Optical packet labeling based on simultaneous polarization shift keying and amplitude shift keying

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We propose and demonstrate label encoding–swapping and transmission for an orthogonally labeled packet by use of a 10-Gbit/s amplitude shift keying payload and a 2.5-Gbit/s polarization shift keying (PolSK) label. A simple scheme for demodulating and demultiplexing the PolSK label based on an injection-locked Fabry–Perot laser diode is described. The extinction ratio of the newly added PolSK label can be precisely controlled and maintained after the intermediate node. © 2004 Optical Society of America

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Optical-label-controlled packet switching is a promising technology for use in future Internet protocol-over-wavelength division multiplexing networks.1 All-optical orthogonal labeling attracted much attention recently2–5 as a promising approach for an optical-label-switched network. The advantages of such labeling include simultaneous detection and recovery of label and payload, less-precise timing control and alignment requirements than with the bit-serial labeling,6 more efficient use of bandwidth, less stringent required wavelength accuracy and notch filtering, and higher-bit-rate operation of labeling than with subcarrier multiplex labeling.7 Here we propose and demonstrate another orthogonal labeling scheme that uses 10-Gbit/s amplitude shift keying (ASK) for the payload and 2.5-Gbit/s polarization shift keying (PolSK) for the label. Compared with our previously reported differential phase shift keying (DPSK)–ASK labeling,4 PolSK–ASK labeling eliminates the need for DPSK preceding circuits and complicated decoding and demodulation at each intermediate node, thus reducing the equipment costs and packet processing latency. The proposed scheme also does not suffer from excess frequency chirp (as is present in the DPSK8 and frequency shift keying9), which would result in a transmission penalty and spectral broadening at the bit boundaries of the DPSK label impressed onto the ASK payload. PolSK–ASK is also simpler to implement than optical code division multiplexing, which needs a large number of coders and decoders.9 Direct detection of PolSK has been studied extensively because of its potential advantages.9 In this Letter we demonstrate an all-optical PolSK label demodulator based on injection locking of a Fabry–Perot laser diode (FP-LD). The FP-LD has the advantages of lower cost (compared with the use of a polarizer with an optical amplifier), intensity compensation, and the potential for all-optical control for use in optically switched networks.

Figure 1 depicts the proposed architecture of an intermediate routing node. On arrival, an optical packet is split. One part goes to the label-extraction unit (LEU), where a FP-LD demodulates the PolSK label that is detected by a photodiode (PD). The PD signal may be processed for label clock recovery, label information retrieval, and new label generation. The other part of the input packet is fed into a label-removal unit (LRU), where polarization-insensitive wavelength conversion is performed by use of a semiconductor optical amplifier (SOA). The old PolSK label is erased, and the ASK payload is preserved by cross-gain modulation. New label information intended for the next routing node can then be inserted orthogonally into the wavelength-converted optical packet in the label-insertion unit (LIU).

The experimental setup is shown in Fig. 2. The ASK payload is generated by modulating an integrated electroabsorption modulator laser (Fujitsu Model FLD5F10NPS) at 10-Gbit/s (pseudorandom bit sequence 231 − 1). The electroabsorption modulation laser emits at the 1547.56-nm wavelength. The extinction ratio (ER) of the ASK payload can be precisely controlled by adjustment of the negative bias applied to the modulator section. The ASK payload is directed to the PolSK label modulation. The anisotropy of the electro-optic coefficient of the LiNbO3 crystal [in the phase modulator (PM)] allows the relative phase shift between the two optical axes to change as a function of applied voltage. When a linearly polarized light is launched at 45° with respect to the principal axis of the crystal, the phase shift between the two axes allows the output polarization to be modulated.9 Orthogonal modulation of the PolSK label at 2.5-Gbit/s (pseudorandom bit sequence 231 − 1) is thus added to the optical carrier. Running the label at a lower bit rate allows the use of lower-cost electronics for processing. The erbium-doped fiber amplifier and the filter (3-dB bandwidth of 1 nm) compensated for loss and selected the signal wavelength, respectively.

![Fig. 1. Proposed architecture of the intermediate node: OPs, optical packets; FDL, fiber delay line. Other abbreviations defined in text.](image-url)
At the intermediate node, 20% of the signal power was sent to the LEU, which consisted of a FP-LD and a distributed-feedback laser diode (DFB-LD). The −6-dBm control gating pulse was produced by direct modulation of a 1549.36-nm wavelength DFB-LD at 155.5 MHz. The gating pulse width should be a multiple of the label bit period. In this proof-of-concept experiment the label and the gating synchronization used the clock from the bit-error rate (BER) tester. In practical systems, optical clock recovery using the synchronization bits inside the packet would be needed. The control signal can test the switching operation of the FP-LD. Both the PolSK–ASK signal and the control gating signal were launched into the FP-LD via a 50/50 coupler and a circulator. The FP-LD has a central wavelength of 1543 nm and a longitudinal mode spacing of 1.68 nm, and it was biased at 28 mA. As the FP-LD structure favors lasing in the TE mode, any injected signal that spectrally aligned with one of the longitudinal modes of the FP-LD will have its TE component amplified. The TE component will be amplified with the intensity clamped and stabilized by injection locking, whereas the TM component will be suppressed. The injection-locked FP-LD thus acts as an intensity-compensating polarizer with TE-polarized output, so it can demodulate the PolSK signal with intensity compensation. The optical spectrum of the Fabry–Perot demodulator is shown in the inset of Fig. 2. Packet gating may be achieved by use of a control gating signal injected simultaneously with the data signal. In this case the control signal will cause a redshift of the Fabry–Perot modes, and the FP-LD will injection lock to the control signal when it is present instead of to the original data signal, thus allowing all-optical switching.

A 1-nm, 3-dB-bandwidth optical filter selected the demodulated PolSK label, which was detected by a 2.5-Gbit/s avalanche photodiode.

The LRU consisted of a SOA and a DFB-LD. The SOA was biased at 190 mA, and the DFB-LD generated continuous-wave (cw) output at 1557.0 nm. The SOA acted as a wavelength converter and copied the ASK payload of the PolSK–ASK signal to the 1557-nm wavelength (thus updating the wavelength label). For the new label to transmit successfully to the next routing node, it is necessary for the ER of the ASK output from the LRU to be only 2.4 dB, and this is achieved by use of an appropriate input power (−4 dBm) from the DFB-LD. The original PolSK label was erased, as the SOA that was used had a polarization-dependent gain of only 0.4 dB. A polarization controller provided a 45° linear input polarization to the PM that added the new label in the LIU. For system implementation, a short length of polarization-maintaining fiber could be used between the LRU and LIU to provide the appropriate polarization. The BER of the orthogonally modulated ASK payload was measured for use of a 10-Gbit/s p-i-n PD, and the label BER, was measured for an injection-locked Fabry–Perot demodulator together with an avalanche photodiode.

For carrying the PolSK-modulated label, a limited ER of the ASK payload is necessary to ensure sufficient optical power even during a long run of zeros in the payload. We measured the receiver sensitivity of both the back-to-back payload and label and found that the ER was 2.4 dB (in payload) and gave the same BER for the label and the payload. In practice, the payload may be much longer than the label, and it may be better to combine a higher ER for the payload and error-correction codes to make the label more tolerant to higher BER.

Figure 3 shows the BER measurements for the ASK payloads and PolSK labels at different nodes of the experiment. A power penalty of 0.6 dB was observed in the payload after label swapping. A 1-dB power penalty for the demodulated label at the intermediate node was observed relative to the source node. The corresponding eye diagrams are also included in the insets. The results show that, with appropriate dispersion compensation, error-free detection and multihop transmission are possible. Since the random birefringence of buried optical fiber networks typically causes only 2°–10° fluctuations in the polarization angles of the propagating signals, slow dynamic polarization control can be used to compensate for the polarization fluctuations between different intermediate nodes. The power penalty for the payload during label swapping was due to the residual polarization-dependent gain of the SOA. Alternative wavelength-conversion methods such as polarization-diversified four-wave mixing or injection locking could also be deployed in the LRU. The spectral width of the PolSK–ASK signal, 0.016 nm, is narrower than for our previously reported DPSK–ASK signal (spectral width, 0.061 nm). The low ER of the ASK label allows the spectral width of the PolSK–ASK signal to
be narrower than is typical for ASK. A transmission of 40-km single-mode fiber and 6.8-km dispersion-compensating fiber was performed. Figure 4(a) shows an oscilloscope trace of the demodulated PolSK label after transmission. Figures 4(b) and 4(c) show traces of the control gating and the demultiplexed output, respectively. The FP-LD works as an all-optical switch: the FP-LD transmits the data when the control signal is OFF and blocks the data when the control signal is ON. The switch-on and switch-off times ($\sim 40$ ps) of the Fabry–Perot demultiplexer depend on the response time of injection locking. As the response time is less than 1 bit period (400 ps) of the label, guard time for the packet demultiplexer is not needed. For a given FP-LD structure the response time is less than 1 bit period (400 ps). The state of polarization of the label encoding swapping and transmission of an orthogonal labeling scheme that involves superposition of a 2.5-Gbit/s PolSK label on a 10-Gbit/s ASK payload. A simple method of demodulation and demultiplexing of a PolSK label by use of injection locking of a FP-LD was performed. The ER of the newly added PolSK label can be maintained for the next routing.

In conclusion, we have proposed and demonstrated label encoding--swapping and transmission of an orthogonal labeling scheme that involves superposition of a 2.5-Gbit/s PolSK label on a 10-Gbit/s ASK payload. A simple method of demodulation and demultiplexing of a PolSK label by use of injection locking of a FP-LD was performed. The ER of the newly added PolSK label can be maintained for the next routing.

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