All-Optical Label Swapping with Wavelength Conversion for WDM-IP Networks with Subcarrier Multiplexed Addressing

D. J. Blumenthal, *Senior Member,* A. Carena, L. Rau, V. Curri, and S. Humphries

***Abstract*—We report the first demonstration of all-optical label swapping with wavelength conversion and subcarrier multiplexed addressing for WDM-IP. This demonstration utilizes a module which is based on cascaded semiconductor optical amplifier wavelength converters that perform the functions of label removal, label rewriting, payload 2R regeneration and double sideband subcarrier label regeneration. Replacement of double-sideband subcarrier labels on a hop-by-hop basis addresses the problem of dispersion induced fading in a multihop fiber network. A direct detection subcarrier receiver is used to recover the label. Switching over four wavelengths covering 16 nm is demonstrated with noninverting wavelength conversion of 2.5-Gb/s payloads and burst mode recovery of 50-Mb/s labels. BER measurements of better than 10^{-9} for the wavelength-converted payload and rewritten labels at all wavelengths are presented.**

***Index Terms*—All-optical label swapping, all-optical networks, IP over WDM, optical IP, optical packet switching, wavelength-division multiplexing.**

I. INTRODUCTION

WAVELENGTH-DIVISION-MULTIPLEXED (WDM) fiber transmission and switching are seen as potential solutions to the performance and scaling bottlenecks in Internet Protocol (IP) networks and offer the potential for limited transparency to packet data-rate and format. However, IP packet routing and forwarding presents a potential bottleneck as individual fiber link rates approach Tbps. IP label swapping is a low latency, low overhead routing technique that simplifies packet forwarding and enables scaling to terabit rates [1]. IP label swapping can avoid route lookups, reducing the number of packets that must pass through the IP layer. The label swapping technique is not restricted to IP alone and can support other protocols as well.

The basic concept of WDM-IP routing with optical label swapping and subcarrier multiplexed addressing is shown in Fig. 1. IP packets are generated and received at the source and destination nodes. At the input to the core optical network, edge routers containerize IP packets by adding subcarrier-multiplexed (SCM) labels without modifying the IP header or payload. The all-optical core routers perform routing and forwarding operations within the core optical network by wavelength conversion and SCM label swapping. As packets leave the core optical network, the edge routers remove the SCM labels and perform a final wavelength conversion.

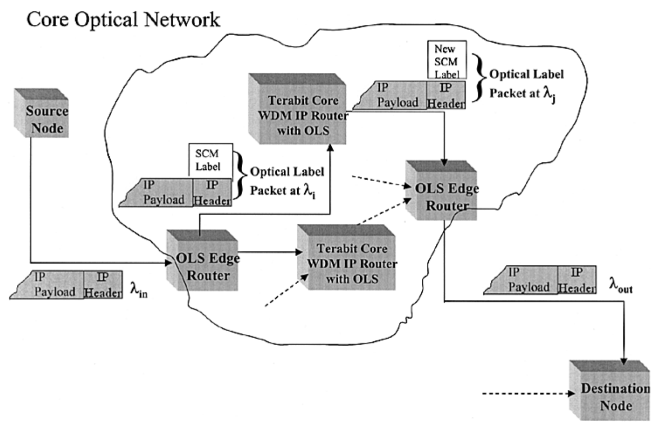

Fig. 1. WDM-IP routing with optical label swapping in an optical core network illustrating the containerization of WDM-IP packets by the edge routers and the forwarding and routing operations performed by the core routers.

In this letter, we report the first experimental demonstration of all-optical label swapping (AOLS) architecture with optical SCM addressing for WDM-IP networks [2], [3]. The AOLS technique reported here, was realized by cascading a cross gain modulated semiconductor optical amplifier wavelength converter (XGM-WC) and an interferometric wavelength converter (IWC) [4]. The AOLS module is used to collapse the label swapping and forwarding functions. Key embedded functions in this module include SCM header erasure, all-optical packet-rate wavelength conversion for routing level functions, IP packet regeneration, and new SCM label reinsertion. Our approach advances the prior state-of-the-art reported in [10] where a cascaded XGM-IWC structure was used only to regenerate the payload and reinsert a new header. In [10], reinsertion was performed in the XGM stage, while the IWC was used to regenerate the payload. In our approach, the XGM stage is used to erase labels and perform signal conditioning on the IP packet. The IWC section is used to perform packet-

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D. J. Blumenthal, L. Rau, and S. Humphries are with the Optical Communications and Photonic Networks Laboratory, Department of Electrical and Computer Engineering, University of California at Santa Barbara, Santa Barbara, CA 93106 USA.

A. Carena and V. Curri are with the Dipartimento di Elettronica, Politecnico di Torino, Torino, 10129, Italy.

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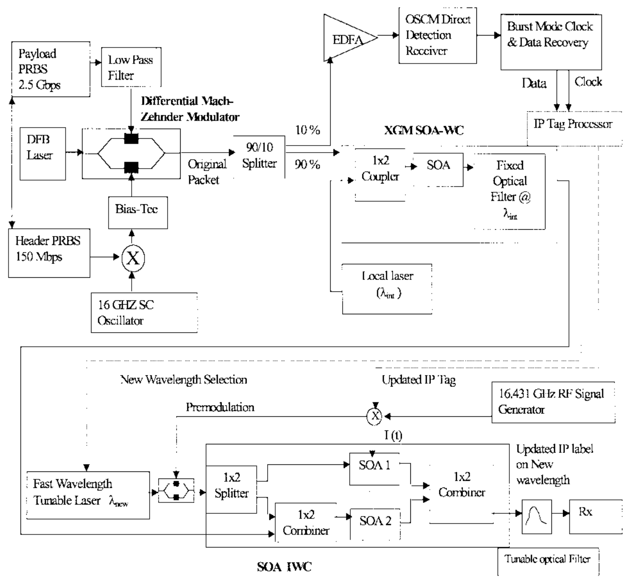

Fig. 2. Experimental setup for the optical label swapping technique with the two-stage cascaded wavelength converters.

rate wavelength conversion, IP packet regeneration and label reinsertion.

SCM label addressing offers the potential to extend the success of WDM at the transmission level by layering the routing information on a low bit-rate modulated out of band subcarrier that can be recovered with low cost electronics. Recovery of RF subcarriers and direct detection of labels is possible using MMIC's [5], a technology whose cost has been driven down by widespread use in wireless applications. In the 2-stage wavelength converter architecture, label swapping and label regeneration is performed using a previously reported technique to remove and replace SCM headers without returning the baseband to the electronic domain [6]. This architecture also minimizes fiber dispersion induced power penalties for double-sideband modulated SCM signals because the label is regenerated at every hop.

A schematic of the AOLS module is shown in Fig. 2. An OSCM packet transmitter [6] generates 1-μs packets consisting of a 150 Mb/s label on an RZ coded, ASK modulated 16-GHz subcarrier. In our experiment the packets were synchronous, therefore guardbands were not used. In practice, guardbands will be required between the packets to accommodate for the switching time of the tunable laser and the response time of the subcarrier receiver. Labels consist of a 16-bit preamble, an 84-bit tag, and a 4-bit framing sequence. The payload is an NRZ coded 2.5-Gb/s PRBS. The 16-GHz subcarrier supports payload bit rates up to 10 Gb/s. Label clock and data are recovered on a packet-by-packet basis following a 10% fiber tap, an EDFA, and an SCM direct-detection receiver. The SCM receiver utilizes a fast Schottky barrier diode for envelope detection. A SAW filter is used to recover the tag clock for each packet as shown in Fig. 3, with a fixed digital delay required to realign data and clock. More advanced burst mode detector techniques that employ fast clock and data recovery [11] are currently under investigation in our lab. A tag switching processor is needed to perform serial-to-parallel conversion, compute a new label, multiplex the new label onto a RF subcarrier, and set the wavelength of a fast tunable laser. In our experiment we used a fixed mapping from the packet label to the output wavelength. The fast tunable laser used in our experiment was a GCSR laser [9] that can be tuned to a new wavelength in under 12 ns. The laser was switched between the four different wavelengths by varying the coupler current alone. The average output power of each of the four wavelengths was 0 dBm and the power variation between the four wavelengths was less than 1 dB. The laser output was stable with respect to the wavelength and the power for time periods longer than a day. The wavelength current tuning and output power were repeatable such that power deviations at the output of the filter due to wavelength drift were not observed over the length of our experiment. The sidemode suppression under switching conditions for every wavelength was greater than 30 dB.

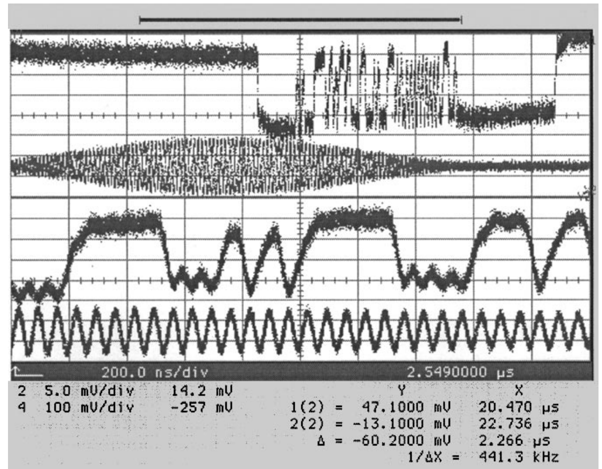

Fig. 3. Traces of the payload and the recovered clock. The first trace shows the NRZ payload at 2.5 Gb/s, the second trace shows the recovered clock before the XGM, the lower two traces are the details of the above two traces.

In the XGM stage, the low pass frequency response of wavelength conversion in an SOA [6] transfers the baseband frequencies and suppresses the SCM label; therefore the OSCM label is removed. The XGM-WC converts incoming WDM packets to a fixed internal wavelength (λ_{int}) that is passed to the next stage using a fixed frequency optical filter and sets the optical power operating point for the IWC for a given bias current. One arm of an InGaAsP IWC [8] is injected with the optically filtered output of the XGM-WC. The output of a rapidly tunable four-section GCSR laser transmitter [9] is injected to both arms of the IWC. The XGM stage inverts the payload bits while the IWC, operated in the inverting mode, results in a final output that has the same polarity as the input. Two header reinsertion configurations are possible as shown in Fig. 2. In the first approach, the injection current of the nonoptically injected SOA is directly modulated with the new SCM tag. In the second approach, the GCSR laser is externally modulated with the new SCM tag. In this experiment we utilized the latter approach due to the limited electrical bandwidth in the wirebonds to the IWC.

Results of the AOLS experiment are shown in Fig. 4. The 2.5-Gb/s packets are forwarded among four output wave-

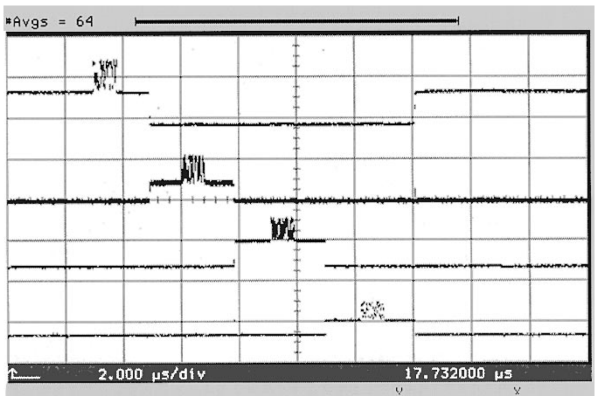

Fig. 4. Trace of the reinserted subcarrier label and the converted payload for four different wavelengths.

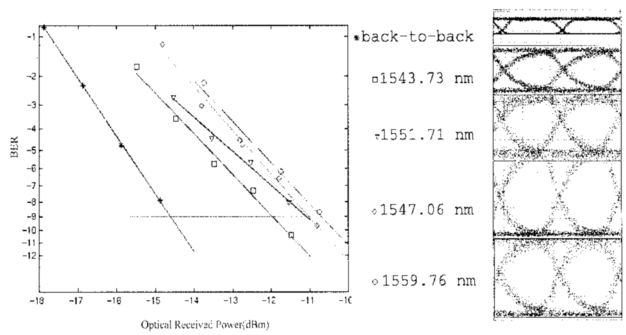

Fig. 5. BER of the wavelength converted payload with new label for four different wavelengths. The maximum power penalty is 4.3 dB.

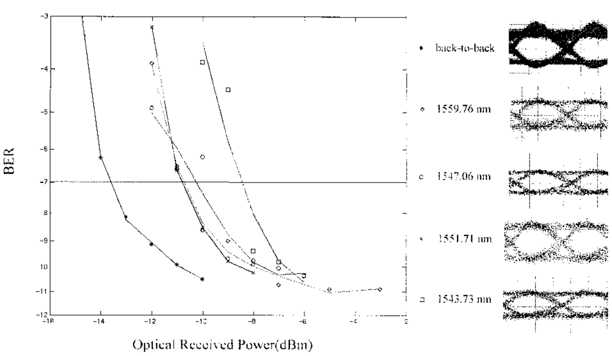

Fig. 6. BER of the reinserted subcarrier label. The floor is obtained due to saturation effects in the RF section of the receiver.

lengths. The channels were then individual received using a tunable optical filter. A broadband receiver can also be used to receive the different packets. The pedestal is due to extinction ratio sacrificed in order to cover the complete wavelength range of the tunable laser using the current IWC. We measured the transmission BER for the label-switched payload with an observed maximum of 4.3-dB power penalty as shown in Fig. 5. The power penalty is expected to decrease when optimally designed wavelength converters are used. The measured BER of the recovered SCM label is shown in Fig. 6. The floor obtained is a result of saturation effects in the RF section of the receiver.

In summary, we have demonstrated for the first time WDM IP all-optical label swapping with wavelength conversion and subcarrier multiplexed addressing. Switching over four wavelengths that span 16 nm was demonstrated with noninverting wavelength conversion of 2.5-Gb/s payloads and burst mode recovery of tag labels. In principle the wavelength converter and the GCSR laser can span 60–80 nm, thus 75–80 channels 100-GHz channel spacing can be effectively managed by this architecture. The scalability issues are currently being investigated in our lab.

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REFERENCES

[1] A. Viswanathan, N. Feldman, Z. Wang, and R. Callon, "Evolution of multiprotocol label switching," *IEEE Commun. Mag.*, vol. 36, no. 5, pp. 165–173, May 1998.

[2] A. Carena, M. D. Vaughn, R. Gaudino, M. Shell, and D. J. Blumenthal, "OPERA: An optical packet experimental routing architecture with label swapping capability," *J. Lightwave Technol.*, vol. 16, pp. 2135–12145, Dec. 1998.

[3] A. Budman, E. Eichen, J. Schlafer, R. Olshansky, and F. McAleavey, "Multigigabit optical packet switch for self-routing networks with subcarrier addressing," in *Optical Fiber Communications Conference, OFC'92*, San Jose, CA, Feb. 4–7, 1992, pp. 90–91.

[4] S. L. Danielsen, P. B. Hansen, K. E. Stubkjaer, M. Schilling, K. Wunstel, W. Idler, P. Doussiere, and F. Pommerau, "All optical wavelength conversion schemes for increased input power dynamic range," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 60–62, Jan. 1998.

[5] D. J. Blumenthal, J. Laskar, R. Gaudino, S. Han, M. Shell, and M. D. Vaughn, "Fiber optic links supporting baseband data and subcarrier-multiplexed control channels and the impact of MMIC photonic/microwave interfaces," *IEEE Trans. Microwave Theory Tech. JLT/MTT Joint Special Issue on Microwave Photonics II*, vol. 45, pp. 1443–1452, Aug. 1997.

[6] M. D. Vaughn and D. J. Blumenthal, "All-optical updating of subcarrier encoded packet headers with simultaneous wavelength conversion of baseband payload in semiconductor optical amplifiers," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 827–829, June 1997.

[7] R. Gaudino and D. J. Blumenthal, "A novel transmitter architecture for combined baseband data and subcarrier-multiplexed control links using differential Mach–Zehnder external modulators," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 1397–1399, Oct. 1997.

[8] R. J. S. Pedersen, N. Nissov, B. Mikkelsen, H. N. Poulsen, K. E. Stubkjaer, M. Gustavsson, W. vanBerlo, and M. Janson, "Transmission through 10 all-optical interferometric wavelength converter spans at 10 Gbit/s," *Electron. Lett.*, vol. 32, no. 11, pp. 1034–1035, May 1996.

[9] P.-J. Rigole, S. Nilsson, T. Klinga, L. Bäckbom, B. Stalnacke, E. Berglind, B. Stoltz, D. J. Blumenthal, and M. Shell, "Wavelength coverage over 67 nm with a GCSR laser tuning characteristics and switching speed," in *Tech. Dig. Optical Fiber Communication Conf. (OFC'97)*, Dallas, TX, Feb. 1997, paper WL63.

[10] D. Chiaroni, C. Chauzat, D. deBouard, F. Masetti, M. Sotom, M. Bachmann, P. Doussiere, and M. Schilling, "Novel all-optical multifunctional regenerative interface for WDM packet-switching systems," in *Proc. ECOC'96*, Oslo, Norway, Sept. 1996, pp. 4.115–4.118, paper ThD 1.4.

[11] Y. Ota, R. G. Schwartz, V. D. Archer, S. K. Korotky, M. Banu, and A. E. Dulop, "High speed, burst-mode, packet capable optical receiver and instantaneous clock recovery for optical bus operation," *J. Lightwave Technol.*, vol. 12, pp. 325–331, Feb. 1994.