All-optical label swapping (AOLS), an approach to transparently route IP packets all-optically, can revolutionize the future Internet. AOLS uses optical encapsulation to route packets independent of their bit-rate, format or length. Photonic technologies like rapidly tunable all-optical wavelength converters play a key role in realizing AOLS. This article also covers semiconductor optical amplifier and nonlinear optical-fiber-based wavelength converter implementations. Results of an AOLS systems demonstration with 40-Gbit/s packets are shown.
Within today’s Internet, data is transported between powerful electronic Internet protocol (IP) routers using optical-fiber transmission and wavelength-division-multiplexing (WDM) systems. Fiber-transmission systems today typically carry 32 wavelengths modulated at 2.5 Gbit/s to 10 Gbit/s (1 Gbit/s = 10^9 bits/sec.) per wavelength. At an IP router, multiple WDM fibers are terminated and signals are converted from optical to electronic at the input and electronic to optical at the output. Today’s routers need to handle in excess of 1 Tbit/s (10^12 bits/sec.) of data in order to redirect incoming Internet packets from fully loaded WDM fibers.

Things become very interesting when we consider that the capacity of optical fibers continues to double every 8-12 months. Today’s state-of-the-art single fiber capacity exceeds 10 Tbit/s. Comparing this increase with that of electronic processor speeds which doubles every 18 months (Moore’s law) and comes at the expense of increased chip power dissipation, we start to see that there is a potential mismatch in bandwidth handling capability between fiber-transmission systems and electronic routers. The story is more complex when we consider that future routers will terminate potentially hundreds or thousands of optical wavelengths and the increase in bit-rate per wavelength will head out to 40 Gbit/s and potentially beyond, to 160 Gbit/s. Additionally, electronic memory access speeds only increase at the rate of approximately 5% per year, an important data point since memory plays a key role in how packets are buffered and directed through the router. It is not difficult to see that the process of moving a massive number of packets per second (100 million packets/s and beyond the 1 billion packets/s mark) through the multiple layers of electronics in a router can lead to router congestion and exceed the performance of electronics and the ability to efficiently handle the dissipated power. Cost is also an important issue: The cost of performing conversion between optics and electronics can consume more than half the cost of a router.

In this article we review all-optical label swapping (AOLS), a technique intended to solve the potential mismatch between fiber capacity and router packet-forwarding capacity. AOLS imparts the functionality to direct packets through an optical network without the need to pass these packets through electronics whenever a routing decision is necessary. Inherent to this approach is the ability to route packets independently of bit-rate, packet or coding format and packet length. For this reason, AOLS is not limited to IP packets, but can handle asynchronous transfer mode (ATM) cells, bursts, data-file transfer and other data structures. We review research results obtained at the University of California at Santa Barbara (UCSB) in collaboration with Professors John Bowers’ and Larry Coldren’s groups at UCSB, under the support of the DARPA NGI program, Cisco Systems, Spirent Technologies, the DARPA-sponsored MOST Center and a State of California CORE grant sponsored by New Focus. An AOLS network is illustrated in Fig. 1(a). IP packets enter the network through an “ingress” node and are encapsulated with an optical label and then retransmitted on a new wavelength. The optical label and new wavelength are determined by reading the packet’s IP header (called “IP layer 3” information) and using information stored in a pre-established local lookup table. Once inside the network, only the optical label is used to make routing decisions and the wavelength is used to dynamically redirect (forward) packets. Nodes inside the network have an increased functionality over their ingress node counterparts. At these internal nodes, labels are read and optically erased.
then a new label is attached to the packet and the optically labeled packet is converted to a new wavelength using all-optical wavelength conversion. Throughout this process, the contents (e.g., the IP packet header and payload) are not passed through electronics and are kept intact until the packet exits the optical network through the “egress” node where the optical label is removed and the original packet is handed back to the electronic routing hardware.

A module that performs the label-swapping function is shown schematically in Fig. 2. As packets enter the module, a small percentage of light is redirected, using an optical tap, to a lower label-processing circuit where it is converted to an electronic signal and the new label and new wavelength are computed. While the new label and new wavelength computation are being performed, the labeled packet passes through a fixed fiber delay-line that matches the electronic-processing delay. The electronic circuit then sets up the new label and wavelength in the upper photonic processing circuit. The packet arrives at the first stage of the photonic processing circuit and the incoming label is optically erased. The packet is then converted to a new wavelength and a new optical label is reattached all-optically. Today we use electronics to process labels even though the packet is switched all-optically. We achieve this by converting the packet into an electronic format, processing the label, and then converting it back to an optical packet.

The choice of wavelength-converter technology tends to be strongly coupled to the label-coding technique. Two main approaches to optical label coding are bit-serial and subcarrier multiplexed, as illustrated in Fig. 1(b). Here we focus on serial labels to illustrate the process of erasing and rewriting labels using wavelength converters. The packet arrives at the head of the IP packet following an optical guard-band. This guard-band is used to facilitate label removal and insertion without static packet buffering and to accommodate finite switching times of optical switching and wavelength conversion.

The bit-serial label is encoded on the same optical wavelength as the IP packet.

Two types of wavelength converters—semiconductor optical amplifier (SOA) based and nonlinear optical fiber based—have been employed for AOLS. A popular converter configuration that performs most of the AOLS functions is the SOA interferometric wavelength converter (SOA-IWC). The SOA-IWC uses cross-phase modulation (XPM) in an SOA to realize an optically driven modulator and has been shown to operate at data rates exceeding 40 Gbit/s. Its operation is based on the well-known principle of constructive and destructive interference of optical waves. A tunable laser, located at one input of the SOA-IWC as shown in the inset of Fig. 3, is split into two optical waveguides. The optical signal coming from the SOA-IWC is then passed to a wavelength demultiplexer and router. Two types of wavelength converters—semiconductor optical amplifier (SOA) based and nonlinear optical fiber based—are used to convert the optical signal back to the original wavelength of the IP packet.
ities in an optical fiber has been demonstrated. This converter employs XPM in a dispersion-shifted fiber to phase modulate continuous wave (cw) light from the local tunable laser using the intensity-modulated signal on the original wavelength as shown in Fig. 5. The resulting phase-modulated signal is converted to intensity modulation by optically filtering the converter output. The fiber XPM converter is capable of erasing and writing new labels. The high-speed packet bits are coded return to zero (RZ) and the lower-speed serial-label bits are coded non-return to zero (NRZ). XPM effectively converts the RZ bits and not the NRZ bits. Therefore the label is automatically erased. A new NRZ label is premodulated onto the local laser and passes straight through the converter on the final wavelength.

A systems experiment that demonstrated AOLS using a fiber XPM wavelength converter with 40 Gbit/s packets is shown in Fig. 6. The payload was 40 Gbit/s RZ and the serial label at 2.5 Gbit/s NRZ. In the lower left hand trace, the packets with labels at the input to the converter are compared to the output where the labels are erased. In the lower right hand scope, traces are packets being switched between two output wavelengths.

In summary, we have described all-optical label swapping (AOLS) and its potential application to the future Internet. AOLS uses optical encapsulation to transparently route packets independent of bit-rate, format or length. The basic functions of AOLS are reviewed, including label erasure, rewriting and all-optical wavelength conversion. Two types of wavelength converters to implement the AOLS and packet routing, one semiconductor optical amplifier based and the other nonlinear fiber based, were reviewed. This approach has been shown to operate at packet bit-rates out to 40 Gbit/s.

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References