Transmission of an ASK-Labeled RZ-DPSK Signal and Label Erasure Using a Saturated SOA

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***Abstract*—We demonstrate an optically labeled signal based on return-to-zero differential phase-shift keying for payload at 10-Gb/s and amplitude-shift keying for label at 622-Mb/s. Receiver sensitivity of ~ -36 dBm and penalty-free transmission over 80-km standard single-mode fiber are achieved for both the payload (with dispersion compensation) and the label. This labeling scheme allows the use of a deeply saturated semiconductor optical amplifier to perform polarization-insensitive label erasure. Label swapping is demonstrated with moderate penalty.**

***Index Terms*—Differential phase-shift keying (DPSK), packet switching, semiconductor optical amplifiers (SOAs).**

I. Introduction

OPTICAL PACKET switching is an attractive technology that enables more efficient and flexible utilization of the capacity of optical networks by providing subwavelength granularity. It may potentially allow seamless integration of data and optical networking [1]. Optical-label switching, as one of the promising switching schemes, offers several key features that are important to future Internet protocol (IP) networks such as being able to route IP data without having to detect the payload [2]. Optical-label packet transmission based on amplitude-shift-keying/differential-phase-shift-keying (ASK/DPSK) orthogonal modulation format was recently proposed [3]–[5] and experimentally demonstrated [6], in which the payload is carried by ASK, while the label is carried by DPSK. Recently, it was found that using DPSK/ASK for payload/label modulation and a balanced receiver for DPSK detection is more advantageous [7]. When DPSK is used for high-speed payload modulation, the temperature stability and polarization insensitivity of the delay-line interferometer (needed in DPSK demodulation) are much improved. In addition, the laser linewidth requirement is relaxed. Receiver sensitivity of ~ -32 dBm was achieved for both payload and label with 2.5-Gb/s ASK-labeled 10-Gb/s nonreturn-to-zero (NRZ) DPSK signal [7]. More recently, Chi *et al.* applied return-to-zero (RZ) DPSK for payload modulation and single detector for DPSK detection, and achieved label erasure by using inverted label modulation [8]. All-optical OOK label swapping on optical frequency-shift keyed payload was also demonstrated by utilizing the gain saturation and nonlinear polarization rotation in a semiconductor optical amplifier (SOA) [9].

In this letter, we report the transmission of a 622-Mb/s ASK-labeled 10-Gb/s RZ-DPSK signal with balanced detection for improved performance. We further demonstrate a simple label erasure method based on a deeply saturated SOA, which is enabled by the use of RZ-DPSK [10].

II. Principle and Experiment Setup

The DPSK/ASK optical-label switching scheme in principle consists of a few key network elements such as DPSK/ASK transmitter, DPSK/ASK receiver, ASK label erasure and insertion modules, and wavelength converter. At the transmitter, to further improve the DPSK performance and reduce pattern dependence, we select RZ-DPSK (instead of previous NRZ-DPSK [7]) for the payload modulation. At the receiver, balanced detection for DPSK is used since it provides ~3-dB improvement in receiver sensitivity [11], [12] and allows the extinction ratio (ER) for the ASK labeling to be high, which in turn improves the label receiver performance [7]. For wavelength conversion needed in IP routers, a phase-maintaining four-wave-mixing (FWM) process may be used. The FWM process can be realized in a highly nonlinear fiber [6] or a fast SOA. Compared with the previous scheme [6] where label is phase-modulated, the ASK label erasure and insertion here can be greatly simplified. For label erasure, simple and compact saturating SOA is a natural cost-effective solution. However, when operating in the deep saturation regime, SOA is known to introduce chirp onto the signal, which may corrupt the phase-encoded payload data. It was recently realized that the performance of RZ-DPSK is virtually immune to SOA saturation-induced chirp since each bit has an identical temporal intensity profile and, thus, experiences the same chirp profile which, upon differential detection, causes no penalty in receiver sensitivity [10]. This concept can be extended to an ASK-labeled RZ-DPSK signal as long as we ensure that the label modulation is sufficiently slow and smooth to avoid noticeable change in the temporal pulse profiles of adjacent payload (RZ-DPSK) bits. This is achieved by using a much lower rate for the label (622-Mb/s) than for payload (10 Gb/s), and by low-pass filtering the radio-frequency (RF) label signal before driving the label modulator.

Fig. 1 shows the schematic diagram of the experimental setup for the transmission of an ASK-labeled RZ-DPSK signal as well as label erasure and reinsertion. The continuous-wave source

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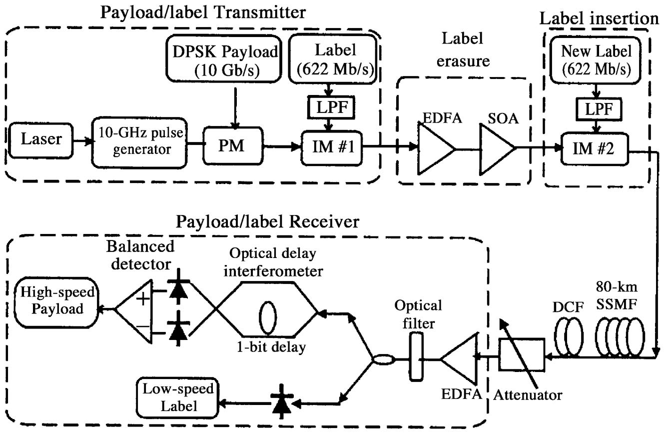

Fig. 1. Schematic diagram of the experimental setup for the transmission of an ASK-labeled RZ-DPSK/ASK signal and label erasure by the use of a saturated SOA. PM: phase modulator. IM: intensity modulator.

was a tunable laser operating at 1550 nm. A pulse generator created a 10-GHz RZ pulse train (with 50% duty cycle), which was synchronously phase-modulated by 10-Gb/s payload data through a Mach–Zehnder modulator (MZM) biased at null and driven at 2 V_π to achieve phase modulation [12]. A second MZM inserted label information at 622-Mb/s on the RZ-DPSK signal by intensity modulation with ~4-dB ER, which was selected to have roughly equal receiver sensitivity for the payload and label. The finite ER was achieved by under-driving MZM while maintaining the bias point at the quadrature point. Both the payload and label data were pseudorandom bit sequences of length $2^{31} - 1$ asynchronously from two independent pattern generators. To simplify the RZ-DPSK modulation, we used an integrated two-stage x cut (chirp-free) modulator with 10-GHz bandwidth and 5.5-dB total insertion loss. A low-pass filter with a 3-dB bandwidth of ~500 MHz was used to filter the label signal before driving the modulator (in order to avoid the chirp due to sharp transitions upon label erasure in saturated SOA). For label erasure, an Er-doped fiber amplifier was used to amplify the signal power to ~0 dBm, which was sufficiently high to deeply saturate the SOA. The SOA was a 2.6-mm-long ridge waveguide bulk InGaAsP–InP SOA with a gain recovery time of ~200 ps. The optical signal-to-noise ratio at the SOA input was ~35 dB (defined with 0.1-nm bandwidth for the noise power). For label reinsertion, polarization-insensitive intensity modulator, e.g., electroabsorption modulator, can be used. In the experiment, we used a low-speed MZM for insertion of a new label signal, which came from the complementary port of the same pattern generator for the original label, and was also decorrelated with the original label. We note that the needed driving voltages for label modulation are ~1 and ~0.4 V for IM#1 and IM#2 to achieve the same ER, respectively.

The transmission span consisted of an 80-km standard single-mode fiber (SSMF) with $D = 17$ ps/km/nm, and a dispersion-compensating fiber (DCF) with -1337-ps/nm dispersion. After transmission, an attenuator was used to vary the received power before the preamplified receiver to assess the receiver sensitivity. The optical bandpass filters had a 3-dB bandwidth of ~0.6 nm. The optically amplified and filtered signal was then separated into two paths, one entering a DPSK receiver consisting of a 100-ps delay interferometer, a balanced detector, and a differential RF amplifier for payload detection, and the other entering an ASK detector for label detection.

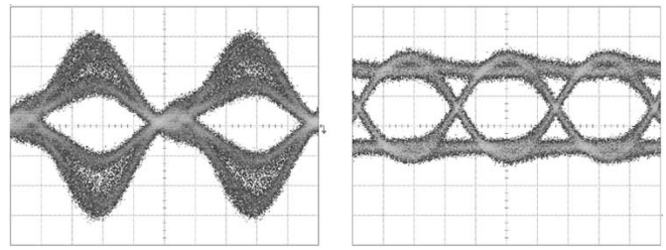

Fig. 2. Received electrical 10-Gb/s RZ-DPSK eye diagram (left) at 20 ps/div and 622-Mb/s ASK eye diagram (right) at 500 ps/div.

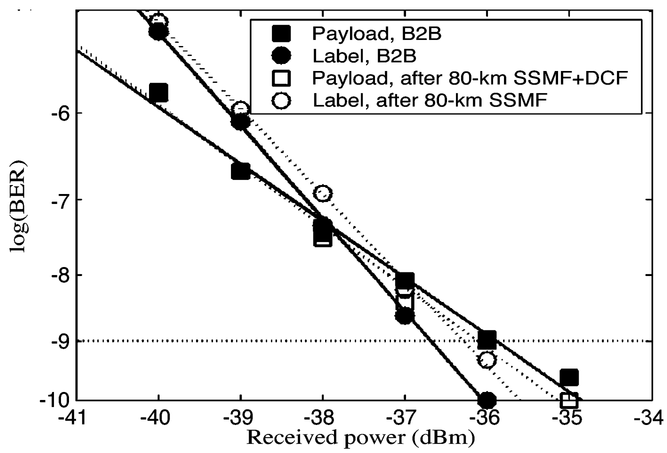

Fig. 3. Measured BER performance of the 10-Gb/s DPSK payload (squares) and 622-Mb/s ASK label (circles) at B-to-B (solid symbol) and after transmission over 80-km SSMF (empty symbol). No dispersion compensation is needed for the label.

III. Transmission Performance

Fig. 2 shows the back-to-back (B-to-B) performance eye diagrams detected at the DPSK receiver and ASK receiver (with a 500-MHz Bessel filter). The performance of the label degraded faster with the decrease of receiver power due to nonoptimal decision level at low receiver powers, while for the DPSK payload, the optimum decision level was always ~0, thanks to the use of the balanced detector [7]. Fig. 3 shows the dependence of bit-error rate (BER) for both the payload and the label on the received optical power. At B-to-B configuration, receiver sensitivity of ~ -36 dBm was achieved for both the payload and the label. As compared to NRZ-DPSK [7], RZ-DPSK substantially improves the receiver sensitivity and reduces the pattern dependence in performance. Without the label, the B-to-B DPSK receiver sensitivity is ~ -40 dBm.

After transmission through the 80-km SSMF and DCF, no degradation in payload performance was found. For the label, negligible performance degradation was found even without dispersion compensation (by removing the DCF). In fact, the dispersion tolerance (at 1-dB penalty) of the 622-Mb/s label signal is expected to be >500 km in SSMF. This is attractive since label information can be processed in an optical label-switched network with cost-effective low-speed electronics and without dispersion compensation.

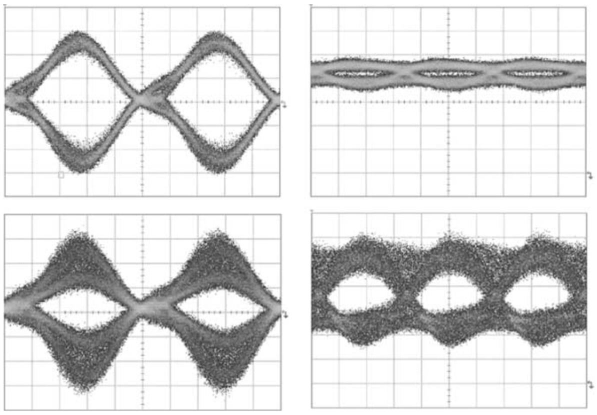

Fig. 4. Received electrical 10-Gb/s RZ-DPSK eye diagram (left column) at 20-ps/div and 622-Mb/s ASK eye diagram (right column) at 500 ps/div after label erasure (upper row) and after reinsertion a new label (lower row).

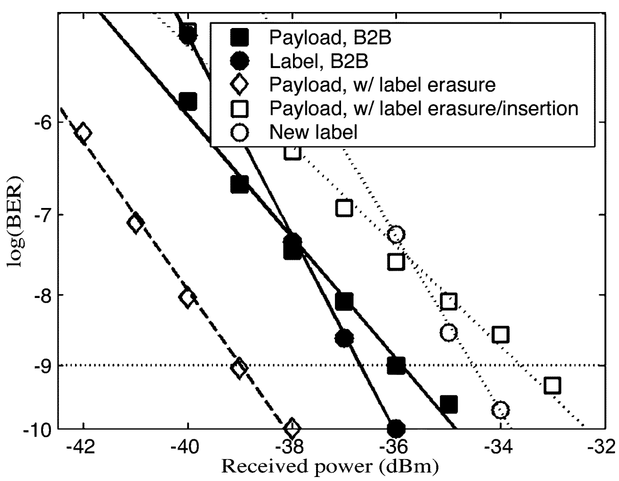

Fig. 5. Measured BER performance of the 10-Gb/s DPSK payload (squares) and 622-Mb/s ASK label (circles) at B-to-B (solid symbol) and after label erasure and reinsertion of a new label (empty symbol). The diamonds are for payload after label erasure.

IV. Label Removal and Insertion

Fig. 4 shows the eye diagrams for both the payload and the label after label erasure through the saturated SOA and after reinsertion of a new label. Clearly, the label was effectively erased without introducing noticeable eye closure for the payload. The remaining label had a modulation depth of <1 dB, which can be further reduced by using another saturated SOA.

Fig. 5 shows the BER performance of the payload after label erasure, which was actually improved by $\sim$3 dB (at BER $= 10^{-9}$). This improvement is reasonable since after label erasure, the labeled RZ-DPSK signal became an intrinsic RZ-DPSK, which should be more tolerant to optical noise. Fig. 5 also shows the BER performance of the payload after insertion of a new label. The performance of the payload with new label was degraded by $\sim$2.4 dB (at BER $= 10^{-9}$). This can be attributed to the residual modulation of the original label. Also, the performance of the new label is $\sim$2.2 dB (at BER $= 10^{-9}$) worse than that of the original label for the same reason. It is expected that the penalty can be reduced by using an SOA with better saturation characteristics or by using two cascaded SOAs with moderate saturation.

V. Conclusion

We have demonstrated a novel optical label switching scheme in which high-speed payload is RZ-DPSK modulated and is received by a balanced detector modulation, while a low-speed label is ASK modulated and is erasable by a polarization-insensitive saturated SOA. Superior receiver sensitivity and transmission performance are demonstrated for both the payload and label. Label erasure and reinsertion are also realized with moderate penalties.

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