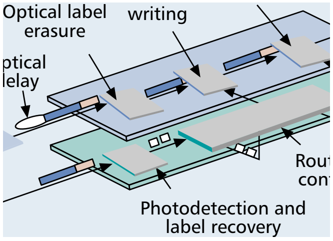

OPTICAL SIGNAL PROCESSING FOR OPTICAL PACKET SWITCHING NETWORKS

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ABSTRACT

Optical packet switching promises to bring the flexibility and efficiency of the Internet to transparent optical networking with bit rates extending beyond that currently available with electronic router technologies. New optical signal processing techniques have been demonstrated that enable routing at bit rates from 10 Gb/s to beyond 40 Gb/s. In this article we review these signal processing techniques and how all-optical wavelength converter technology can be used to implement packet switching functions. Specific approaches that utilize ultra-fast all-optical nonlinear fiber wavelength converters and monolithically integrated optical wavelength converters are discussed and research results presented.

INTRODUCTION

Within today's Internet, data is transported using wavelength-division multiplexed (WDM) optical fiber transmission systems that carry 32–80 wavelengths modulated at 2.5 Gb/s and 10 Gb/s per wavelength. Today's largest routers and electronic switching systems need to handle close to 1 Tb/s in order to redirect incoming data from deployed WDM links. Meanwhile, next-generation commercial systems will be capable of single-fiber transmission supporting hundreds of wavelengths at 10 Gb/s per wavelength, and world record experiments have demonstrated 10 Tb/s transmission.

The ability to direct packets through the network when single-fiber transmission capacities approach this magnitude may require electronics to run at rates that outstrip Moore's Law. The bandwidth mismatch between fiber transmission systems and electronic routers becomes more complex when we consider that future routers and switches will potentially terminate hundreds of optical wavelengths, and the increase in bit rate per wavelength will head out beyond 40 Gb/s to 160 Gb/s. Even with significant advances in electronic processor speeds, electronic memory access times only improve at the rate of approximately 5 percent per year, an important data point since memory plays a key role in how packets are buffered and directed through a router. Additionally, optoelectronic interfaces dominate the power dissipation, footprint, and cost of these systems, and do not scale well as the port count and bit rates increase. Hence, it is not difficult to see that the process of moving a massive number of packets per second through the multiple layers of electronics in a router can lead to congestion and exceed the performance of electronics and the ability to efficiently handle the dissipated power.

In this article we review the state of the art in optical packet switching and more specifically the role optical signal processing plays in performing key functions. We describe how all-optical wavelength converters can be implemented as optical signal processors for packet switching, in terms of their processing functions, wavelength agile steering capabilities, and signal regeneration capabilities. Examples of how wavelength-converter-based processors can be used to implement both asynchronous and synchronous packet switching functions is reviewed. Two classes of wavelength converter will be touched on: monolithically integrated semiconductor optical amplifier (SOA) based and nonlinear fiber based. We conclude this article with a discussion of the future implications for packet switching.

PACKET SWITCHING IN TODAY'S OPTICAL NETWORKS

Routing and transmission are the basic functions required to move packets through a network. In today's Internet Protocol (IP) networks, the packet routing and transmission problems are designed to be handled separately. A core packet network will typically interface to smaller networks and/or other high-capacity networks.

A router moves randomly arriving packets through the network by directing them from its multiple inputs to outputs and transmitting them on a link to the next router. The router uses information carried with arriving packets (e.g., IP headers, packet type and priority) to *forward* them from its input to output ports as efficiently as possible with minimal packet loss and disruption to the packet flow. This process of merging multiple random input packet streams onto common outputs is called *statistical multiplexing*. In smaller networks, the links between routers can be made directly using Ethernet; however, in the higher-capacity metropolitan, enterprise, and long-haul core networks, transmission systems between

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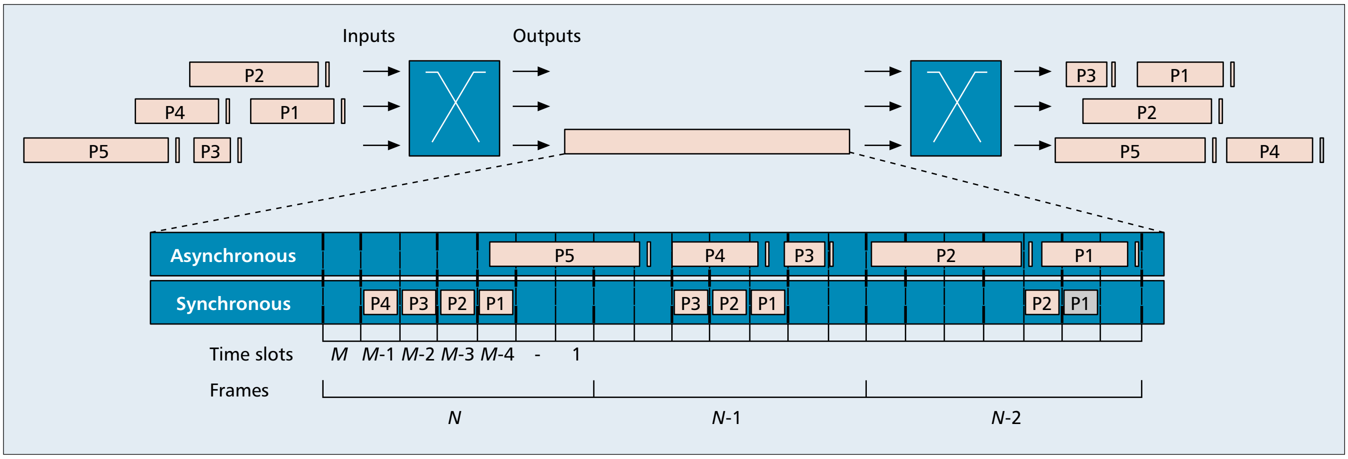

FIGURE 1. The function of a router is to take randomly arriving packets on its inputs and statistically multiplex them onto its outputs. Packets may then be transmitted between routers using a variety of asynchronous or synchronous network access and transmission techniques.

routers employ synchronous transport framing techniques like synchronous optical network(SONET), packet over SONET (POS), or Gigabit Ethernet (GigE). This added layer of framing is designed to simplify transmission between routers and decouple it from the packet routing and forwarding process. Figure 1 illustrates that the transport network that connects routers can be designed to handle the packets asynchronously or synchronously. The most commonly used approaches (SONET, POS, GigE) maintain the random nature of packet flow by only loosely aligning them within synchronous transmission frames. Although not as widely used in today's networks, packets may also be transmitted using a fixed time slotted approach, similar to the older token ring and fiber distributed data interface (FDDI) networks, where they are placed within an assigned slot or frame, as illustrated in the lower portion of Fig. 1.

All-Optical Packet Switching Networks

In all-optical packet-switched networks the data is maintained in optical format throughout the routing and transmission processes. One approach that has been widely studied is all-optical label swapping (AOLS) [1–6]. AOLS is intended to solve the potential mismatch between dense WDM (DWDM) fiber capacity and router packet forwarding capacity, especially as packet data rates increase beyond that easily handled by electronics (> 40 Gb/s). Packets can be routed independent of the payload bit rate, coding format, or length. AOLS is not limited to handling only IP packets, but can also handle asynchronous transfer mode (ATM) cells, optical bursts [7], data file transfer, and other data structures without SONET framing. Migrating from POS to packet-routed networks can improve efficiency and reduce latency [8]. Optical labels can be coded onto the packet in a variety of ways; the one we describe here is the mixed-rate serial approach. In this approach a lower bit rate label is attached to the front end of the packet. The packet bit rate is then independent of the label bit rate, and the label can be detected and processed using lower-cost electronics in order to make routing decisions. However, the actual removal and replacement of the label with respect to the packet is done with optics. While the packet contains the original electronic IP network data and

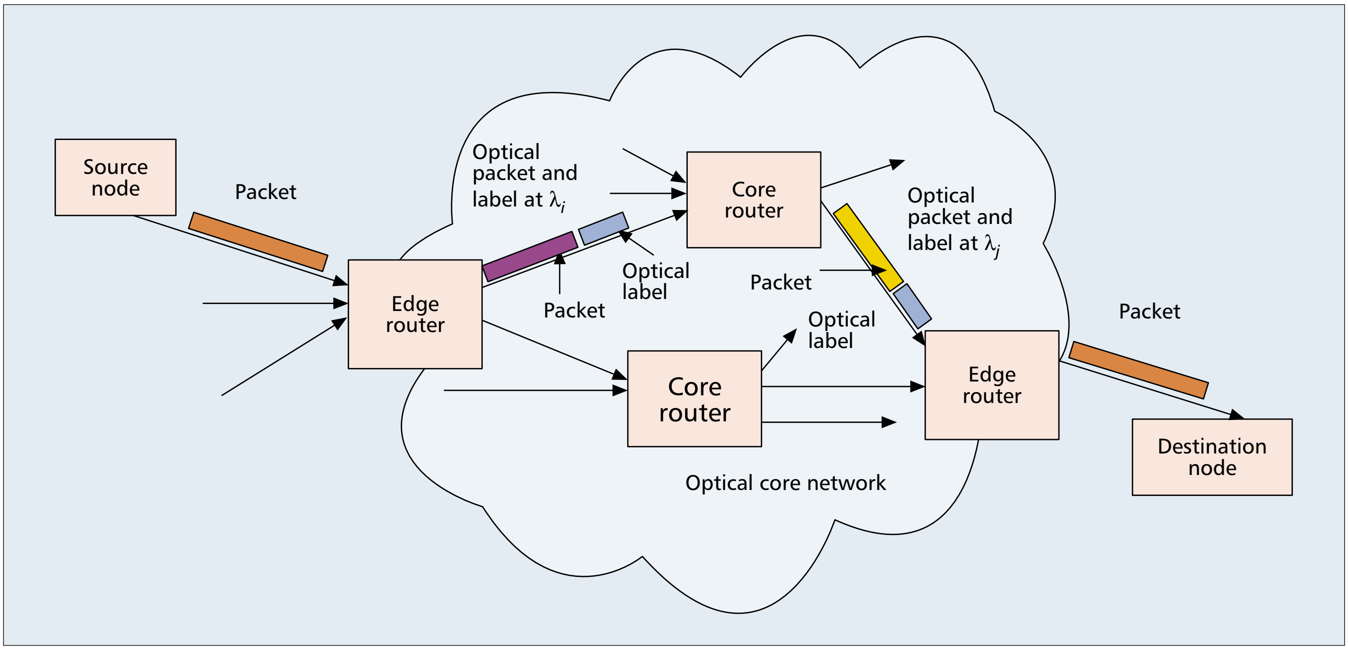

FIGURE 2. An all-optical label-swapping network for transparent all-optical packet switching.

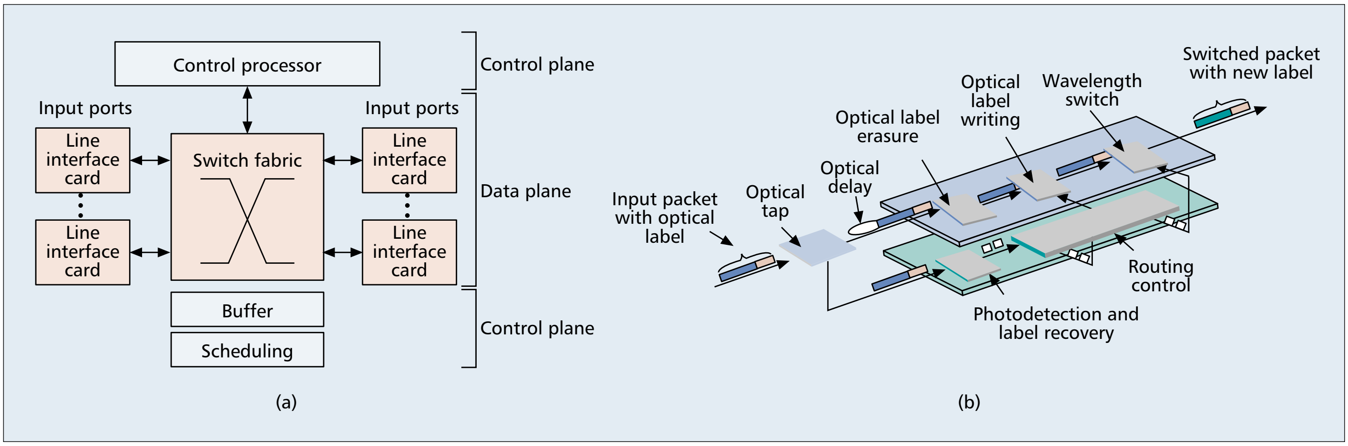

FIGURE 3. An optical label swapping module with a photonic switching plane and an electronic control plane.

routing information, the label contains routing information specifically used in the optical packet routing layer. The label may also contain bits for error checking and correction as well as source and destination information and framing and timing information for label electronic label recovery and processing.

An example AOLS network is illustrated in Fig. 2. IP packets enter the network through an ingress node where they are encapsulated with an optical label and retransmitted on a new wavelength. Once inside the AOLS network, only the optical label is used to make routing decisions, and the packet wavelength is used to dynamically redirect (forward) them to the next node. At the internal core nodes, the label is optically erased, the packet is optically regenerated, a new label is attached, and the packet is converted to a new wavelength. Packets and their labels may also be replicated at an optical router realizing the important *multicast* function. Throughout this process, the contents that first entered the core network (e.g., the IP packet header and payload) are not passed through electronics and are kept intact until the packet exits the core optical network through the egress node where the optical label is removed and the original packet is handed back to the electronic routing hardware the same as it entered the core network. These functions — label replacement, packet regeneration, and wavelength conversion — are handled in the optical domain using optical signal processing techniques and may be implemented using optical wavelength converter technology, described in further detail in the next sections.

The overall function of an optical labeled packet switch is shown in Fig. 3a. The switch can be separated into two planes, data and control. The data plane is the physical medium over which optical packets are switched. This part of the switch is bit-rate-transparent and able to handle packets with basically any format out to very high bit rates. The control plane has two levels of functionality. The decision and control level executes the packet handling process including switch control, packet buffering, and scheduling. This control section operates not at the packet bit rate but instead at the slower label bit rate and does not need to be bit-rate-transparent. The other level of the control plane supplies routing information to the decision level. This information is more slowly varying and may be updated throughout the network on a less dynamic basis than the packet control.

The optical label swapping technique is shown in more detail in Fig. 3b. Optically labeled packets at the input have a majority of the input optical power directed to the upper photonic packet processing plane and a small portion of the optical power directed to the lower electronic label processing plane. The photonic plane handles optical data regeneration, optical label removal, optical label rewriting, and packet rate wavelength switching. The lower electronic plane recovers the label into an electronic memory and uses lookup tables and other digital logic to determine the new optical label and the new optical wavelength of the outgoing packet. The electronic plane sets the new optical label and wavelength in the upper photonic plane. A static fiber delay line is used at the photonic plane input to match the processing delay differences between the two planes. In the future, certain portions of the label processing functions may be handled using optical techniques.

An alternative approach to the *random access* techniques described above is to use *time-division multiple access* (TDMA) techniques where packet bits are synchronously located within time slots dedicated to that packet. For example, randomly arriving packets, each on a different input wavelength, are bit interleaved using an all-optical orthogonal time-division multiplexer (OTDM). For example, if a 4:1 OTDM is used, every fourth bit at the output belongs to the first incoming packet, and so on. A TDM frame is defined as the duration of one cycle of all time slots, and in this example a frame is 4 bits wide. Once the packets have been assembled into frames at the network edge, packets can be removed from or added to a frame using optical add/drop multiplexers (OADMs). By imparting *multicast* functionality to the OADMs, multiple copies of frames may be made onto different wavelengths.

Optical Signal Processing and Optical Wavelength Conversion

Packet routing and forwarding functions are performed today using digital electronics, while the transport between routers is supported using high-capacity DWDM transmission and optical circuit-switched systems. Optical signal processing (OSP), or the manipulation of signals while in their analog form, is currently used to support transmission functions like optical dispersion compensation and optical wavelength multiplexing and demultiplexing. The motivation to extend the use of OSP to packet handling is to leave data in the optical domain as much as possible until bits have to be manipulated at the endpoints. OSP allows information to be manipulated in a variety of ways, treating the optical signal as analog (traditional signal processing) or digital (regenerative signal processing).

Today's routers rely on dynamic buffering and scheduling to efficiently route IP packets. However, optical dynamic buffering techniques do not currently exist. To realize optical packet switching, new techniques must be developed for scheduling and routing. The optical wavelength domain can be used to forward packets on different wavelengths with the potential to reduce the need for optical buffering and

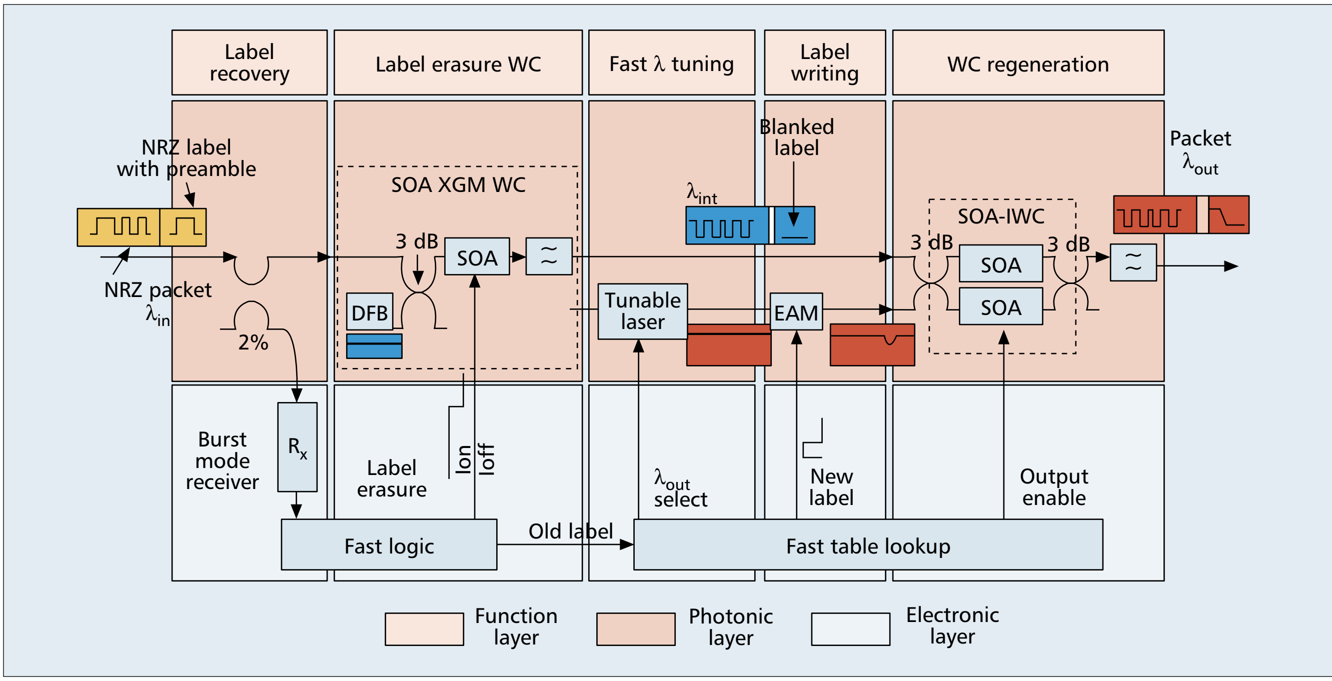

FIGURE 4. Optical packet label swapping and signal regeneration using cascaded InP SOA based wavelength converters and an InP fast tunable laser.

decreased collision probability. As packet routing moves to the all-optical domain, the total transmission distance between regeneration points is extended from core router to core router to edge router to edge router, and optical regeneration will become increasingly important. Consequently, as signal processing migrates from the electrical into the optical domain, an increasing number of functionalities need to be realized.

Asynchronous Optical Packet Switching and Label Swapping Implementations

The AOLS functions described in Fig. 3 can be implemented using monolithically integrated indium phosphide (InP) SOA wavelength converter (SOA-WC) technology [4, 5]. An example that employs a two-stage wavelength converter is shown in Fig. 4 and is designed to operate with non-return-to-zero (NRZ) coded packets and labels. In general this type of converter works for 10 Gb/s signals and can be extended to 40 Gb/s and possibly beyond. The functions are indicated in the top layer, and the photonic and electronic plane implementations are shown in the middle and lower layers. A burst mode photo-receiver is used to recover the digital information residing in the label. A gating signal is then generated by the post receiver electronics in order to shut down the output of the first stage, an InP SOA cross-gain modulation (XGM) wavelength converter. This effectively blanks the input label. The SOA converter is turned on after the label passes and the input NRZ packet is converted to an out-of-band internal wavelength$_{int}$. The lower electronic control circuitry is synchronized with the well-timed optical time-of-flight delays in the photonic plane. The first stage WC is used to optically preprocess the input packet by:

- Converting input packets at any wavelength to a shorter wavelength, λ_{int}, which is chosen to optimize the SOA XGM extinction ratio. The use of an out-of-band wavelength allows a fixed optical bandpass filter to be used to separate out the converted wavelength.
- Converting the random input packet polarization state to a fixed state set by a local InP distributed feedback (DFB) laser for optical filter operation and second stage wavelength conversion.
- Setting the optical power bias point for the second stage InP wavelength converter.

The recovered label is also sent to a fast lookup table that generates the new label and outgoing wavelength based on prestored routing information. The new wavelength is translated to currents that set a rapidly tunable laser to the new output wavelength. This wavelength is premodulated with the new label using an InP electro-absorption modulator (EAM) and input to an InP interferometric SOA-WC (SOA-IWC). The SOA-IWC is set in its maximum transmission mode to allow the new label to pass through. A short time after the label is transmitted (determined by a guard band), the WC is biased for inverting operation, and the packet enters the SOA-IWC from the first stage and drives one arm of the WC, imprinting the information onto the new wavelength. The second stage wavelength converter:

- Enables the new label at the new wavelength to be passed to the output using a fixed optical band reject filter.
- Reverts the bit polarity to its original state.
- Is optimized for wavelength upconversion.
- Enhances the extinction ratio due to its nonlinear transfer function.
- Randomizes the bit chirp, effectively increasing the dispersion limited transmission distance. The chirp can in most cases also be tailored to yield the optimum transmission, if the properties of the following transmission link are well known.

The label swapping functions may also be implemented at the higher 40 and 80 Gb/s rates using return-to-zero (RZ) coded packets and NRZ coded labels [9]. This approach has been demonstrated using the configuration in Fig. 5. The silicon-based label processing electronic layer is basically the same as in Fig. 4. In this implementation a nonlinear fiber cross-phase modulation (XPM) is used to erase the label, convert the wavelength, and regenerate the signal. An optically amplified input RZ packet efficiently modulates sidebands through fiber XPM onto the new continuous wave (CW)

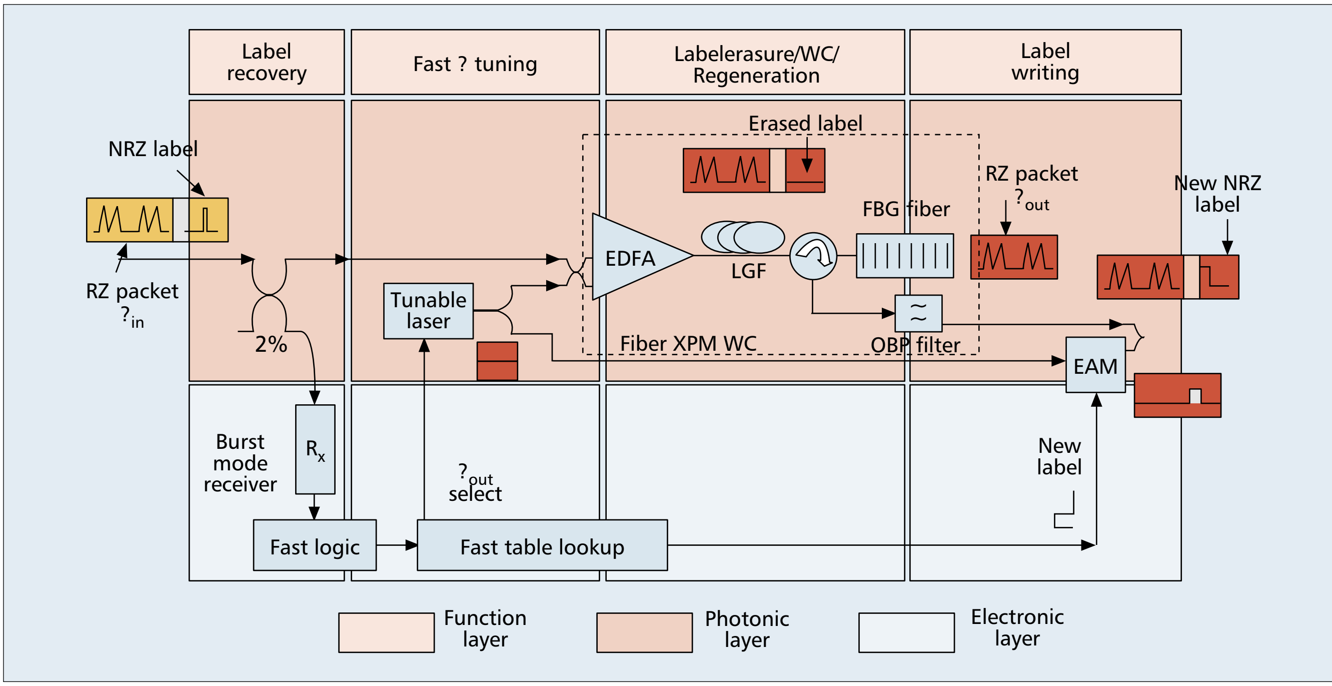

FIGURE 5. Optical packet label swapping and signal regeneration using a nonlinear fiber cross-phase modulation wavelength converter and a fast tunable laser.

wavelength, while the NRZ-label XPM-induced sideband modulation is very inefficient and the label is erased or suppressed. The RZ modulated sideband is recovered using a two-stage filter that passes a single sideband. The converted packet with the erased label is passed to the converter output where it is reassembled with the new label. The fiber XPM converter also performs various signal conditioning and digital regeneration functions including extinction ratio (ER) enhancement of RZ signals and polarization mode dispersion (PMD) compensation.

Using the nonlinear fiber XPM converter, AOLS with variable length 80 Gb/s packets with 10 Gb/s optical labels was demonstrated for the first time. This work also showed that it was possible to swap labels and convert wavelengths over two node hops with unicast and multicast operation. This level of functionality at these bit rates cannot be handled with today's electronics. The results of this experiment are shown in Fig. 6. Three different length 80 Gb/s packets (1 μs, 1.2 μs, and 1.5 μs) were generated using a fiber ring laser and passive optical interleaved multiplexer. At the ingress node, the 80 Gb/s packets were wavelength converted using the ultra-fast fiber XPM wavelength converter and the labels attached. The 1.0 and 1.5 μs packets were converted to 1543 nm, and the 1.2 and 1.5 μs packets to 1548 nm. Therefore, the 1.5 μs packet can be either unicast or multicast, while the other two packets are unicast only. At the core router, all packets were converted back to 1555 nm using the fiber XPM-WC; the optical label was removed, and a new one generated and replaced at 10 Gb/s.

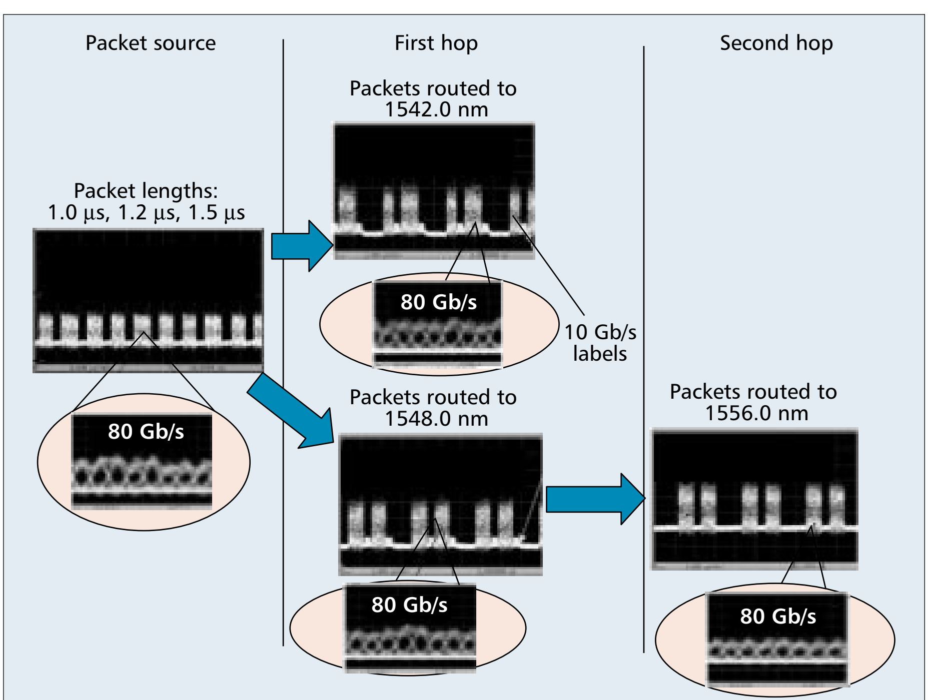

FIGURE 6. Demonstrated optical label swapping using fiber XPM wavelength converters for 80 Gb/s packets encapsulated with 10 Gb/s labels.

SYNCHRONOUS OTDM

Synchronous switching systems have been used extensively for packet routing; however, their implementation using ultrafast optical signal processing techniques is fairly new. In the remainder of the article we summarize the optical time domain functions for a synchronous packet network. These include the ability to:

- Multiplex several low-bit-rate DWDM channels into a single high-bit-rate OTDM channels
- Demultiplex a single high-bit-rate

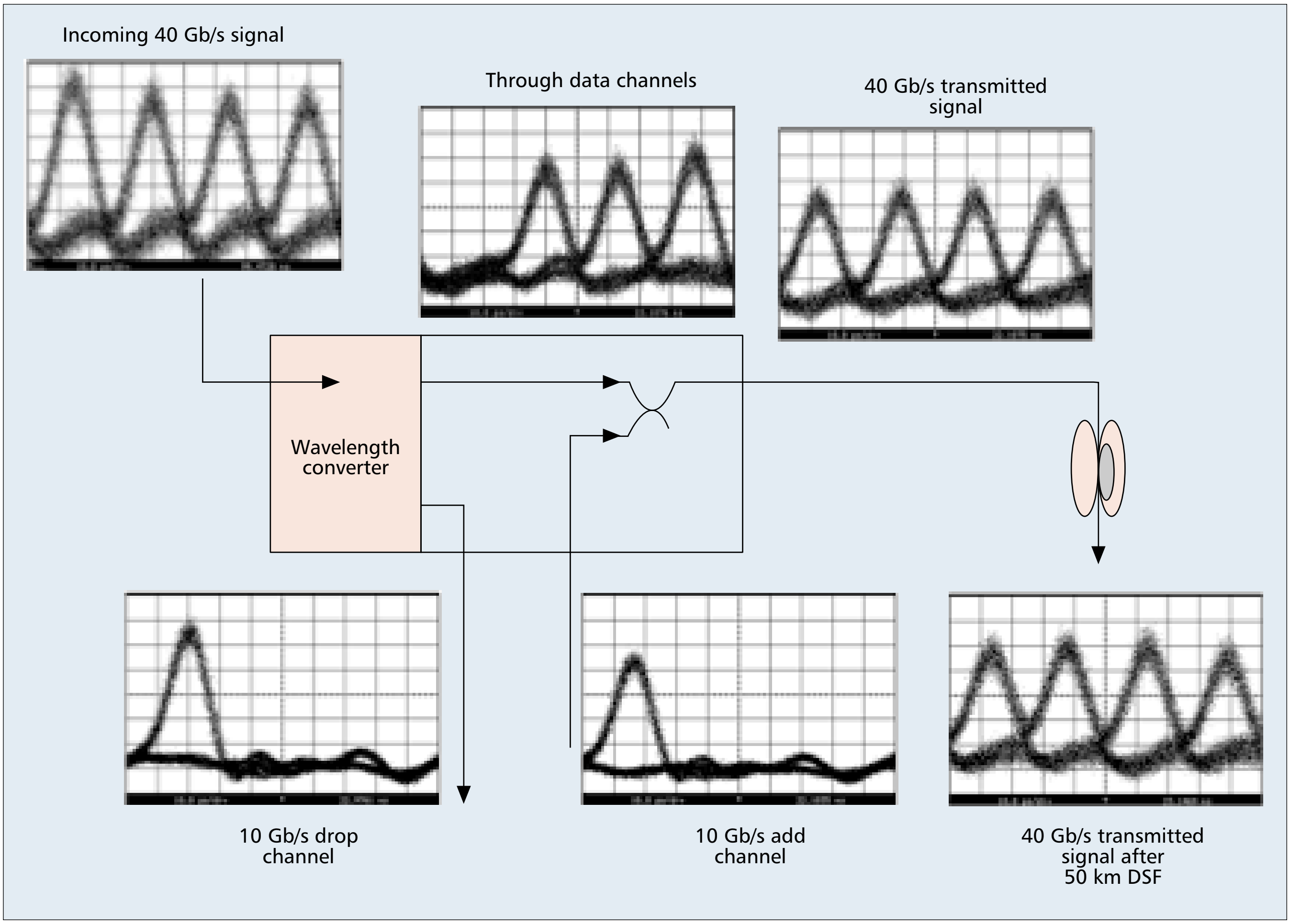

FIGURE 7. An experimental demonstration of OTDM add/drop using a nonlinear fiber XPM wavelength converter.

OTDM channel into several low-bit-rate DWDM channels
- Add and/or drop a time slot from an OTDM channel
- Wavelength route OTDM signals.

The added capability to multicast high-bit-rate signals is an important feature for packet networks that can be realized using these approaches.

The advantages of performing these functions all-optically are scalability and potential lower costs by minimizing the number of O-E-O conversions. A broad range of these ultra-high-speed functions can be realized using a nonlinear fiber-based wavelength converter [9] described in the previous section and may also be combined with the label swapping capabilities described above.

Consider the function of an OTDM OADM used to selectively add/drop a lower-bit-rate TDM data channel from an incoming high-bit-rate stream. This approach has been demonstrated at 40 Gb/s and higher using the OTDM add/drop shown in Fig. 7. The nonlinear fiber wavelength converter is used to drop a 10 Gb/s data channel from an incoming 40 Gb/s OTDM data channel and insert a new 10 Gb/s data channel in its place. This approach can be scaled to very high bit rates since the fiber nonlinearity response times are on the order of femtoseconds. We have demonstrated wavelength conversion over 13 nm, and this range can be extended over the entire C-band. The function of an OTDM OADM can be described as follows: a single channel at bit rate B is removed from an incoming bitstream running at aggregate bit rate NB, corresponding to N multiplexed time domain channels each at bit rate B. In the process of extracting (demultiplexing) one channel from the aggregate stream, the specific time slot from which every Nth bit is extracted is erased and available for new bit insertion. At the input is a 40 Gb/s data stream consisting of four interleaved 10 Gb/s streams. The wavelength converter also digitally regenerates the through-going channels.

SUMMARY

In this article we review optical signal processing and wavelength converter technologies that can bring transparency to optical packet switching with bit rates extending beyond that currently available with electronic router technologies. The application of optical signal processing techniques to all-optical label swapping and synchronous network functions is presented. Optical wavelength converter technologies show promise to implement packet processing functions. Nonlinear fiber wavelength converters and indium phosphide optical wavelength converters are described and research results presented for packet routing and synchronous network functions operating from 10 to 80 Gb/s with potential to operate out to 160 Gb/s.

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BIOGRAPHIES

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