Demonstration of an all-optical switch by use of a multiwavelength mutual injection-locked laser diode

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Error-free all-optical packet switching is demonstrated by use of a multiwavelength mutual injection-locked Fabry–Perot laser diode. A 10-Gbit/s data signal is switched on and off with an extinction ratio of 16.9 dB when an optical control signal is turned off and on with a power difference of only 3 dB. © 2003 Optical Society of America

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Optical networks utilizing fast packet switching are expected to provide the required capacities and flexibility in the next-generation high-speed networks. A variety of all-optical switching devices that perform bitwise logic functions by use of ultrafast nonlinear interferometers have been reported.[1–3] Recent advances in all-optical packet demultiplexing or switching mostly require wavelength conversion.[4,5] In this Letter we demonstrate all-optical packet demultiplexing of a 10-Gbit/s data signal by an optical control signal in a Fabry–Perot laser diode (FP-LD) with a multiwavelength mutual injection-locking technique. The FP-LD transmits the data signal when the control signal is off and suppresses the data signal when the control beam is on. Wavelength conversion is not required. The extinction ratio of the switched data signal is 16.9 dB even when the power difference between the on and off states of the control beam is only 3 dB. The insertion loss of the all-optical packet demultiplexer is 0.4 dB because of amplification of the data signal under injection locking. The switch-on and switch-off times of the data signal are ~60 and ~50 ps, respectively, so the packet is switched within 1 bit period.

The operation principle of the proposed all-optical switch is based on injection locking of a commercially available FP-LD with a double-channel planar buried InGaAsP heterostructure. When an external signal injection locks the FP-LD, the injected signal power increases and the carrier density inside the activity layer of the FP-LD decreases because of stimulated emission. The resulting increase in the refractive index causes a redshift in the longitudinal modes of the FP-LD.[6] We exploit this injection-locking-induced change in the optical gain of the FP-LD at a specific wavelength to implement all-optical switching. Figure 1 shows the output spectra of a FP-LD with and without injection locking by a control signal injected at 1550.78 nm. The output spectra were obtained with a tunable laser with an injected power of −8.7 dBm scanning at step size 0.01 nm. From Fig. 1, injection locking by the control signal (with injected power of −4.8 dBm) suppresses the gain peaks of the FP-LD modes and redshifts them by 0.17 nm. Any signal that is spectrally aligned with the original gain peaks of the FP-LD will experience a power drop of ~20 dB in the presence of the control signal. The resulting change in the gains at a specific wavelength provides the switching action.

All-optical packet demultiplexing is achieved by simultaneous injection of three signals: a data signal, a control signal, and a cw stabilizer signal, into the FP-LD. The duration of the off state in the control signal is equal to the length of the packet that is to be demultiplexed from the data signal. The wavelengths of the data signal and the cw stabilizer signal are aligned with two different longitudinal modes of the FP-LD. The wavelength of the control signal is chosen to be on the longer-wavelength side of a third FP-LD mode. The detuning of the control signal and the power of each beam are chosen such that the FP-LD is always injection locked by one of the three signals in the following priority: the control signal, the data signal, and the cw stabilizer signal.

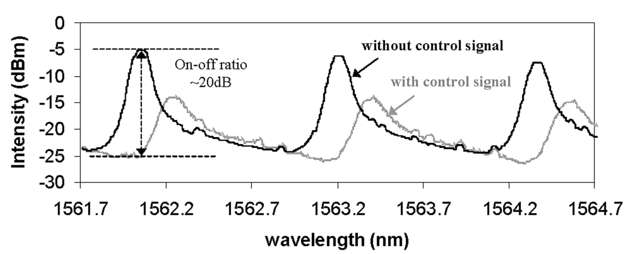

Fig. 1. Output spectra of a FP-LD obtained with tunable laser scanning at step size 0.01 nm with and without injection locking by a control signal injected at 1550.78 nm. The spectrum is redshifted by 0.17 nm when the FP-LD is injection locked.

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That is, the presence of the control signal will always injection lock the FP-LD and induce a redshift in the mode comb of the FP-LD even in the presence of a 1 in the data signal and the cw stabilizer signal. In the absence of a control signal, a 1 in the data signal will injection lock the FP-LD despite the presence of the cw stabilizer signal. The cw stabilizer signal injection locks the FP-LD in the mode comb only in the absence of both the control and data signals. All-optical switching is achieved because when the control signal injection locks the FP-LD the resulting redshift of the FP mode comb suppresses the data signal gain. The FP-LD thus works as an all-optical switch; i.e., the FP-LD transmits the data signal when the control signal is off and blocks the data signal when the control signal is on. The function of the cw stabilizer signal is to suppress the power of the FP-LD modes when the intensities of both the data signal and control signal are low, i.e., 0s, and also to increase the speed of injection locking by stimulated emission.[7] We note that the injection-locking range of the data signal in the presence of the stabilizer signal is less than that without the stabilizer signal because of gain competition between the two signals. Since injection locking is a threshold phenomenon, a small power difference (3 dB in the experiment) in the control signal is sufficient to switch the data signal on and off with an extinction ratio of 16.9 dB.

Figure 2 shows the experimental setup for the demonstration of all-optical packet demultiplexing. The 10-Gbit/s nonreturn-to-zero data signal at 1545.9 nm was generated by external modulation of a tunable laser (TL_1) with an injected power (measured at port 2 of the circulator before the FP-LD) of −20.5 dBm. The control signal at 1551.8 nm was produced from a distributed-feedback laser after amplification and modulation by another external modulator. The injected power of the control signal was 5.6 dBm, which could be adjusted by the attenuator. The cw stabilizer signal at 1553.9 nm was generated by another tunable laser (TL_2) with an injected power of 1.4 dBm. The bias current of the FP-LD was $1.1I_{\mathrm{th}}$, where I_{th} is the threshold current. The injection-locking ranges of the data signal without and with simultaneous injection of the stabilizer signals were 0.07 and 0.05 nm, respectively. The injection-locking range of the data signal was directly proportional to its power. To test the switching operation of the FP-LD, first we did not modulate the control signal. Figure 3(a) depicts the spectra of all three signals injected into the FP-LD measured at port 3 of the circulator. We set the cw 1551.8-nm control signal to the off state by attenuating its power to 2.6 dBm, a drop of 3 dB. The FP-LD was injection locked by the 10-Gbit/s 1545.9-nm data signal when the data signal was a 1 but was injection locked by the 1553.9-nm cw stabilizer signal when the data signal was a 0. When it was injection locked, the data signal was amplified with a measured power (at port 3 of the circulator) of −19.9 dBm, i.e., a gain of 0.6 dB. The packet demultiplexer, however, had an overall insertion loss of 0.4 dB, which was the power difference of the data signal measured at ports 1 and 3 of the circulator. We then set the cw 1551.8-nm control signal to the on state by restoring the injection power to 5.6 dBm. The FP-LD was then injection locked by the control signal. The resulting redshift of the Fabry–Perot mode comb was 0.17 nm. Figure 3(b) shows that the power of the 10-Gbit/s 1545.9-nm data signal drops by 16.9 dB when the control signal is on.

Figures 4(a) and 4(b) depict the switch-on and switch-off times, respectively, of the all-optical switch when it was injected with a control signal with a gating period of 160 ns and a cw data signal. The control signal was externally modulated with the 10-Gbit/s pattern generator. The measured rise and fall times of the switched data signal were 60 and 50 ps, respectively. The response times of the data signals are almost identical to those of the control signals. Figures 4(c) and 4(d) show eye diagrams of the switched data signal with and without the presence

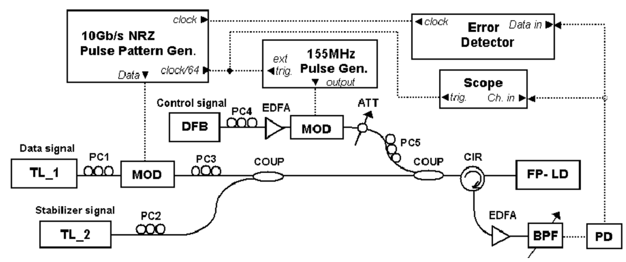

Fig. 2. Schematic of the all-optical switch used for packet demultiplexing with a multiwavelength injection-locked laser diode. NRZ, nonreturn-to-zero; TL_1, TL_2, tunable lasers; DFB, distributed-feedback laser; MOD, modulator; ATT, attenuator; PC1–PC5, polarization controllers; COUPs, couplers, CIR, circulator; EDFAs, erbium-doped fiber amplifiers; BPF, tunable bandpass filter; PD, photodiode.

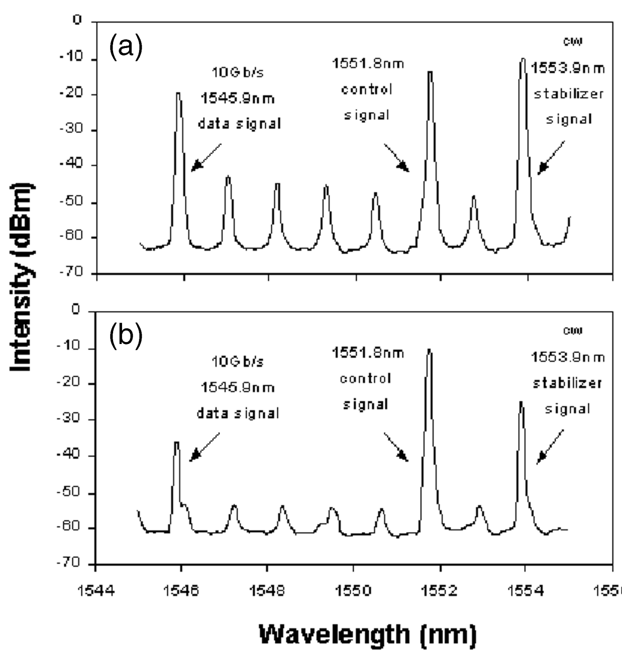

Fig. 3. Measured spectra for packet demultiplexing when the all-optical switch is (a) open and (b) closed. The data signal can be switched by 16.9 dB by use of a control signal with power difference 3 dB.

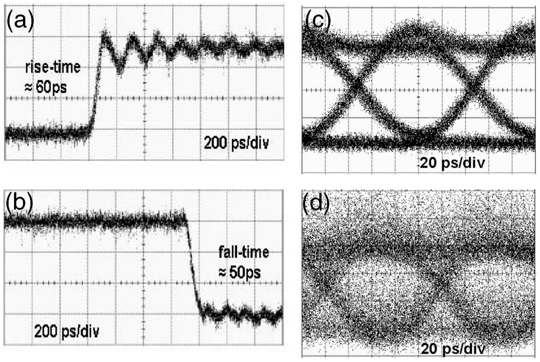

Fig. 4. Temporal profile of (a) the switch-on (rise-time) and (b) the switch-off (fall-time) response of the all-optical switch. Eye diagrams for the switched signal after the all-optical switch (c) with and (d) without cw stabilizer signal are also shown.

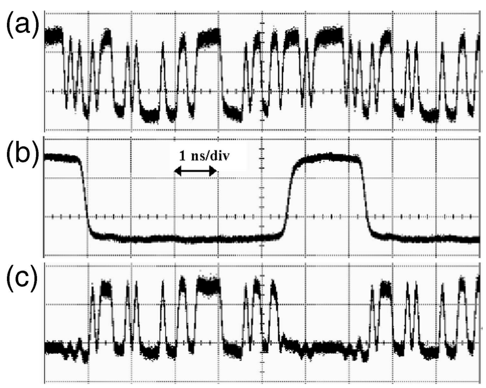

Fig. 5. Timing diagrams for (a) a 10-Gbit/s data signal, (b) the synchronized 155-MHz control signal with 1.8-ns pulse width, and (c) the switched 10-Gbit/s data signal with the same wavelength of (a) after the all-optical switch (time scale, 1 ns/div).

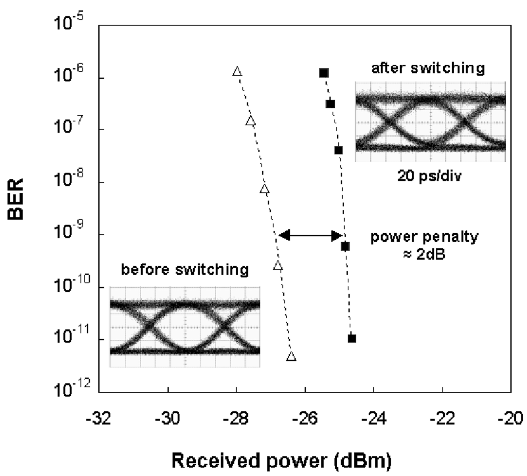

Fig. 6. BER performance for the data signal (△) before and (■) after switching by the all-optical switch (insets, corresponding eye diagrams for the data signal).

of the cw stabilizer signal, respectively. The cw stabilizer signal suppresses the emission of the other FP-LD modes when the power of both the data signal and the control signal is low and thus dramatically improves the eye opening. Finally, we demonstrate all-optical packet demultiplexing by modulating the control signal into a 1.8-ns duration gating signal with 155-MHz repetition rate. The demultiplexed packet will therefore be 46 bits long with a separation of 18 bit periods. We synchronized the control signals with the 10-Gbit/s data signal by adjusting the delay of the control signal with 2 ps resolution. Figures 5(a) and 5(b) show the timing diagrams of the 10-Gbit/s data signal and the 155-MHz control signal, respectively. The operation parameters are chosen as before. Figure 5(c) shows the packet-switched data signal measured without averaging. We observe that the data packet is switched within 1-bit duration. The bit-error rate (BER) performance of the 10-Gbit/s data signal before and after packet demultiplexing is shown in Fig. 6. Error-free switching (BER $<10^{-12}$) can be achieved. The power penalty for the switched signal at a BER of 10^{-9} is $\sim$2 dB.

In conclusion, we have demonstrated all-optical packet demultiplexing of a 10-Gbit/s data stream, using multiwavelength mutual injection locking of a Fabry–Perot laser diode. The switch-on and switch-off times of the FP-LD are within a bit period, so only 1 bit is required to serve as a guard period between the packets for packet demultiplexing. Only 3-dB difference in the power of the control beam is sufficient to achieve an extinction ratio of 16.9 dB in the switched data signal. Since the mutual injection-locking scheme has been demonstrated for a pulse width of 17 ps,[7] all-optical packet demultiplexing at 40 Gbits/s may be feasible with the proposed scheme. Finally, since the performance of the proposed all-optical switch is sensitive to the polarization of the input signal, practical realization of the proposed scheme will require polarization control in the input data signal.[8]

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