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All-optical header processing using control signals generated by direct modulation of a DFB laser

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Abstract

On-the-fly all-optical header processing and control signal generation were simultaneously realized using a dual-wavelength injection-locked Fabry–Pérot laser diode. The special two-level input control signal was generated by direct modulation of a distributed feedback laser. The header processing rate is 2.5 Gb/s, the payload data rate is 10 Gb/s, and the packet length is 25.6 ns. The switching ratio for the switched control signals measured spectrally was improved from 3 dB to over 20 dB by using a polarizer.

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1. Introduction

All-optical packet switching is a promising technology to deliver future broadband interactive services because it removes the speed bottleneck due to opto-electronic (O/E) conversion. In the all-optical packet switching schemes proposed to date, the headers of the packets are extracted optically [1–3] and then processed either in the optical domain [1,2] or the electrical domain [3]. The outputs from these header processors are then sent to another module for further processing in the switching fabrics. In this paper, we demonstrated simultaneous all-optical header processing for an input data packet (2.5 Gb/s header and 10 Gb/s data payload) and control signal generation using

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dual-wavelength injection-locking in a single Fabry–Pérot laser diode (FP-LD) without using any high speed electronic DSP chip or fast O/E conversion. A special input control signal with two-intensity-level was proposed which can be generated by direct modulation of a distributed feedback (DFB) laser. The switching ratio of the header processor can be improved from 3 dB to more than 20 dB by using a polarizer at the FP-LD output. The proposed scheme realizes a recently proposed self-routing address protocol for networks with arbitrary topologies in which every output port of all the nodes in the network is associated with a single bit in the address header [4]. The scheme can also find applications in all-optical fast bit-control wavelength tunable lasers [5], all-optical tunable optical wavelength converter (TOWC) [6], wavelength-routed packet switch in optical node [7], and all-optical buffer [8] etc. The switched control signals output can then be used to switch ON or OFF the data packets, for example using again multi-wavelength mutual injection-locking in a FP-LD as described in [9].

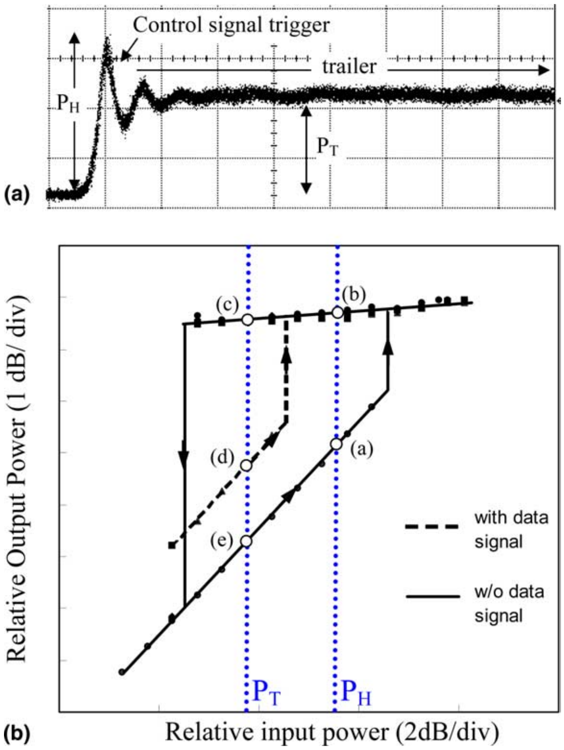


Fig. 1. (a) The temporal profile of the input 2-level control signal for the proposed all-optical header processor. (b) Measured hysteresis traces for the cw control signal under single beam (solid lines) and two-mode injection-locking (dash lines) in FP-LD. The dash lines indicate the measurement for two-mode injection-locking with the presence of the data signal at -10 dBm.

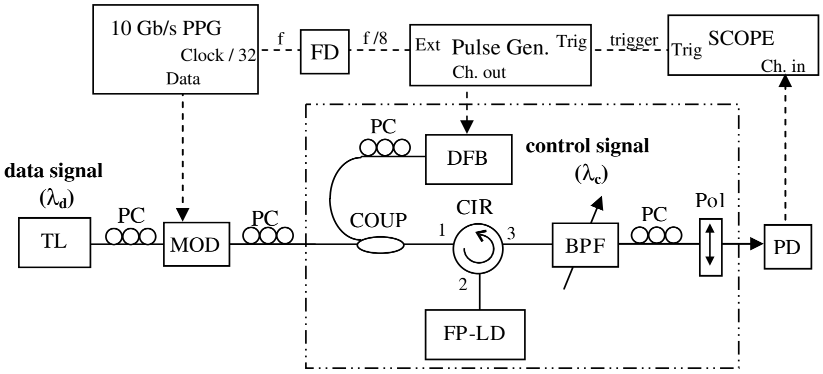
2. Operation principles

The proposed all-optical header processing and control signal generation scheme requires a specially formatted control locally generated signal. Fig. 1(a) shows the two-level control signal which consists of a short trigger header at higher power P_{H} and a long trailer at lower power P_{T}. The length of the control signal is the same as that of the data packet. The header processor performs both header processing and control signal generation simultaneously in a commercially available FP-LD, with a double-channel planar-buried InGaAsP heterostructure and multiquantum-well (MQW) active region, under two-mode injection locking. If the header bit of an input data signal at wavelength λ_{d} temporally coincides with the trigger header of the local control signal at wavelength of λ_{c} in the FP-LD, the control signal will be switched on after injection-locking. The operation principle of the proposed all-optical header processing and control signal generating unit is based on the hysteresis property of the FP-LD under two-mode injection-locking as shown in Fig. 1(b), the wavelength of the data packet and the control signal should be located at zero detune and the longer wavelength side of two different longitudinal modes of the FP-LD, respectively. The powers of the control signal trigger and trailer are chosen such that $P_{\mathrm{th3}} < P_{\mathrm{T}} < P_{\mathrm{th2}} \leqslant P_{\mathrm{H}} < P_{\mathrm{th1}}$ where P_{th1}, P_{th2}, and P_{th3} are, respectively, the threshold powers at λ_{c} for injection locking without the data signal, with the data signal, and at which the FP-LD returns to the unlocked state from the locked state. From Fig. 1(b), the injection-locking threshold for the control signal (power required for injection locking) decreases in the presence of the data signal. Therefore by the choices of parameters as discussed, the entire control signal is switched on (off) at the output of the FP-LD only when the control signal trigger coincides with a ‘1’ (‘0’) bit in the data packet header at the input of the FP-LD. Fig. 1b can be used to design the proposed control signal and study its performance. Points (a) and (b) in Fig. 1(b) give the output powers of the control signal trigger when it temporally coincides with a ‘0’ and ‘1’ in the data signal, respectively. Point (c) give the output power of the control signal after the control signal trigger matches with a ‘1’ in the data packet header, i.e., injection-locked the FP-LD, irrespective of the content of the trailer. Points (d) and (e) give the output powers of the trailer of the control signal when the input data signal is ‘1’ and ‘0’, respectively if the trigger of the control signal does not matches with a ‘1’ in the data signal. Thus all-optical header processing and control signal switching are achieved.

The input control signal can be generated by using two Mach–Zehnder modulators set at different extinction ratios for all-optical header processing [10]. In this paper, we show that such control signals can be generated simply by direct modulation of a DFB semiconductor laser with square electrical pulses. The peaks of the natural relaxation oscillations initiated by the modulation can function as the trigger while the steady state output of the laser serves as the trailer of the required control signals. The parameters of the modulation must be chosen such that (i) only the first peak of the relaxation oscillation will initiate injection locking at λ_c in the presence of the data signal, and (ii) the rest of the relaxation oscillation and the steady state output itself cannot initiate injection locking even in the presence of the data signal at λ_d but can sustain injection locking once it is started at the trigger portion of the header region.

3. Experimental results

Fig. 2 shows the experimental setup for the demonstration of all-optical header processing and control signal generation using the directly modulated DFB laser output as the control signals. The FP-LD used in the experiment was biased at 1.5 I_{th} where I_{th} is the threshold current. The control signal is generated from a DFB laser which is directly modulated by a pulse generator (Pulse Gen.) operated at a repetition rate of 39 MHz (synchronized with the master clock of the 10 Gb/s data in the ratio of 1/256). The electrical current (from the pulse generator) applied to the



(a) *All-optical header processor and packet generator*

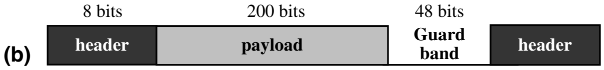


Fig. 2. (a) Experimental setup for the bitwise control signal generation using two-mode injection locking. *Note.* PPG, pulse pattern generator; FD, frequency divider; DFB, distributed feedback laser; TL, tunable laser; PC, polarization controller; MOD, intensity modulator; COUP, intensity coupler; CIR, circulator; BPF, tunable bandpass filter; Pol., polarizer; PD, photodetector. (b) The format for the 10 Gb/s input data packet.

DFB has an offset of -18.2 mA, an amplitude of 3 mA, and duration of 21 ns with a rise time of ~300 ps, where the threshold current for the DFB is about 16 mA. The data packet is generated by externally modulating a tunable laser (TL) with a 10 Gb/s NRZ data sequence with 48-bit guard band, 8-bit header and 200-bit payload. There are two different packets: pk_1 and pk_2. The header of pk_1 is four consecutive ones followed by four consecutive zeroes (‘11110000’) and that of pk_2 is ‘00001111’. The payloads for pk_1 and pk_2 are different. Thus the header rate is 2.5 Gb/s. The input powers for the control signals and data packets measured at port 2 of the circulator are -4.6 and -24.4 dBm, respectively. The wavelengths of the control signals and data packets are 1546.48 and 1555.34 nm, respectively. The wavelength detunes of the control signal and the data packet with respect to the corresponding FP modes are $+0.18$ and $+0.04$ nm, respectively. Fig. 3(a) depicts the temporal profile of the control pulse before injection into the FP-LD. The first relaxation peak of the control signal (with rise time of < 100 ps), after injection into the FP-LD, can injection-lock the FP-LD if it is injected simultaneously with the header bit of pk_1. The power of the control signal trailer, P_T, is sufficiently low that it cannot initiate injection locking even in the presence of ‘1’ in the data signal but is large enough to sustain injection-locking throughout the whole duration of the control signal (~26 ns) once injection locking starts, i.e., $P_{th3} < P_T < P_{th2}$. Fig. 3(a)–(c) show the synchronized temporal profiles for the control signals, and the header regions for pk_1 and pk_2 of the data packets, respectively. The trigger of the control signal matched temporally with the 1’s (0’s) in the header of data packet pk_1 (pk_2). Fig. 4 depicts the spectrum of the FP-LD before and after two-mode injec-

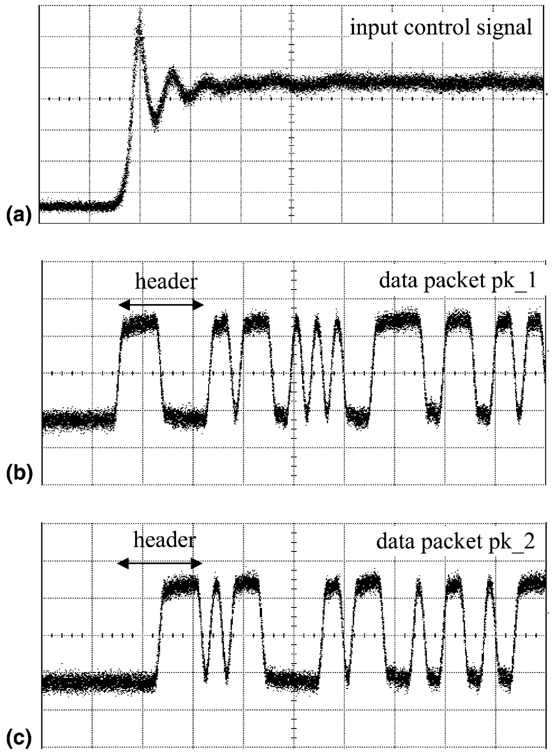


Fig. 3. Synchronized timing diagrams for (a) the input control signal; (b) the input data packet pk_1 in which the 1 bit in the header (with a duration of 400 ps) overlaps temporally with the trigger of the control signal and (c) the input data packet pk_2 in which the 1 bit in the header does not overlap with the trigger of the control signal. *Note*. Timescale = 500 ps/div.

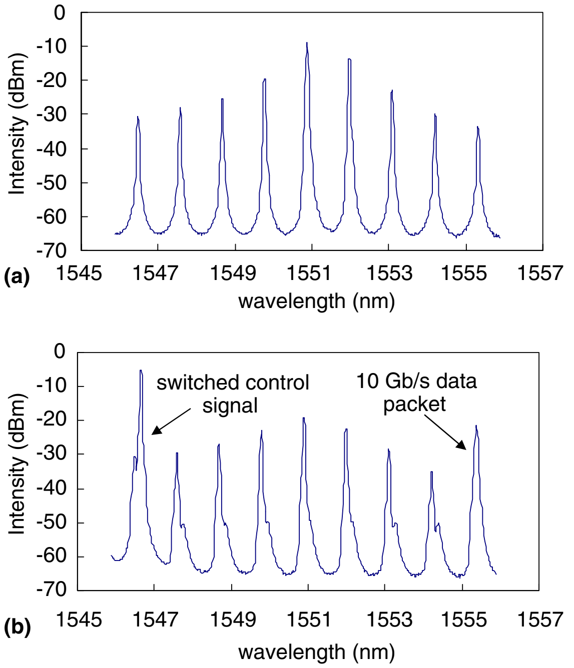


Fig. 4. Spectrum for (a) the free running FP-LD, and (b) the two mode injection-locked FP-LD for all-optical header processing.

tion-locking for the all-optical header processing. Fig. 5 shows the results of bitwise control switching of the control signals by these two types of data packets. Fig. 5(c) depicts the temporal profiles for the output control signals at the output of the FP-LD, the entire control signal is switched ON (OFF) by pk_1 (pk_2). The noise in the switched control signal at OFF state (Fig. 5(c)), i.e., the increase in the thickness of the upper rail, is due to the power gain by the trailer region of the control signals in the presence of '1' bits in the data packet (Fig. 1(b)). The switching ratio which is the power ratio between the ON and OFF states for the control signal is relatively small. To enhance the switching ratio of the control signals, we observe that there is a large difference in the states of polarization (SOP) between the injection-locked and unlocked control signals, i.e., the ON and OFF states, as shown on the Poincaré sphere in Fig. 6. Thus, the switching ratio can be significantly improved by using a polarizer at the output of the FP-LD as shown in Fig. 5(d). The switching ratio achieved is 20.7 dB. The SOP of the unlocked control signal output can deviate significantly from that of the locked output because an injection-locked FP-LD can act as an all-optical polarizer [11]. Fig. 7(a) and (b) depict the switched-off and switched-on control signals, respectively, measured after a polarizer. A clear eye is observed when we externally modulated the switched

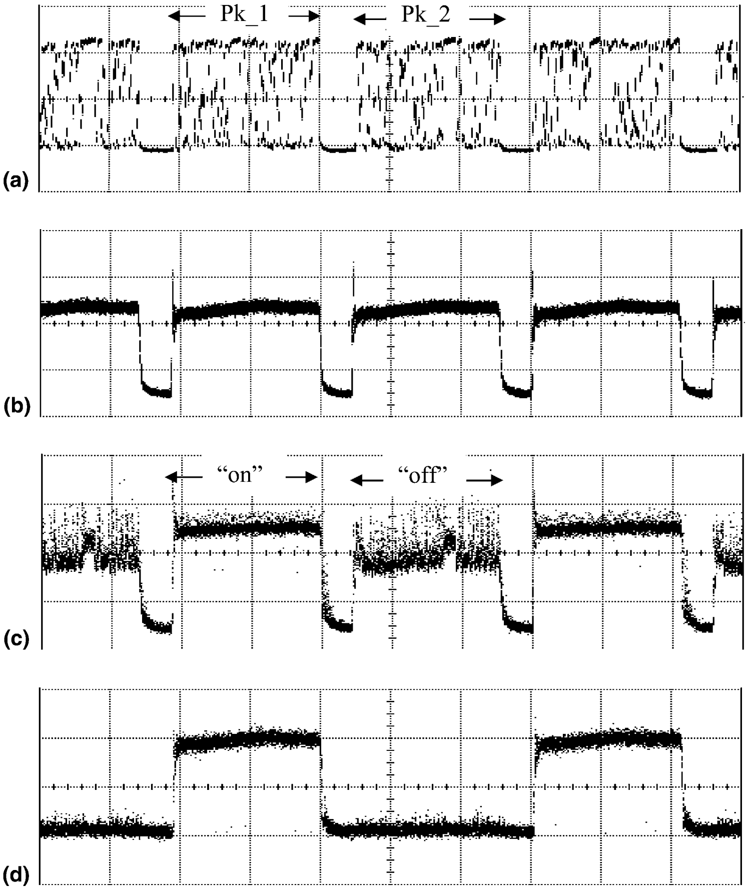


Fig. 5. Synchronized temporal profiles for (a) the input data packets; (b) the input control signal; (c) the output control signal without passing through a polarizer; and (d) the output control signal after passing through a polarizer. *Note.* Timescale = 10 ns/div.

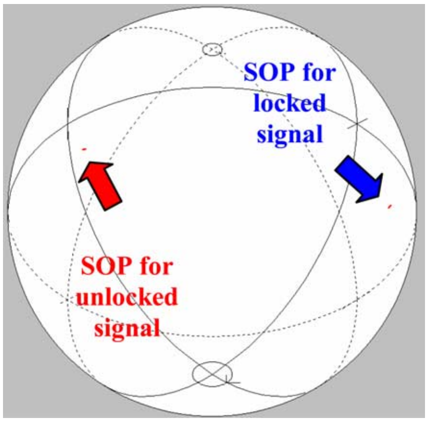


Fig. 6. Measured SOPs for both locked and unlocked control signals in Poincaré sphere.

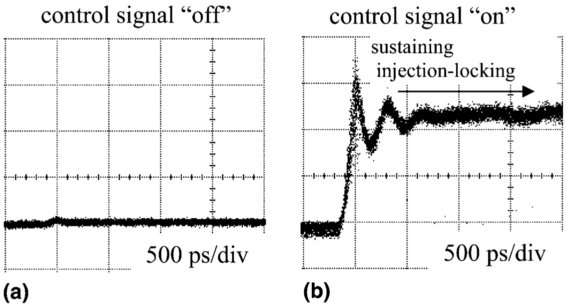


Fig. 7. Measured temporal profiles for (a) the output control signal at OFF state; (b) the output control signal at ON state after the all-optical header processor.

control signal from the all-optical header processor at 10 Gb/s, which indicated the output control signal is stable for practical use.

4. Conclusions

In conclusion, we demonstrated that the directly modulated output of a DFB laser can serve as the special two-level control signals required to implement a recently proposed simultaneous all-optical header processing and control signal switching scheme using a dual-wavelength injection-locked FP-LD. The header processing rate is 2.5 Gb/s while the payload data rate is 10 Gb/s. We also showed that the switching ratio of the switched control signals can be improved to over 20 dB by using a polarizer. The scheme provides a method for on-the-fly header processing and simultaneous control signal generation that significantly reduces the complexity and processing latency of the present O/E systems. Thus the scheme can be useful for optical communication given that synchronization of two inputs and power consistency from the data packet input are achieved. Finally, the all-optical header processor is sensitive to the input polarization of the data packets, an all-optical polarization stabilizer [11] can be used to control the SOP of the input signal for applications in future all-optical networks.

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