. .high repetition rate pulsed lasers, ultra-fast optical switches, time delay elements etc. which have a direct relevance to both these types of networks.

Optical Time Division Multiplexing (OTDM)

OTDM increases the transmission speed by carrying the data bits on temporally narrow (small fraction of the entire bit period) optical pulses. Multiple data channels share the bit period by temporally placing their pulses in different timeslots within the bit period. At the receiver end, the individual timeslot channels are all-optically demultiplexed into the base band rate for further signal processing or conversion into the electronic domain. Clock-recovery schemes are used to facilitate synchronization of the receiver.

OTDM can be used in conjunction with WDM to increase the capacity of data traffic on a transport network with lower cost per bit and a reduction in the size of the terminal equipment [1]. However, perhaps the most attractive aspect of OTDM systems is its suitability for bit-level optical processing and for implementing transparent, reconfigurable optical networks. Several experimental demonstrations have shown that OTDM can meet many of the demanding needs of a high performance switching fabric including full connectivity, low latency, high aggregate throughput, reliability, and scalability [2-6]. OTDM based techniques have also been used to demonstrate photonic packet switching with optically transparent routing of packets [7]. Many of the practical advantages of OTDM networks and systems have been demonstrated using novel architectures and devices [6-10]. These systems have taken advantage of simplified management and control protocols, flexible bandwidth provisioning for bursty traffic sources, and the use of statistical multiplexing, all of which are available in OTDM systems [10].

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Optical Code Division Multiple Access (OCDMA)

OCDMA provides an approach to trade the huge bandwidth of optical fiber for enhanced system level functionalities. Unique codes – created by combining various parameters such as time slots, frequency, polarization, and phase - can be assigned to users to enable truly asynchronous multiple access with simplified network control. In addition, OCDMA offers other advantages such as increased physical layer privacy and on-demand bandwidth sharing and bandwidth management [11].

The development of coding schemes with very large code spaces provides the flexibility to trade 'extra' codes for enhanced spectral efficiency and security. Code properties allow the co-existence of users with multiple rates [12] and multiple service requirements [13] – of significance to networks that support a wide range of traffic types. The use of ultrafast technologies allows enhanced scalability, on-demand bandwidth management and dynamic variation of service guarantees. Thus, ultrafast technologies in conjunction with OCDMA can enable the 'tailoring' of the fiber bandwidth resource according to application requirements. The use of ultrafast nonlinear switches for code and format conversion allows for multi-hop OCDMA networks that can interface to WDM networks.

OTDM and OCDMA network architectures offer many advantages over WDM due to the development of ultrafast techniques that enable optical processing in the time domain. A key advantage is the ultra-fast, reconfigurable nature of these networks enabled by delay line technologies with latency of the order of nanoseconds. This ultra-fast reconfigurability not only has tremendous significance in simplifying the network architecture but also in the security of the network. E.g. OCDMA codes can be dynamically changed to ensure data confidentiality in the event of a code being compromised. By comparison, reconfigurable WDM networks are limited due to the slow wavelength tuning and selection techniques.

Ultrafast Technologies

A. Laser Sources

Considerable progress has been made in the development of compact lasers that can produce stable, ultra-short pulses with high repetition rates [14]. The various technologies that have been developed include actively mode-locked fiber lasers [15, 16], mode-locked semiconductor lasers [17] and gain-switched DFB lasers. Pulse widths of the order of a few femtoseconds and repetition rates as high as 40GHz, have been demonstrated. Several of these technologies are currently commercially available.

Supercontinuum generation in optical fibers with spectral slicing has been used for developing multi-wavelength laser sources for use in OCDMA [18] and OTDM/WDM networks [19]. On propagation through appropriate fibers, the high peak power of the ultra-short pulses results in additional spectral components through nonlinear mechanisms, while the fiber dispersion profile maintains the temporal pulse width through the length of the fiber. Several demonstrations have been made for supercontinuum generation, primarily differing in the type of nonlinear fiber and the optical pump used [20, 21]. The development of photonic crystal fibers [22] with greater control on the nonlinear and dispersion characteristics has brought a fresh impetus to this area.

B. Time-delay elements

As mentioned earlier, ultra-fast tunable optical delay lines, capable of rapidly changing the delay time of optical pulses, have important applications in OTDM and OCDMA systems. They can be used in the en/decoders in 1D and 2D OCDMA systems [13], to rapidly vary the code assignment. In OTDM systems, they can be used at the transmitter/receiver ends to obtain rapid channel assignment/access respectively. Delay lines have been developed with the capability to provide advanced networking services [23] like multicasting, speed up mode etc.

A serial switched delay line was demonstrated [24] that provides a tunable delay to the pulse by switching the pulse between paths of fixed different delays. The tuning latency of the structure depends on the switching technology used; e.g. $LiNbO_3$ switches can attain tuning speeds of the order of a few GHz. Gated delay lines have also been developed [25, 26] that uses selective gating of replicated pulse trains to attain the desired tuning delay. The feed-forward structure of these delay lines [27] results in a logarithmic increase in complexity with the number of accessible timeslots. Various other schemes have also been demonstrated [28, 29].

C. All-optical switches

All-optical switches are used in photonic networks for various applications such as demultiplexing, packet routing, clock extraction, wavelength conversion, 3R regeneration and high speed all-optical analog sampling. These switches are generally based on the nonlinear interaction between optical waves in a variety of materials e.g. fiber, semiconductors, $LiNbO_3$ [30].

Fiber-based switches that have been developed include ones based on four-wave mixing (FWM) [31], cross-phase modulation (XPM) [32], and the widely studied nonlinear loop mirror (NOLM) [33]. FWM switches are typically polarization dependent and require high control powers due to the low FWM efficiency. XPM based switches utilize control beam induced carrier frequency shifts to spectrally separate a channel from a high-speed data stream. NOLM switches have attained very high switching rates (e.g. 640Gb/s [34]) due to the ultra-fast response of the nonlinearity in optical fiber. Techniques have been developed to reduce its intrinsic polarization dependence [35]. However, in general, due to the low nonlinear coefficient, high optical powers and long interaction lengths are required to achieve efficient switching.

Semiconductor optical amplifier (SOA) based switches are very compact and offer the possibility for monolithic integration together with other photonic devices. The vast majority of these switches utilizes the nonlinear gain and phase changes in an SOA between two data components to achieve switching (As an exception, FWM have also been used for switching with SOAs [36]). The high nonlinear coefficient of the SOA as compared to fiber, gain potential of the SOA, and the integratability has made SOA based switches very attractive for switching applications. Various designs have been implemented [30]. e.g. SLALOM, TOAD, symmetric Mach-Zehnder (SMZ), counter-propagating Mach-Zehnder (CPMZ) and UNI. In all these devices, the switching window duration is determined by the relative time delay with which the two interfering data components pass through an SOA saturated by control pulse, and is not limited by the recovery time of the SOA. An overview of SOA-based switches and their features is given in Table 1. Integration of these switches has been reported using both monolithic and hybrid technologies [30]. Techniques have been proposed to improve the extinction ratio and reduce the noise [37], and to increase the repetition rate of switching [38] of these SOA-based switches.

Table 1
All-optical switches based on SOA as nonlinear medium

Nonlinear medium	Semiconductor optical amplifier				
Type of all-optical switch	FWM in SOA	TOAD	Mach-Zehnder interferometer	UNI	GT–Switch
Demonstrated working speed	200Gb/s	250Gb/s	168Gb/s	100Gb/s	160Gb/s
Integratability	Yes	Yes	Yes	Yes	Yes
Polarization sensitivity	Yes	No	No	Yes	-
Advantages	-	Low switching energy	Low switching energy	Low switching energy	Low noise

Passive materials with relatively large nonlinearity such as $LiNbO_3$, semiconductors (e.g. InGaAsP), have been used to develop all-optical switches and are widely studied for their integration compatibility, potentially low switching energies and for their low amounts of noise (compared to the SOA based switches) [39, 40]. Efficient switching with very low control energy has been obtained in periodically poled lithium niobate (PPLN) using the phenomenon of sum frequency mixing due to second-order nonlinearity [41]. PPLN-based switches offer the advantages of ultra-fast response, potentially low switching energy, wide wavelength range of operation and integration compatibility.

Our talk will cover these various technologies and the implications of them on OTDM and OCDMA applications.

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