Fig. 3: Eye diagram of a 160 Gb/s data signal (upper traces) and recovered 10 GHz optical clock (lower traces). Scale: 20 ps/div.

Fig. 4: Single sidemode phase noise of the recovered optical clock signal.

Fig. 5: Experimental set-up for demultiplexing experiment.

3. Results
Fig. 3 shows the eye diagram of the 160 Gb/s data signal and the 10 GHz recovered optical clock signal measured using an electrical sampling oscilloscope with 50 GHz bandwidth. The oscilloscope was triggered by the 10 GHz clock signal of the transmitter. The persistence was set to 1000 waveforms and no channel hopping was observed for several hours.

We measured the single sidemode phase noise of the recovered optical clock signal between 100 Hz and 10 MHz (Fig. 4). From this curve, an rms-jitter of 270 fs is obtained.

Finally, we tested the clock recovery in a 160 Gb/s to 10 Gb/s demultiplexing experiment. The set-up is shown in Fig. 5. The transmitter comprised a 10 GHz mode-locked semiconductor laser emitting 1.5 ps pulses which were encoded with a PRBS 2^7-1 bit sequence. The 160 Gb/s OTDM data signal was generated by multiplexing the signal by a fiber delay line multiplexer. To maintain the pseudo-random characteristic, the bit sequences were shifted by (2^7-1)/n bit periods with n = 2, 4, 8, 16 in each stage of the multiplexer. The optical demultiplexer consisted of a 1.3 µm semiconductor optical amplifier based on Gain Transparent Ultrafast-Nonlinear-Interferometer (GT-UNI) [9].

The demultiplexer was driven by the optical pulses of a mode-locked semiconductor laser, which was controlled by the local oscillator (VCO). An optical delay line before the clock recovery was used to select different OTDM channels. A 10 Gb/s receiver was placed at the output of the demultiplexer and the bit-error rate (BER) was measured as a function of the received power P_{rec} as indicated in Fig. 5. An erbium doped fiber amplifier was used in the clock recovery branch to provide an average optical power of about 3 dBm at the input of the clock recovery.

4. Conclusion
10 GHz clock recovery from a 160 Gb/s data signal was demonstrated using a bidirectionally operated single electroabsorption modulator (EAM). Without any change, the clock recovery was also applied for clock recovery from 40 and 80 Gb/s data signals. A differential scheme was used to obtain a large bipolar feedback signal. The EAM acts as a bidirectional electro-optical phase comparator between the 160 Gb/s optical data signal and the local clock signal. Excellent locking stability with no channel hopping was achieved.

The recovered optical clock signal had a rms-jitter of 270 fs and allowed error-free 160 Gb/s to 10 Gb/s demultiplexing with no penalty. The design is polarization independent. Furthermore it has potential for hybrid planar lightwave circuit integration by replacing the circulators with 3 dB couplers.

5. References

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Demonstration of All-Optical Packet Demultiplexing Using a Multi-Wavelength Mutual Injection-Locked Laser Diode
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All-optical packet demultiplexing is demonstrated using a multi-wavelength mutual injection-locked Fabry-Perot laser diode. Error-free packet-demultiplexing of a 10 Gb/s data signal with an extinction ratio of 16.9 dB is observed.

1. Introduction
Optical networks utilizing fast packet switching are expected to provide the required capacities and flexibility in next generation high speed networks. A variety of all-optical switching devices that perform bitwise logic functions have been reported using ultrafast nonlinear interferometers [1,2]. Recent advances in all-optical packet demultiplexing or switching mostly required wavelength conversion [3,4]. In this paper, we demonstrate all-optical packet demultiplexing of a 10 Gb/s data signal by an optical control signal in a Fabry-Perot laser diode (FP-LD) using multi-wavelength mutual injection locking technique. The FP-LD transmitted the data signal when the control signal is OFF and suppresses the data signal when the control signal is ON. Wavelength conversion is not required. The extinction ratio of the demultiplexed data signal is 16.9 dB even when the power difference between the ON and OFF states of the control signal is 3 dB only.

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 time and switch-off time of the data signal are ~60 ps and ~50 ps respectively so that the packet is demultiplexed within one bit period.
2. Operation Principles

All-optical packet demultiplexing was carried out by simultaneously injecting three different wavelength signals: a data signal, a control signal, and a cw stabilizer signal into a commercial available FP-LD with a double-channel planar-buried InGaAsP heterostructure. The duration of the OFF state in the control signal is equal to the length of the packet to be de-multiplexed from the data signal. We also assume that the control signal and the data signal are synchronized. 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 FL-LD mode. The detuning of the control signal and the powers of each signals 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. That is, the presence of the control signal will always injection-lock 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 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 red-shift 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 functions of the cw stabilizer signal are to suppress the power of the FP-LD modes when the intensities of both the data signal and control signal are low, i.e., zeroes, and to increase the speed of injection locking by stimulated emission. Since injection locking is a threshold phenomenon, a small power difference (3 dB in the experiment) in the control signal is sufficient to switch on and off the data signal.

3. Experimental Results

Figure 1 shows the experimental setup for the demonstration of all-optical packet demultiplexing. The 10 Gb/s non-return-to-zero (NRZ) data signal at 1545.9 nm is generated by 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 is produced from a DFB laser and modulated by another external modulator. The injected power of the control signal is 5.6 dBm which can be adjusted by the attenuator (ATT). The cw stabilizer signal at 1553.9 nm is generated by another tunable laser (TL_2) with an injected power of 1.4 dBm. The bias current of the FP-LD is 1.1Ith, where Ith is the threshold current. To test the switching operation of the FP-LD, we did not modulate the control signal. Figure 2a 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, i.e., a drop of 3 dB. The FP-LD is injection-locked by the 10 Gb/s 1545.9 nm data signal when the data signal is a “1” but is injection-locked by the 1553.9 nm cw stabilizer signal when the data signal is a “0.” When injection-locked, the data signal is amplified with a measured power (at port 3 of the circulator) of -19.9 dBm, i.e., a gain of 0.6 dB after compensation for the insertion loss from the FP-LD. The packet demultiplexer however has an overall insertion loss of 0.4 dB, which is the power difference of the data signal measured at port 1 and port 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 is then injection-locked by the control signal. The resulting red-shift of the FP mode comb is 0.17 nm. Figure 2b shows that the power of the 10 Gb/s 1545.9 nm data signal drops by 16.9 dB when the control signal is ON. Figure 3a depicts the switch-on time and switch-off time of the all-optical packet demultiplexer.
when injected with a control signal with a gating period of 160 ns and a cw data signal. The control signal is externally modulated with the 10 Gb/s pattern generator. The response time of the switched data signal is 20 ps.

Error-free switching (BER < 10^-12) can be achieved when both the powers of the data signal and control signals are low. The response time of the switched data signal measured without averaging is 60 ps.

Figure 3b shows the eye diagrams for the switched data signal with and without the presence of the cw stabilizer signal. The eye opening is dramatically improved by injecting a control signal with a gating period of 160 ns.

Finally, we demonstrated 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 data signal by adjusting the delay of the control signal with 2 ps resolution.

4. Conclusions

In conclusion, we have demonstrated all-optical packet demultiplexing of a 10 Gb/s data stream using a multi-wavelength mutual injection locking of a Fabry-Perot laser diode. The switch-on and switch-off time of the FP-LD is within a bit period so that guard periods between the packets are not necessary for packet demultiplexing. Only 3 dB difference in the power of the control signal is sufficient to achieve an extinction ratio of 16.9 dB in the switched data signal. Since mutual injection-locking scheme has been demonstrated for a pulsewidth of 17 ps, all-optical packet de-multiplexing at 40 Gb/s may be feasible using the current scheme.

5. References