A Compact All-Optical Subcarrier Label-Swapping System Using an Integrated EML for 10-Gb/s Optical Label-Switching Networks

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***Abstract*—We propose a compact and simple all-optical subcarrier-multiplexed (SCM) label-swapping system employing an integrated electroabsorption modulation laser and a semiconductor optical amplifier based Mach–Zehnder interferometer wavelength converter. The experiments demonstrated error-free all-optical label swapping for the 155-Mb/s label and 10-Gb/s payload over two optical label-switching network nodes with less than 0.7-dB power penalty on the payload. The majority of the components in this SCM label-swapping system can be realized on a semiconductor platform (*e.g.*, InP), which implies a step toward possible monolithic or hybrid integration of the all-optical label-swapping system in the future.**

***Index Terms*—Electroabsorption modulator, fiber Bragg grating (FBG), optical label swapping, optical label switching (OLS), subcarrier multiplexing (SCM), wavelength conversion.**

I. Introduction

OPTICAL label-switching (OLS) technology [1] achieves efficient and transparent forwarding of ultrahigh-speed optical packets by using a shim layer that employs optical labels. Therefore, label swapping plays an important role in enhancing scalability in OLS networks. All-optical label swapping avoids the complexity of optical-to-electrical and electrical-to-optical conversions of high-speed data payloads in OLS networks [2]; however, this capability is critically dependent on the optical label-encoding scheme. Recently demonstrated optical label-swapping techniques have been based on bit-serial labeling scheme [3], subcarrier-multiplexed (SCM) labeling scheme [4]–[7], and orthogonal modulation labeling scheme [8], [9]. [3] showed bit-serial label swapping by synchronous operation and fiber-loop mirror-based wavelength conversion, which required relatively accurate timing control, high-power operation, and bulky fiber spools. In [4]–[7], the SCM label-swapping techniques involved a relatively complex single-sideband modulation method [4], an over-modulating scheme with intermodulation crosstalk [5], a bulky setup with external $LiNbO_3$ modulators [6], or a relatively low-speed method (2.5 Gb/s) limited by dynamic characteristics and intermodulation crosstalk of the components [7]. In [8] and [9],

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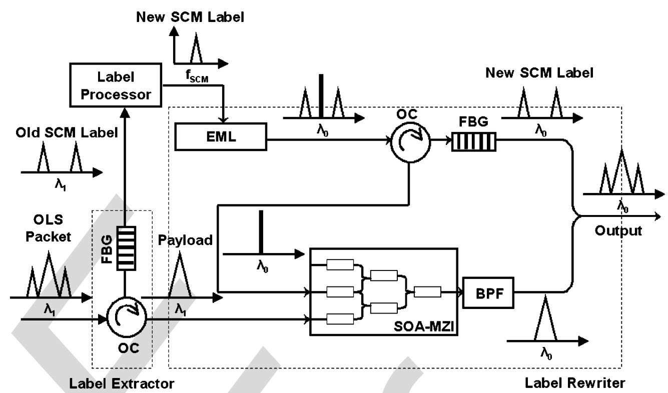

Fig. 1. Schematic diagram of proposed all-optical SCM label-swapping system. BPF: Optical bandpass filter. EML: Integrated EML. SOA-MZI: SOA-MZI wavelength converter.

the amplitude-shift keying payloads were modulated on the differential phase-shift keying/frequency-shift keying labels. Such schemes typically sacrifice the extinction ratio [8] or bandwidth efficiency [9] to sustain reasonable label performance.

The integrated electroabsorption modulation laser (EML) is a compact device that can provide low-cost solutions for optical communication systems. In addition, the semiconductor optical amplifier-based Mach–Zehnder interferometer (SOA-MZI) wavelength converter has the capability to reamplify and reshape (2R regeneration) the signal while performing wavelength conversion [10]. In this letter, we report a novel 10-Gb/s all-optical SCM label-swapping system based on an EML and an SOA-MZI. Compared to the previous approach illustrated in [7], the major technical improvements here include utilization of a two-arm configuration for the SCM transmitter to avoid intermodulation crosstalk between the label and the payload, employment of an EML and an SOA-MZI with higher operation speeds to overcome device limitations, and implementation of fiber Bragg gratings (FBGs) with wider reflection bandwidths and steeper frequency responses to accommodate high-speed data payload. The experimental results prove low-penalty (<0.7 dB) operation using the proposed scheme.

II. Operation Principle

Fig. 1 shows the principle of the proposed SCM label-swapping technique. When an OLS packet enters the label extractor, the FBG and the optical circulator (OC) all optically separate the SCM label and the payload [5]. After the label extractor, the SCM label goes into the label processor to prompt new label

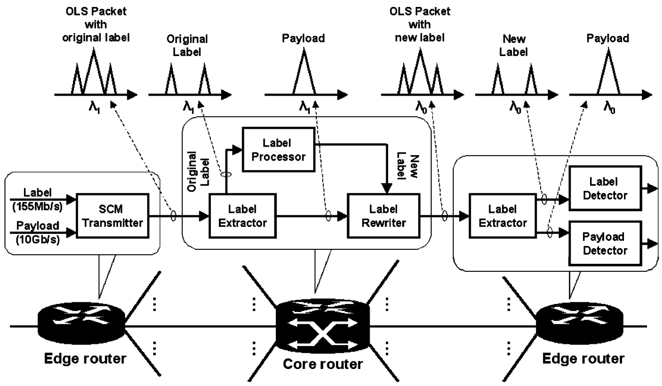

Fig. 2. System architecture of the experimental demonstration.

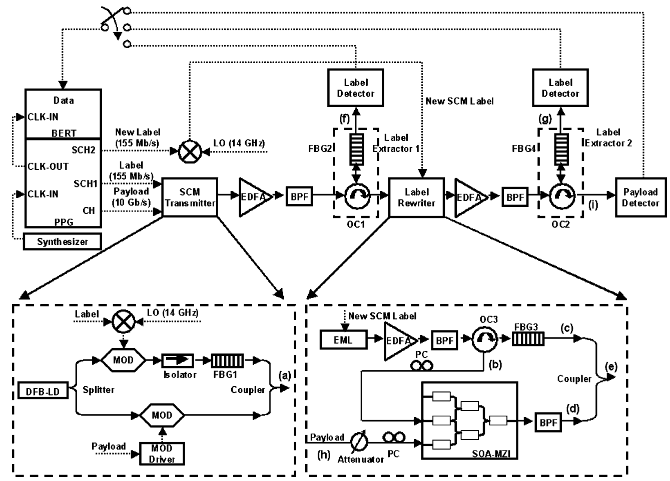

Fig. 3. Experimental setup for all-optical SCM label swapping. PPG: Parallel pattern generator. LO: Local oscillator. DFB-LD: DFB laser diode. Mod: $LiNbO_3$ optical modulator. Mod driver: Modulator driver. EDFA: Erbium-doped fiber amplifier. BPF: Optical bandpass filter. EML: Integrated EML. PC: Polarization controller. SOA-MZI: SOA-MZI wavelength converter.

generation, while the payload enters the label rewriter to attain new label insertion. Inside the label rewriter, the new SCM label from the label processor drives the integrated EML to generate a double-sideband optical signal. In the frequency domain, the double-sideband optical signal contains two SCM label sidebands and an optical carrier [7]. The OC and the FBG in the label rewriter pass through the new SCM label and reflect the optical carrier to the SOA-MZI wavelength converter as a probe light. The cross-phase modulation in the SOA-MZI wavelength converter imprints payload information onto the optical carrier from the EML while achieving 2R regeneration of the payload. Finally, a fiber coupler at the output of the label rewriter combines the new SCM label and the payload to form a new OLS packet. Compared to our previous approach in [6], this label-swapping system is much more compact and stable since the EML-based system achieves superior bias stability.

III. Experimental Setup and Results

Fig. 2 illustrates the system architecture of the experimental demonstration. At the ingress edge router, the SCM transmitter generates SCM-labeled OLS packets with 155-Mb/s labels and 10-Gb/s payloads. When the OLS packets reach the core router, the label extractor removes the original SCM labels from the payloads and the label rewriter reinserts new SCM labels onto the payloads. After the label swapping, the labels and the payloads are separated again at the egress edge router. Note that, as a subsystem demonstration, the experiments discussed below did not include the label processor and the BER measurements utilized continuous data containing $2^{31} - 1$ pseudorandom bit sequence patterns for both the label and the payload. In real OLS router systems, each label will contain a preamble to initiate the label processor, and the label processor will generate a new label for each incoming packet; meanwhile, the payload will be buffered in a fixed-length fiber delay line to compensate for the label processing delay. Reference [2] has demonstrated an 11-hop optical packet switching experiment with a similar scheme.

Fig. 3 shows the experimental setup. The parallel bit-error-rate tester (ParBERT) simultaneously generates 155-Mb/s labels and 10-Gb/s data payloads in electrical baseband formats. The SCM transmitter in a two-arm configuration modulates the label and the payload separately before combining them into an OLS packet. The distributed-feedback (DFB) laser diode at 1549.21 nm provides continuous-wave light to both arms through the 50/50 fiber splitter. The $LiNbO_3$ modulator in the lower arm converts the payload to an optical format. After mixing with a 14-GHz subcarrier, the label drives the $LiNbO_3$ modulator in the upper arm, generating a double-sideband optical SCM signal. FBG1 has a narrow ($\sim$0.16-nm FWHM) high reflectivity band ($>$99.9%) peaking at 1549.21 nm. FBG1, together with the isolator, suppresses the optical carrier of the double-sideband signal to avoid coherent crosstalk between the two arms. The SCM label and the payload are then combined with a fiber coupler to form an OLS packet. Fig. 4(a) shows the optical spectrum measured at the output of the SCM transmitter. After being amplified, the OLS packet reaches Label Extractor 1 for label-payload separation. The label detector receives the extracted label and sends it to the ParBERT for bit-error-rate (BER) measurements. In the label rewriter, the EML operating at 1555.68 nm takes the new SCM label from the ParBERT and creates a double-sideband signal. The EML, containing a DFB laser with a monolithically integrated electroabsorption modulator, is a commercially available device that is optimized for 10-Gb/s time-division-multiplexing and wavelength-division-multiplexing transmission systems supporting dispersion up to 1600 ps/nm. FBG3 and OC3 pass through the SCM label sidebands [as shown in Fig. 4(b)] and reflect the baseband optical carrier [as shown in Fig. 4(c)] to the SOA-MZI. After wavelength conversion, a fiber coupler combines the new SCM label and the payload, completing the SCM label-swapping process. Fig. 4(d) and (e) illustrate the optical spectra of the payload after wavelength conversion and the OLS packet after label rewriting, respectively. Label Extractor 2 separates the label and the payload again, and forwards them to the label and payload detectors. The detectors send the label and the payload contents to the ParBERT for BER measurements.

Fig. 5 shows the BER measurement results and eye diagrams of the labels and the payloads before and after label swapping.

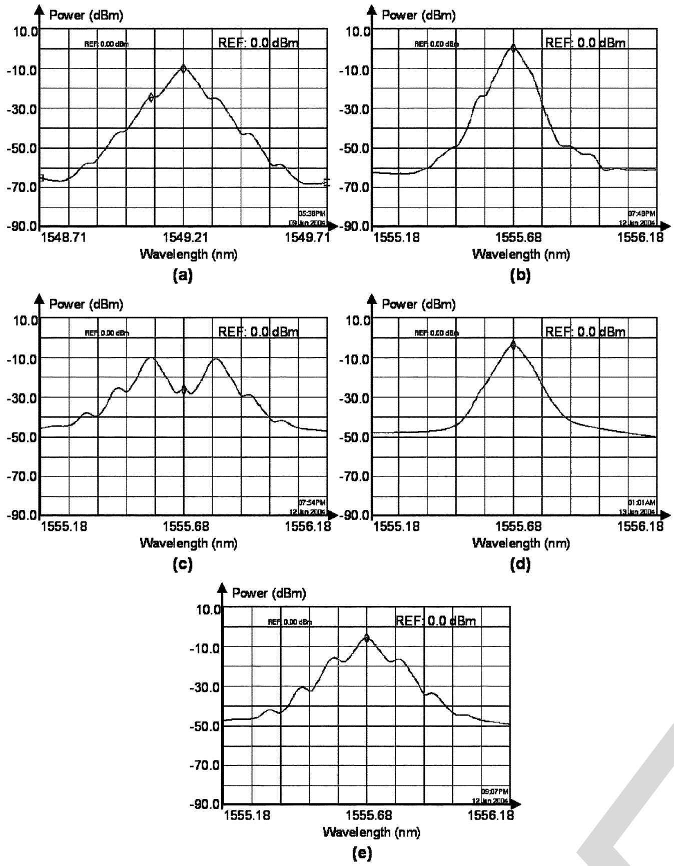

Fig. 4. Optical spectra (measured in 1-nm wavelength span and with 0.06-nm resolution bandwidth) of (a) OLS packet generated by SCM transmitter; (b) optical carrier reflected by FBG3; (c) new SCM label after FBG3; (d) payload after wavelength conversion; and (e) OLS packet after label-swapping.

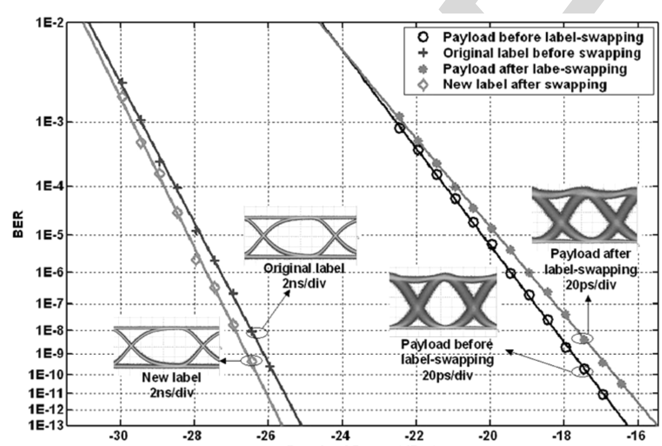

Fig. 5. BER results for label swapping.

The BER curves of the labels before and after label swapping and the payloads before and after label swapping were measured at locations (f), (g), (h), and (i) in Fig. 3, respectively. The BER measurement results prove that the proposed SCM label-swapping technique achieved error-free operations. In Fig. 5, the inset label and payload eye diagrams also indicate clear openings. However, the eye-diagram of the payload after label swapping was slightly asymmetric and the payload suffered from a less than 0.7-dB power penalty after label swapping. This may have resulted from the nonideal responses of the SOA-MZI wavelength converter, primarily due to the finite gain recovery time. Using a wavelength converter with faster response is likely to solve this problem.

IV. Summary

We have proposed and demonstrated a compact 10-Gb/s all-optical SCM label-swapping system employing an integrated EML and an SOA-MZI wavelength converter. The system was experimentally demonstrated over two 10-Gb/s OLS network nodes. The experimental results show that the proposed technique can achieve error-free operation with less than 0.7-dB power penalty on the payload. The majority of the components in this SCM label-swapping system can be realized on a semiconductor platform (e.g., InP), which implies a step toward possible monolithic or hybrid integration of the all-optical label-swapping system in the future.

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