101-Hop Cascaded Operation of an Optical-Label Switching Router With All-Optical Clock Recovery and 3R Regeneration

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***Abstract*—This paper experimentally demonstrates the cascaded operation of an optical-label switching router for up to 101 hops with 3R regeneration (reamplification, reshaping, and retiming). A semiconductor optical amplifier-based Mach–Zehnder interferometer wavelength converter performs the reshaping. A Fabry–Pérot filter all-optically recovers the clock from the incoming packets. Synchronous modulation by a $\mathbf{LiNbO_3}$ modulator using the recovered clock performs the retiming. The 3R regeneration maintains good signal quality in the cascaded operation, which is important for scalable optical networking.**

***Index Terms*—3R regeneration, clock recovery, optical-label switching (OLS), optical packet switching.**

I. INTRODUCTION

THE Internet is rapidly growing, demanding ever larger bandwidth and more sophisticated routing functions. Optical-label switching (OLS) effectively combines the large bandwidth of optical technology and the functional flexibility of electrical technology. OLS enables high-capacity agile networking with interoperability between packet, burst, and circuit switching [1], [2]. The scalability of OLS technology is important for its application to the next-generation optical network, because OLS routers must maintain good signal quality after a reasonably large ($>$17 hops) number of cascaded packet forwardings [3]. Optical 3R regeneration (reamplification, reshaping, and retiming) can partly limit the accumulation of signal impairments caused by, for instance, optical loss, spontaneous emission noise, optical crosstalk, dispersion, and/or nonlinear effects. However, its applicability in all-optical routers has not been tested, especially for cascaded optical packet switching operations, which are challenging due to its inherent burstiness. This letter applies optical 3R regeneration in an OLS router testbed to achieve a 101-hop cascaded operation at 10 Gb/s. A semiconductor optical amplifier-based Mach–Zehnder interferometer (SOA-MZI) wavelength converter provides 2R regeneration in a way similar to that in a previous 11-hop demonstration at 2.5 Gb/s [4]. In addition, this letter implements the retiming function using a synchronous modulation scheme with all-optical clock recovery by a Fabry–Pérot filter (FPF).

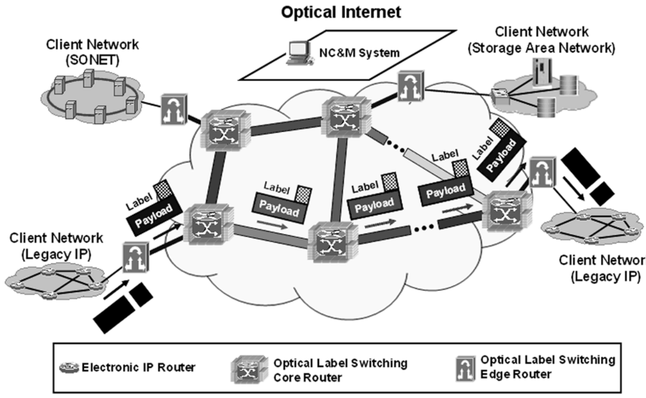

Fig. 1. Multihop OLS network.

II. PRINCIPLE OF CLOCK RECOVERY

The all-optical clock recovery method for retiming must provide a clock signal that is stable in both the time domain (low jitter) and the amplitude domain (low amplitude modulation). For efficient packet switching networks, the lock-in time of the clock recovery should be short compared to the packet length. The FPF method with postamplitude equalization satisfies these requirements [5]–[7]. This method extracts the clock components from the return-to-zero (RZ) signal utilizing the comb-shaped filter peaks of an FPF. The finesse value of the FPF is critical. Greater finesse values result in lower jitter and amplitude modulations in the extracted clock [6], [8], but also induce longer lock-in times. Considering the tradeoff, this experiment employs an FPF with a finesse of 100. A saturated SOA after the FPF acts as a limiting amplifier to reduce the amplitude modulation [6].

III. EXPERIMENTAL DESCRIPTION

Fig. 1 illustrates a multihop OLS network. The ingress edge router converts the legacy network packets into OLS packets by packet aggregation and label attachment. At each hop in the OLS network, the router extracts the label, switches the payload, and attaches a new label if necessary. The egress edge router reconverts the OLS packets to the legacy format.

In this demonstration, an OLS router testbed emulates the multihop network by repeatedly switching the packets through

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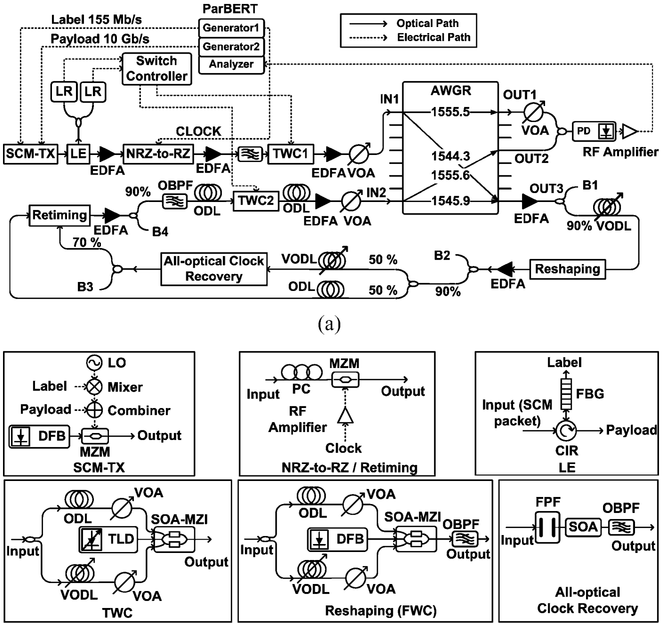


Fig. 2. (a) Experimental setup. In the arrayed-waveguide grating router (AWGR), each value is the wavelength in nanometers for switching from a certain input to a certain output. (b) Functional blocks in (a). CIR: circulator. DFB: distributed feedback laser. EDFA: erbium-doped fiber amplifier. FBG: fiber Bragg grating. FWC: fixed wavelength converter. LE: label extractor. LO: local oscillator. LR: label receiver. MZM: Mach–Zehnder modulator. OBPF: optical bandpass filter. ODL: optical delay line. ParBERT: parallel BER tester. PC: polarization controller. PD: photodetector. SCM: subcarrier-multiplexing. TLD: tunable laser diode. TX: transmitter. VOA: variable optical attenuator. VODL: variable optical delay line.

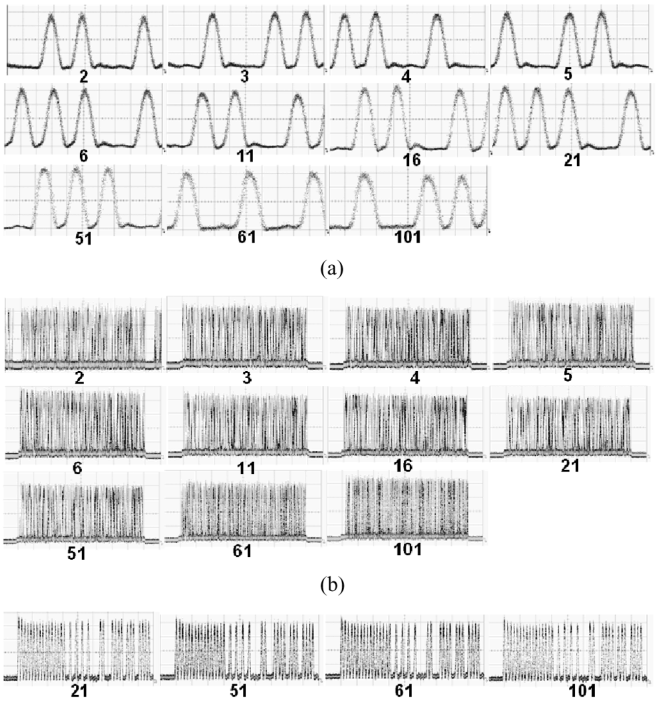


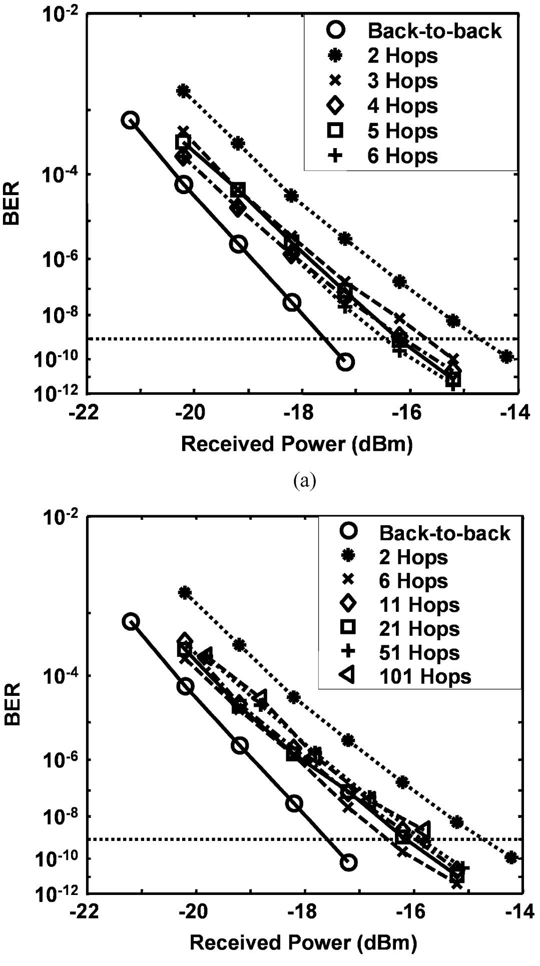
Fig. 3. Oscilloscope traces at OUT2, the final output. The number below each trace indicates the different number of hops traveled. (a) Bit patterns, 50 ps/div. (b) Packet P1, 200 ns/div. (c) Leading bits of P1, 500 ps/div.

the same router until the number of hops reaches the designated value. Fig. 2 shows the experimental setup. The subcarrier-multiplexing transmitter generates optical packets with a 10-Gb/s nonreturn-to-zero (NRZ) payload on the baseband and a 155-Mb/s NRZ label on the 14-GHz subcarrier. The packet length is 1.7 μs; the guard time is 100 ns. The label extractor separates the label from the payload by optical filtering [9]. A 10-GHz clock signal drives a LiNbO_3 modulator to convert the payload format from NRZ to RZ. It is also possible to multiplex an RZ payload or a higher-data-rate payload directly with the subcarrier label. To avoid payload-label crosstalk in these cases, the payload and label will not overlap in the time domain, or the subcarrier frequency will increase. The latter can be implemented using the optical carrier suppression and separation method [10]. The label receiver receives the label. The switch controller makes a switching decision according to the label content and the forwarding table. It then instructs the tunable wavelength converter 1 (TWC1) to duplicate the payload onto a corresponding wavelength that directs the payload from port IN1 to the desired output port of the arrayed waveguide grating router. Those packets labeled for the hop counting and bit-error-rate (BER) measurement assistance will travel to OUT1, while those labeled for the multihop operation will travel to OUT3 and pass the reshaping functional block. The reshaping block cleans up the amplitude-domain noise on the space and mark levels through wavelength conversion with an SOA-MZI [11]. Afterwards, 50% of the power travels to the all-optical clock recovery block which consists of an FPF, an SOA, and an optical bandpass filter. A 16-bit all-“1” preamble leads the packet to enable a short rise time of the recovered clock envelope. The 10%–90% rise time after the SOA is approximately 3 ns. A photodetector and an amplifier receive and amplify the recovered clock to drive a LiNbO_3 modulator. The modulator performs synchronous modulation on the remaining 50% of the payload signal to suppress the time-domain noise [12]. The packets continue to travel to IN2, where TWC2 switches them either back to the router (OUT3) or, when the packets have completed the designated number of hops, to the final output (OUT2). For simplicity, the switch controller keeps track of the hop count through accurate timing rather than through updating the time-to-live field in the label using label swapping [4]. Future work will include 3R regeneration with label swapping. All of the SOA-MZI wavelength converters in the setup operate in the differential mode [13].

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3 shows the oscilloscope traces of the final outputs observed at OUT2 for different numbers of hops. A “hop” refers to the passing of either TWC once. Fig. 3(a) shows the bit patterns. The quality of the RZ pulses remains good through the hops due to the 3R regeneration. Fig. 3(b) shows the final output packet. The complete packet travels through the hops without any cut. Fig. 3(c) shows the leading bits of the final output packet, including the 16-bit all-“1” preamble. The leading bits suffer no obvious degradation through the hops.

Fig. 4 shows the BER measurement results. The packet contains pseudorandom bit sequence $2^{23}-1$ following the 16-bit



(a)

(b)

Fig. 4. BER measurement results. (a) Hop count 2–6. (b) Hop count 2–101. The horizontal dotted line shows the BER $= 10^{-9}$ level.

preamble. The BER measurement excludes the preamble. For clarity, Fig. 4(a) contains the BER curves for two to six hops, while Fig. 4(b) contains the curves for larger hop counts. The back-to-back, two-hop, and six-hop curves appear in Fig. 4(a) and (b) to aid comparison. For the large hop counts of 51 and 101, the random hop distance change caused by environmental fluctuation results in sub-Hertz multiple-bit jitter in the final output, which is not removed by the inline 3R regenerator. To enable the BER measurement for large hop counts, an electrical clock recovery internal to the Agilent 81250 Parallel BER Tester recovers the clock from the combined output of OUT1 and OUT2, a semicontinuous data stream with only 100-ns guard times. The measurement excludes the first 7664 bits of each packet to provide enough time for the nonburst-mode electrical clock recovery to lock in. Despite this, a large change in the hop distance would still cause instability in the BER test. As a result, the 101-hop BER result does not extend below 10^{-9}. All the other BER curves can reach below 10^{-10}. The power penalties at BER $= 10^{-9}$ for 2, 3, 4, 5, 6, 11, 21, 51, and 101 hops are 2.77, 1.80, 1.47, 1.44, 1.23, 1.55, 1.90, 1.78, and 1.80 dB, respectively. The 3R regenerator is optimized for large hop counts; thus, the reshaping block cannot suppress the noise sufficiently for the first pass. As a result, the two-hop result has a relatively large power penalty. After two hops, however, the signal quality stabilizes and the power penalty against the back-to-back remains below 2 dB and within a 0.67-dB-wide band, clearly demonstrating that the 3R regeneration maintains the signal quality for the cascaded operation.

V. SUMMARY

This letter experimentally demonstrated the multihop operation of an OLS router. The optical 3R regeneration scheme using the SOA-MZI wavelength converter, the all-optical clock recovery by FPF, and the synchronous modulation enabled 101-hop cascaded operation at 10 Gb/s with small hop-to-hop penalty beyond two hops. The results indicate that the demonstrated optical 3R regeneration scheme is suitable for multihop packet switching applications.

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