160 Gb/s Variable Length Packet/10 Gb/s-Label All-Optical Label Switching With Wavelength Conversion and Unicast/Multicast Operation

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***Abstract*—We report on the first demonstration of all-optical label switching (AOLS) with 160 Gb/s variable length packets and 10 Gb/s optical labels. This result demonstrates the transparency of AOLS techniques from previously demonstrated 2.5 Gb/s to this 160 Gb/s demonstration using a common routing and packet lookup framework. Packet forwarding/conversion, optical label erasure/re-write and signal regeneration at 160 Gb/s is achieved using a WDM Raman enhanced all-optical fiber cross-phase modulation wavelength converter. It is also experimentally shown that this technique enables packet unicast and multicast operation at 160 Gb/s. The packet bit-error-rate is measured for all optical label switched 16 $\times$ 10 Gb/s channels and error free operation is demonstrated after both label swapping and packet forwarding.**

***Index Terms*—Nonlinear optics, optical fiber communication, optical-label switching, optical-packet switching, optical signal processing, Raman effect, wave mixing.**

I. Introduction

All-OPTICAL label switching (AOLS) is a technique used to forward packets based on information contained in an optical label and to erase and rewrite these labels without passing the packet through optoelectronic conversions [1]. Several techniques to accomplish AOLS have been reported [2]–[4]. Having the capability to direct packets through an optical network without the need to pass the packets through electronics, AOLS will greatly avoid router congestions and solve the problems of the electronics capabilities limits. This is especially important when it comes to routing a massive number of packets per second to accommodate the growth in future Internet traffic. To date the highest speed AOLS experiment reported operated with variable-length 80 Gb/s packets and 10 Gb/s labels [5] and prior experiments have shown operation with 2.5 Gb/s [6] and 40 Gb/s [7] packets. In order to demonstrate the scalability of this technique, it is important to show operation at higher bit-rates, particularly at rates difficult to achieve electronically, using a similar and compatible optical label framework.

In this paper we report the world's first experimental demonstration of AOLS operating with 160 Gb/s variable length packets and 10 Gb/s labels. We experimentally demonstrate packet-rate wavelength switching of these 160 Gb/s packets using ultra-fast wavelength conversion based on Raman-enhanced fiber cross-phase-modulation (RE-XPM). RE-XPM is shown to operate at 160 Gb/s with a small power penalty and 2R regeneration capability and allows all-optical erasure and re-writing of the 10 Gb/s label onto the 160 Gb/s wavelength switched packet. The experimental packet bit-error-rate (BER) measurements show 2R regeneration with a small packet power penalty (0–2 dB) and label erasure extinction ratio sufficient for cascadable operation. We also show for the first time simultaneous up- and down- conversion to two different wavelengths for unicast/multicast switching of 160 Gb/s packets. Packet demultiplexing from 160 Gb/s to 16 $\times$ 10 Gb/s for packet BER measurements are achieved using a Raman-enhanced fiber four-wave-mixing (RE-FWM) fiber demultiplexer.

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II. 160 Gb/s AOLS Packet Wavelength Converter and Demultiplexer

A key building block is the 160 Gb/s all optical wavelength converter (WC) used for label erase/re-write, regeneration and packet forwarding via wavelength conversion. The ultra-fast fiber nonlinear response time allows techniques previously demonstrated at 80 Gb/s [8] to scale to 160 Gb/s. The wavelength converter is based on XPM in dispersion shifted fiber (DSF). Raman gain in the nonlinear fiber is employed to enhance the conversion efficiency and OSNR [9] and can achieve extremely high wavelength conversion bit rates due to the femto-second response time of Raman scattering [10]. Fig. 1 shows the architecture of the RE-XPM wavelength converter. It consists of one spool of nonlinear fiber, one Raman pump laser and a band pass filter (BPF). The fiber acts as both gain medium and XPM interaction medium. XPM imposes modulation sidebands from the data pump light at wavelength λ_2 onto the continuous wave (CW) probe light at λ_1. The Raman pump provides distributed amplification for both the pump light and the probe light providing significant enhancement of XPM conversion efficiency. The BPF is used to select one of the modulation sidebands on λ_2 and converts phase modulation into intensity modulation. The conversion from phase to amplitude modulation results in a nonlinear transfer function that minimizes the fluctuations in the top and bottom levels of the signal and decreases zero and one level random amplitude fluctuations, hence the converter also acts as a 2R packet regenerator. The power level of the data pump light was controlled to be higher than the power of the CW light. Besides

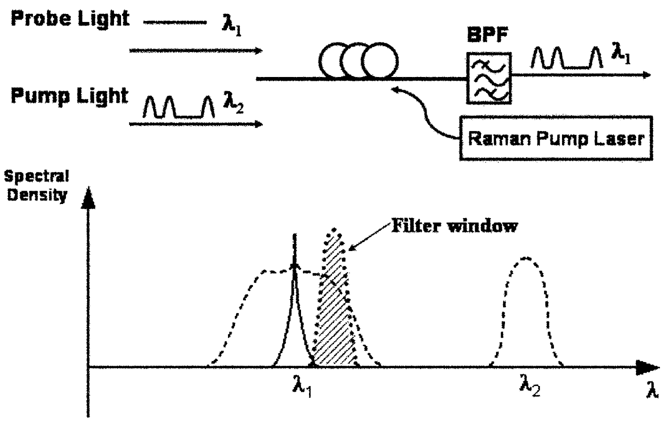
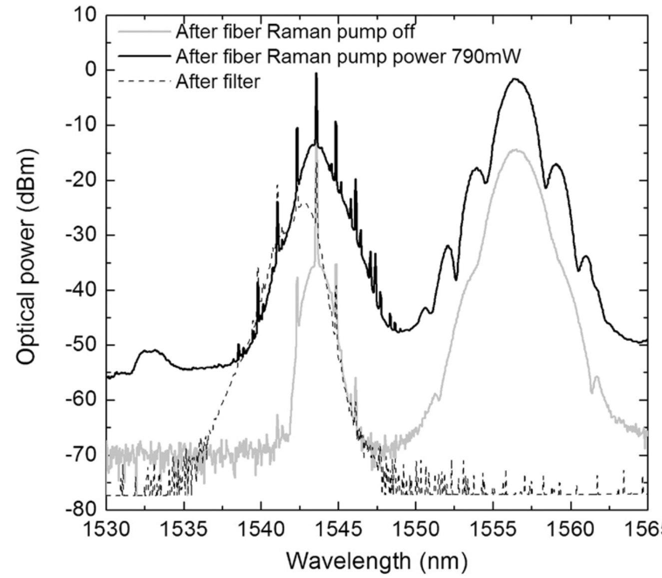


Fig. 1. Cross phase modulation RE-WC architecture.

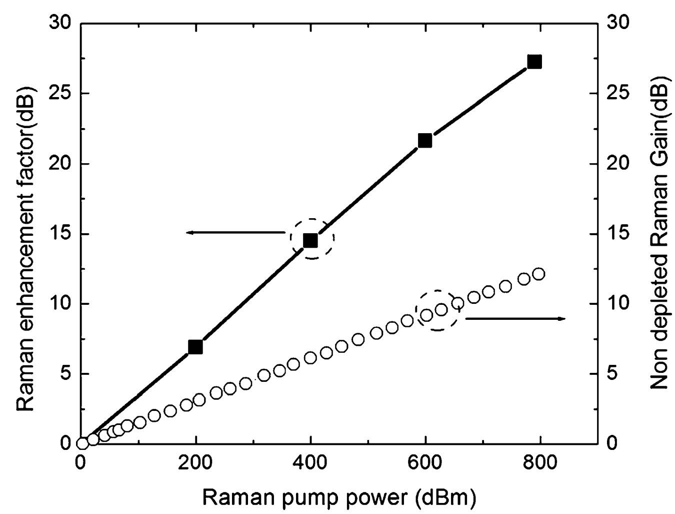
this, the spectrum of the CW light was broadened as soon as it entered the fiber from XPM. Both of these helped minimize the instability from stimulated Brillouin scattering (SBS).

The performance of the wavelength converter was studied first in continuous operation mode and then in the packet mode. The experimental setup was similar to that described in [8], except that one more stage of the interleaving multiplexer was used to multiplex the 80 Gb/s data to 160 Gb/s and the filter bandwidth was increased from 1.2 to 3.5 nm. Fig. 2(a) shows the spectrum measured for continuous mode wavelength conversion over 15 nm bandwidth from 1557 to 1542 nm. A significant XPM sideband increase can be observed with 790 mW of Raman pump power within 1 km of highly nonlinear dispersion shifted fiber (HNLF). Table I shows the parameters of the HNLF used in the experiment in terms of nonlinear coefficient, fiber effective mode area, Raman gain coefficient, and dispersion slope. We define the Raman nonlinear enhancement factor as the conversion efficiency enhancement from the Raman gain and Fig. 2(b) shows the measured enhancement factor as a function of Raman pump power, together with the measured nondepleted Raman pump on off gain. At a Raman pump power of around 800 mW, where the small signal Raman gain is 12 dB, the total conversion efficiency enhancement is close to 27 dB.

To characterize the performance of the wavelength converted 160 Gb/s data, each of the 16 $\times$ 10 Gb/s OTDM channels was demultiplexed using a RE-FWM demultiplexer (DEMUX) described in [11] with BER measurements performed after a 10 Gb/s pre-amplified receiver. The gating signal for the FWM demultiplexer consisted of 4 ps pulses at 1550 nm generated using a 10 GHz mode-locked fiber ring laser (FRL). The DEMUX design is similar to the AOLS wavelength converter except that the HNLF zero dispersion wavelength is at 1527 nm and the Raman pump laser is a WDM pump source with two pump wavelengths at 1440 nm and 1455 nm. WDM pumping was used to increase the gain bandwidth of the Raman amplifier and hence further increased the operation bandwidth of the DEMUX [12]. A 0.6 nm BPF was used to filter the demultiplexed channel prior to photodetection and BER measurement. Fig. 3(a) shows the spectrum after the DEMUX HNLF with and without Raman gain. The doted curve in this figure shows the spectrum of the demultiplexed channels at 1561 nm. A sensitivity increase of 29



(a)



(b)

Fig. 2. (a) Spectrum at various points of the 160 Gb/s RE-XPM wavelength converter for conversion from 1557 nm to 1542 nm. (b) Conversion efficiency enhancement as a function of Raman pump power.

TABLE I
HIGHLY NONLINEAR DISPERSION SHIFTED FIBER PARAMETERS (γ: NONLINEAR COEFFICIENT/A_{eff}: EFFECTIVE AREA/g_R: RAMAN GAIN COEFFICIENT/D': DISPERSION SLOPE)

	Length of fiber(Km)	Fiber Parameter γ(1/W.Km)/A_{eff}(μm^2)/g_R(*10^{-14}m/W)/D'(ps/nm^2.Km)
HNLF	1	10.9/11.8/5.03/0.0167

dB was measured when the 1440 nm pump was set at 300 mW and the 1455 nm pump laser was set at 400 mW. By tuning the delay of the gating pulse to the appropriate time slot and varying it 6.25 ps at a time, we were able to demultiplex the converted 160 Gb/s data into 16 10 Gb/s channels. Fig. 3(b) shows the eye diagrams of all 16 demultiplexed 10 Gb/s channels. Eye diagrams were measured with a 50-GHz digital sampling scope and a 40-GHz photodetector, and open eyes were observed for all 16 channels. BER measurements for all the channels are shown in Fig. 3(c), together with the BER measurements for

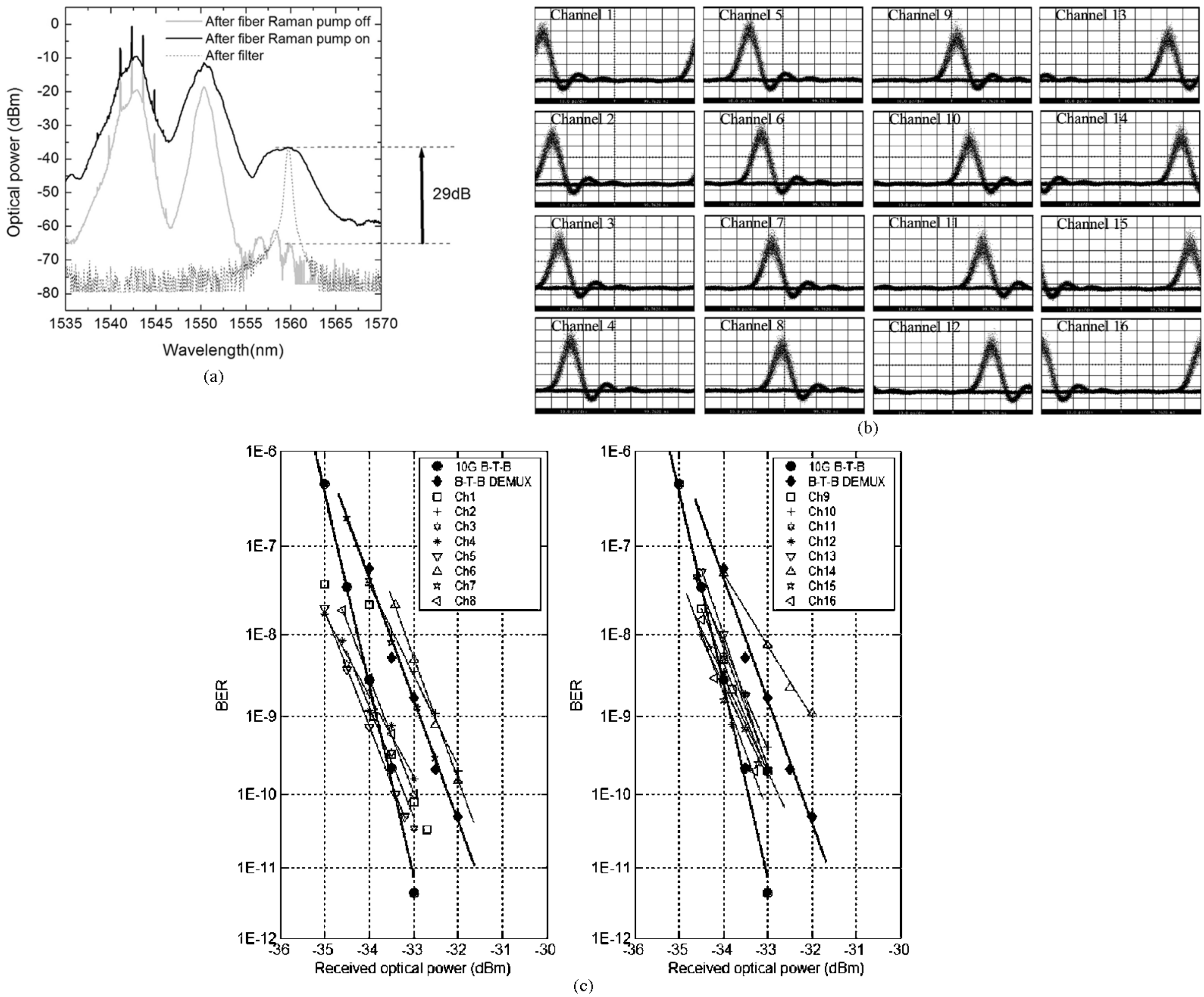


Fig. 3. (a) Spectrum at various points of the 160 Gb/s RE-FWM DEMUX for demultiplexing wavelength converted signal at 1542 nm (resolution BW: 0.1 nm). (b) Eye diagrams of all 16 demultiplexed 10 Gb/s wavelength converted channels (10 ps/div). (c) Bit error rate measurements for 160 Gb/s wavelength conversion over 15 nm bandwidth.

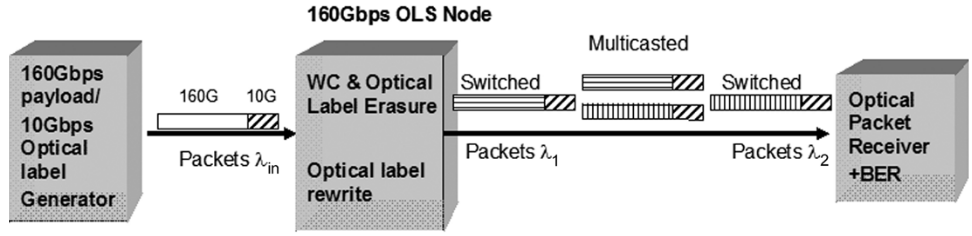
original 10 Gb/s channel and back to back measurements on the demultiplexed input 160 Gb/s data. Error free performance was achieved on all 16 demultiplexed channels, averaging 1 dB Negative power penalty for 13 out of 16 channels. The negative power penalty can be explained by the nonlinear transfer function of the wavelength converter [8]. The difference among the channels can be attributed to the nonperfect multiplexing process and be improved by using a polarization maintaining multiplexer.

III. Optical Label Switching Experiment

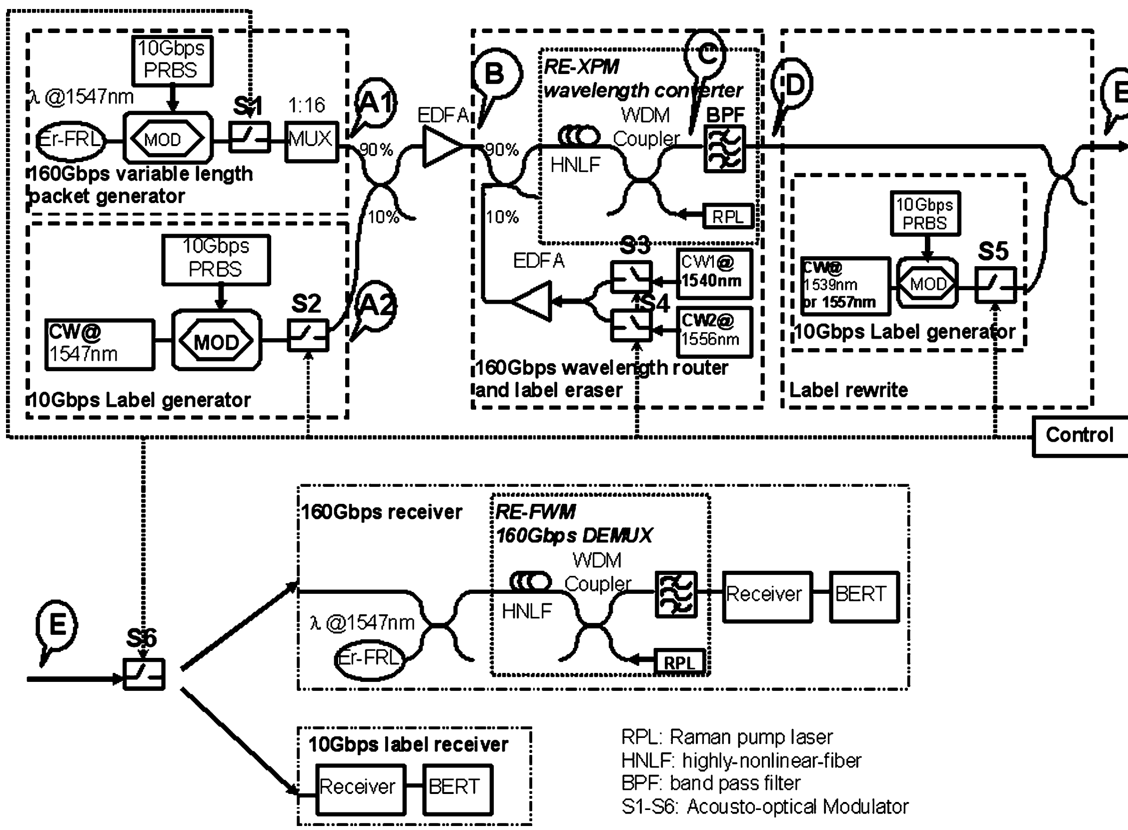
Fig. 4(a) shows the diagram of the AOLS experiment. One advantage of the described WC is its ability to simultaneously convert high speed signal on a single input wavelength to multiple new wavelengths. By placing two CW wavelengths into the WC, one longer and one shorter than the original signal wavelength, we were able to perform simultaneous up- and down- conversion of the incoming packets. As a result, we demonstrated a system with unicast operation, where an incoming packet was switched to one of the two different wavelengths; or multicast operation, where the incoming packet was simultaneously copied onto two different wavelengths on a per packet basis.

The detailed experimental setup is shown in Fig. 4(b). The 160 Gb/s packet generator consists of an actively mode-locked fiber ring laser that generates 1.5 ps pulses at 1547 nm with 10 GHz repetition rate. A $LiNbO_3$ modulator is used to encode 10 Gb/s PRBS $2^{31} - 1$ data onto the pulses. An acousto-optical modulator (AOM) gates a series of variable length 160 Gb/s packets. The 160 Gb/s packets are achieved by a passive 10 to 160 Gb/s four stage split, delay and time interleave multiplexer. The packets are combined with a 10 Gb/s 700 ns long optical label. An erbium-doped-fiber-amplifier (EDFA) compensates the loss from the multiplexer and the AOMs.

160 Gb/s packet wavelength conversion and label erasure is achieved with a WDM mode RE-XPM WC. In this experiment,



(a)



(b)

Fig. 4. (a) 160 Gb/s AOLS with unicast/multicast operation. (b) 160 Gb/s AOLS experimental setup. Er-FRL: Eribium-doped fiber ring lasr. MOD: LiNbo3 modulator. PPG: Pulse Pattern Generator. RPL: Raman Pump Laser. HNLF: Highly-Nonlinear-Fiber. BPF: Band Pass Filter. ATT: Attenuator.

two local CW lasers are gated by two AOMs, where each laser sets the converted wavelength of the 160 Gb/s packets on a per-packet basis. The CW wavelengths are chosen to be on either side of the original wavelength, so that the crosstalk caused by spectral broadening between these two conversion processes is minimized. To operate at more than two wavelengths, these two lasers can be replaced by multiple fixed wavelength lasers or a fast switched laser that can switch between different wavelengths within a short period of time [13]. The RE-XPM WC consists of an isolator, 1 km of HNLF with a zero dispersion wavelength of 1553 nm, a tunable Raman pump laser with a maximum output power of 850 mW at 1455 nm and a two stage band pass filter with an effective bandwidth (BW) of 3.5 nm. A counter propagating pump scheme is used to minimize the effect of pump fluctuation on the amplifier gain [14] and the band pass filter is used to select either the up or the down conversion sideband. Due to the peak power dependent property of this wavelength converter, the NRZ labels are not converted and are automatically erased after the wavelength conversion [15].

New NRZ labels are rewritten onto the front of the wavelength converted payloads using a 10 Gb/s label generator that operates at the same wavelength as the converted 160 Gb/s packet. The 160 Gb/s packets are demultiplexed to 10 Gb/s for BER measurements using the 160 Gb/s RE-FWM fiber demultiplexer [11]. The RE-FWM demultiplexer consists of an actively mode-locked fiber ring laser generated 4 ps pulses at 1547 nm with 10 GHz repetition rate, 1 km of HNLF with a zero dispersion wavelength of 1527 nm, a tunable Raman pump laser and a 0.6 nm bandpass filter and a measured switching window of approximately 3 ps and an extinction ratio of 12.5 dB.

IV. Results and Discussion

Fig. 5(a) shows the oscilloscope traces of the original 160 Gb/s payload, 10 Gb/s label generation and label writing. The AOM in the payload generator gates a series of packets with 3.0, 2.5 and 2.0 μs in duration after the data are generated. The 700 ns long label is aligned in front of the payload with a 150 ns

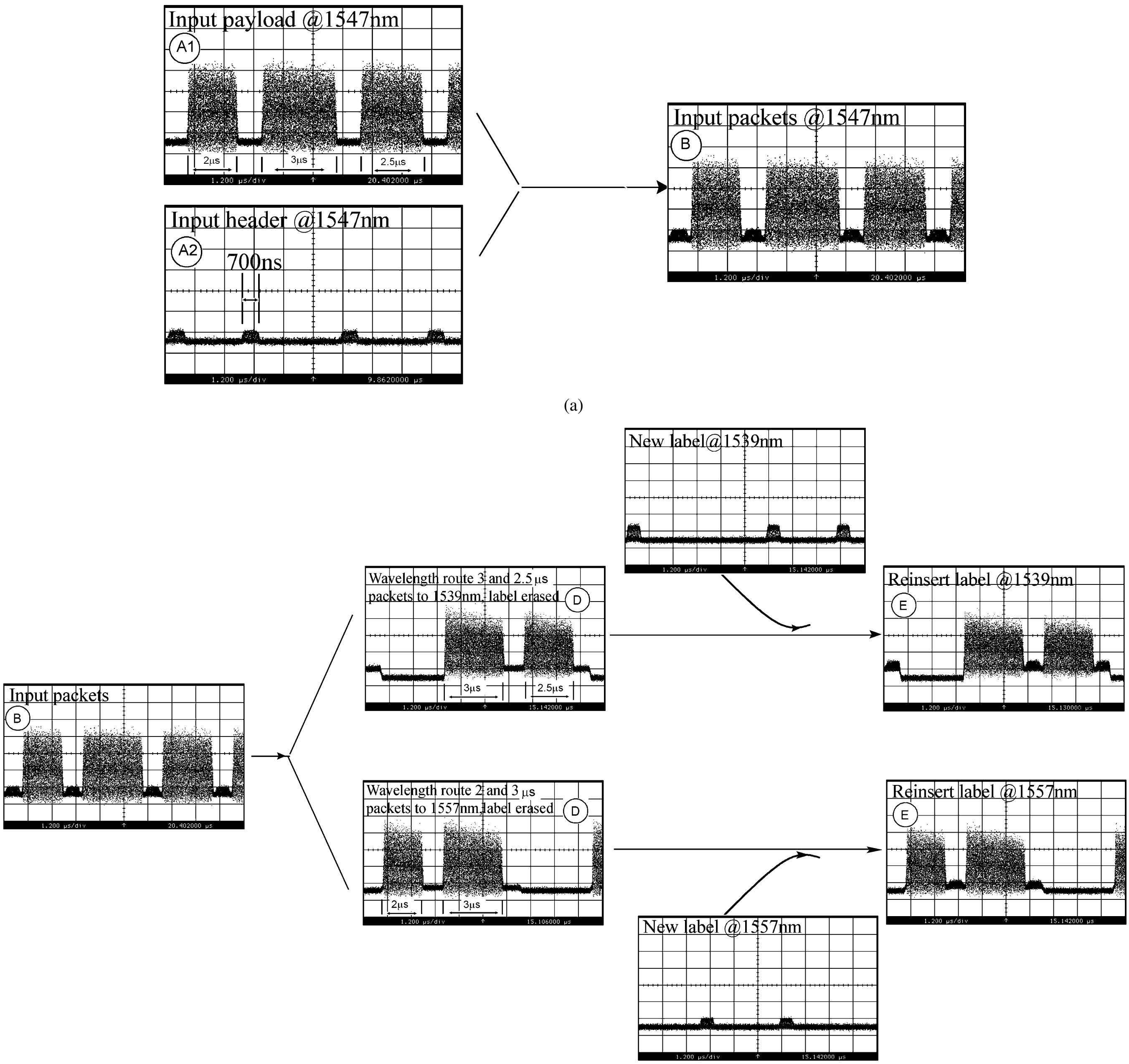


Fig. 5. (a) Oscilloscope traces of 160 Gb/s payload/10 Gb/s label generation and label writing (1.2 $\mu s/\mathrm{div}$). (b) Oscilloscope traces of 160 Gb/s AOLS packet wavelength switching with unicast and multicast and label replacement (1.2 $\mu s/\mathrm{div}$).

guard-band determined by the 100 ns rise time in the AOM, and a 150 ns guard band is inserted between each packet. Fig. 5(b) shows the oscilloscope traces of functions of packet forwarding, label erasure and label rewrite in the AOLS node. These traces were taken from the experimental setup shown in Fig. 4(b) at the places indicated with corresponding letters. The timing of AOMs S3 and S4 marked in Fig. 4(b) were controlled so that the 3.0 and 2.5 μs packets were converted to 1539 nm and the 3.0 and 2.0 μs packets were converted to 1557 nm. As a result, the 3.0 μs packet could be unicast or multicast while the other two packets were unicast (switched) only. The filter BW was chosen to minimize intersymbol interference (ISI) during the wavelength conversion process. However, such a broad bandwidth made the complete suppression of the CW light difficult, degrading the extinction ratio of the converted signal. The extinction ratio of the converted 160 Gb/s signal was measured to be 9 dB for down conversion and 14 dB for up conversion.

Fig. 6(a) shows the full timing diagrams of the 160 Gb/s AOLS experiment for the 6 AOMs in the system. After the AOLS node, AOM S6 was used to gate the packets accordingly for payload BER measurements or label BER measurements. The timing diagram of S6 showed in Fig. 6(a) shows the controller timing for payload BER measurement for both up- and down- conversions. For label BER measurement, it is set at the same timing as AOM S5 used for new label generation.

Full packet BER measurements for all 16 channels of both up and down conversion were performed. Fig. 6(b) shows four of the BER curves for down converted packets compared with

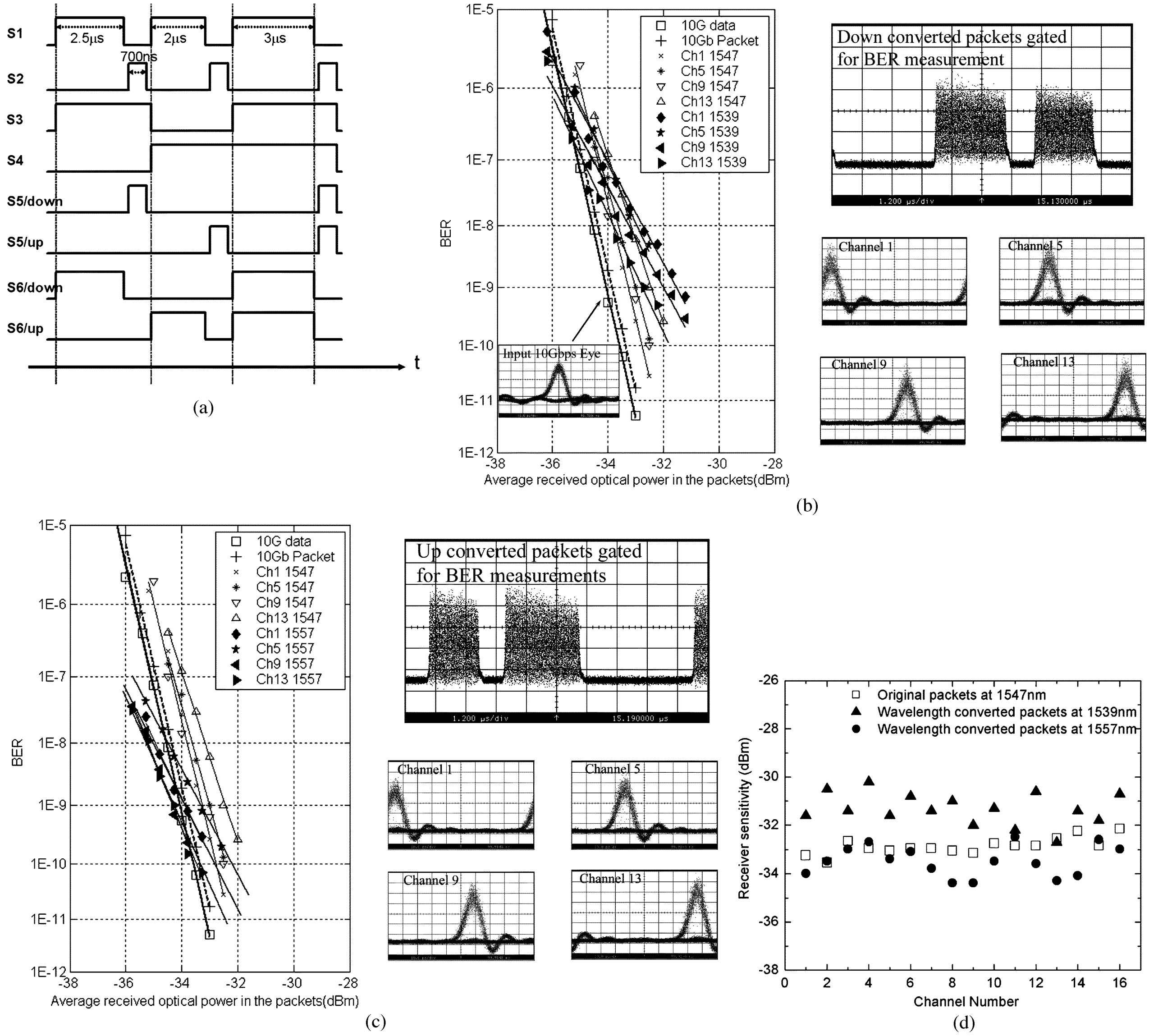


Fig. 6. (a) Timing diagram of 160 Gb/s AOLS experiment (S1–S6: acousto-optical modulator controller). (b) Measured packet BER for down-conversion, oscilloscope traces of gated down converted packet for demultiplexing and eye diagrams of 4 demultiplexed 10 Gb/s channels corresponding to the BER curves. (c) Measured packet BER for up-conversion, oscilloscope traces of gated up converted packet for demultiplexing and eye diagrams of 4 demultiplexed 10 Gb/s channels corresponding to the BER curves. (d) Measured receiver sensitivity for back to back DEMUX and both up- and down-conversion DEMUX of the wavelength routed packets.

corresponding channels demultiplexed back-to-back BER, the oscilloscope trace of the gated payload at 1539 nm, and the eye diagrams of the 10 Gb/s demultiplexed channels. Fig. 6(c) shows four of the BER curves for up-converted packets, the oscilloscope trace of the gated payload at 1557 nm, and the corresponding eye diagrams of the 10 Gb/s demultiplexed channels. Fig. 6(d) shows the measured receiver sensitivities for all 16 channels for back-to-back DEMUX and both up- and down-conversion DEMUX of the optical label switched packets at a BER of 10^{-9}. The dots inside the eye diagrams in Fig. 6(b) and (c) were due to the 100-ns rise time of the AOM. The oscilloscope was running under the continuous mode when these eye diagrams were taken. The BER tester was gated and error measurements were performed on $\sim$85% of the bits in the packets due to the number of bits required to synchronize the tester. No error floor was observed and the variation in receiver sensitivity of 2 dB is attributed to the imperfection of the OTDM multiplexer. The slope change of the BER curves after the conversion was partially due to the extinction ratio degradation from the nonoptimal filtering and can be improved by adding two notch filters at the CW wavelengths before the 4 nm filter to improve the extinction ratio.

There is approximately a 2-dB power penalty for down-conversion and almost 0-dB power penalty for up-conversion as compared to the original 160 Gb/s signal. In Fig. 6(c), it can be observed that the BER curves for the converted signals cross the 10 Gb/s baseline. This was due to the mismatch between the 0.6 nm BPF in the preamplified receiver and the spectral width of the original 10 Gb/s signal ($\sim$5 nm). Thus the receiver sensitivity of the 10 Gb/s baseline was in fact better than measured (-34 dBm). Fig. 7 shows the BER curves for the reinserted labels. A power penalty of 6 dB was observed for down conversion

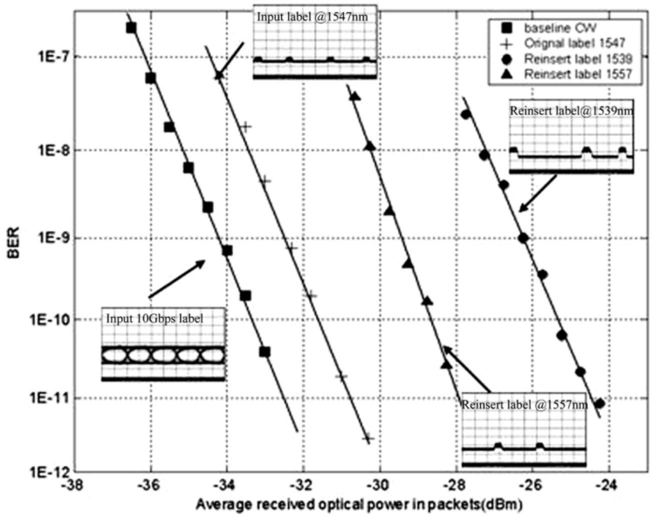
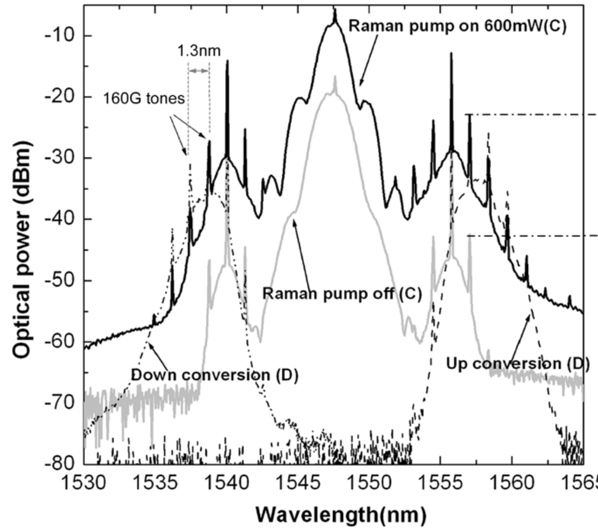
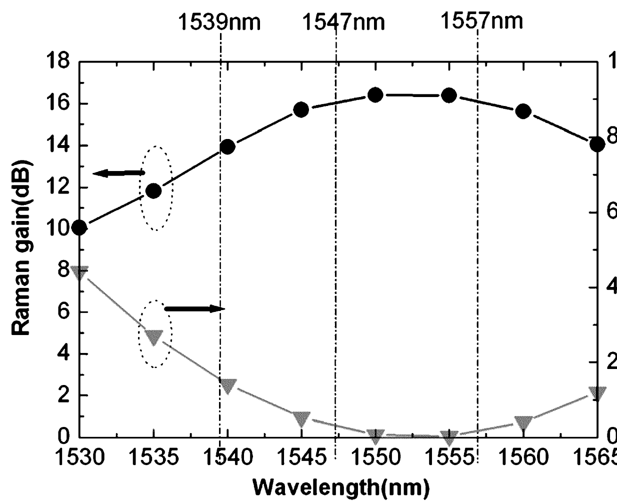


Fig. 7. BER measurements for labels before and after swapping.



(a)



(b)

Fig. 8. (a) Spectrum at various points of the wavelength AOLS switch: after wavelength converter highly-nonlinear fiber with Raman pump off, after wavelength converter with Raman pump power set at 600 mW, after wavelength converter band pass filter for down conversion, after wavelength converter band pass filter for up conversion. (b) Raman gain and walk off time parameter of the wavelength converter highly-nonlinear-fiber.

and 3 dB for up conversion due to the addition of the payload. This is consistent with the extinction ratio measurement of the converted 160 Gb/s packets and can also be improved by using the notch filters.

The difference in extinction ratio between up- and down-conversion can be explained in the spectral domain. The optical spectrum measured after the HNLF with and without Raman gain is shown in Fig. 8(a). A significant XPM sideband increase was observed with 600 mW Raman pump power for both up and down conversion. The 160 Gb/s frequency tones were observed with approximately 1.3 nm spacing on each side of the CW wavelengths. The dotted lines in the figure show the spectrums of the wavelength converted packets. After filtering the right sideband of the up-converted spectrum and the left sideband of the down-converted spectrum, the converted signal at both wavelengths had an OSNR of more than 50 dB. The conversion efficiency enhancement was measured to be around 20 dB at this pump power level and optimized for both up- and down-conversion to work simultaneously with minimum amount of crosstalk. The amount of the spectral broadening of the up- conversion was larger than that of the down- conversion. Larger spectral broadening for up conversion led to more offset of the filter position to the probe CW wavelength, bringing less extinction ratio degradation. The reason for this difference in spectral broadening could be explained as a combined effect of nonflat Raman gain shape and different pulse walk off time as shown in Fig. 8(b). The dotted lines in this figure marked the position of the wavelength groups chosen for this experiment. The Raman gain for the up-conversion wavelength was 3 dB higher than the down-conversion wavelength. Higher Raman gain means more conversion efficiency enhancement, which leads to more spectral broadening. The HNLF had a dispersion slope of 0.027 $\mathrm{ps/nm^2.km}$. The walk off time for up- conversion was calculated to be less than 1 ps, while the walk off for down- conversion was more than 2 ps. For the WC based on XPM, the increased walk off time decreased the conversion efficiency. This further contributed to the difference in spectral broadening for the two conversion processes. Equal performance among all channels required careful design of the fiber parameters, including gain map of the Raman amplifier and the dispersion map of the HNLF.

V. Conclusion

We have demonstrated the first time operation of AOLS with variable length 160 Gb/s packets and 10 Gb/s optical labels using Raman enhanced fiber XPM. Error free and regenerative continuous mode single wavelength operation was first analyzed with 15 nm conversion bandwidth demonstrated. Unicast and multicast packet optical label switching with both up (8 nm) and down (10 nm) conversion was demonstrated. Packet BER measurements on 160 Gb/s packets show a small power penalty (0–2 dB) with 2R regeneration. Removal and rewrite of 10 Gb/s optical labels are demonstrated with good extinction ratio and BER performance. Also demonstrated is packet demultiplexing of 160 Gb/s down to 10 Gb/s using a RE-FWM fiber based demultiplexer.

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