All-optical flip-flop memory based on two coupled polarisation switches

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into the HNL-DSF was +18 dBm. The polarisation of the 160 GHz clock pulses was adjusted for zero transmission through the PBS in the absence of the control pulses. The data signal switched the clock pulses by using XPM-induced polarisation rotation in the HNL-DSF. The polarisation of the 160 Gbit/s control pulses was then adjusted for optimum XPM.

In the wavelength shifter we used supercontinuum (SC) generation in 850 m HNL-DSF with $\lambda_0 = 1550.3$ nm. The spectrum of the switched data at $\lambda_{out} = 1537$ nm was broadened coherently by self-phase modulation (SPM) in the HNL-DSF, and the wavelength-converted copy of the data was obtained [6] by filtering out the generated SC light with an optical bandpass filter with a centre wavelength of 1541 nm. The average input power of the switched data into the HNL-DSF was +20 dBm. Note that by using ultra-broad bandwidth of the SC, arbitrary wavelength allocation of the 3R-wavelength converted signal can be realised.

Results: Fig. 3 shows the BER measurements against the power of the 160 Gbit/s data signal at the input of the receiver for two different measurements. In the reference measurement, the 160 Gbit/s receiver was directly connected to the transmitter. In the second measurement, the 3R-wavelength converter was placed between transmitter and receiver as described in Fig. 1. There is no significant difference between both measurements. Even if we consider that obviously a different pulse width and wavelength was used for the reference measurement, we think that the results show no degradation of the data signal after the 3R-wavelength converter.

Conclusion: We have proposed a novel all-optical wavelength converter with 3R-regenerating capability and demonstrated error-free operation at 160 Gbit/s. This is the highest bit rate of a 3R-wavelength converter reported to date. One critical issue of using a fast optical gate in a wavelength converter is the conversion of jitter in the incoming data signal to amplitude noise in the output data signal. By using a pulse shaper at the input of the decision gate we were able to reduce this effect and to achieve error-free performance. With an additional fibre-based wavelength shifter, the wavelength of the output data signal can be chosen arbitrarily in a wavelength range determined by supercontinuum generation including the same wavelength as the input data signal.

Fig. 3 BER measurements of 3R wavelength converter
× reference measurement
○ 3R-wavelength converter

All-optical flip-flop memory based on two coupled polarisation switches

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An all-optical flip-flop memory with separate set and reset inputs is presented. The flip-flop is realised from two coupled polarisation switches. The concept is explained and experimental results are presented that demonstrate that a contrast ratio of 20 dB and a switching power of <1 dBm can be obtained. The all-optical flip-flop can be utilised in all-optical packet switches.

Introduction: The need to produce a transparent all-optical packet switch has been well documented [1]. A key component of the all-optical packet switch is an all-optical flip-flop memory [2]. In this Letter we present an all-optical flip-flop memory with separate optical set and reset inputs. The concept is explained and experimental results are presented that demonstrate that a contrast ratio of 20 dB and a switching power of <1 dBm can be obtained. The all-optical flip-flop can be utilised in all-optical packet switches.

System concept: The all-optical flip-flop concept is shown in Fig. 1. It consists of two coupled nonlinear polarisation switches. This all-optical flip-flop implementation has a simple structure, separate set and reset inputs and large input wavelength range. Moreover, this all-optical flip-flop memory made from two coupled nonlinear optical elements. An all-optical flip-flop memory made from two coupled lasers is presented in [3] and an all-optical flip-flop memory realised from two coupled Mach-Zehnder interferometers is presented in [4]. The last configuration allows ultra-fast operation. In this Letter, we demonstrate an all-optical flip-flop memory made from two coupled nonlinear polarisation switches. This all-optical flip-flop implementation has a simple structure, separate set and reset inputs and large input wavelength range. Moreover, this all-optical flip-flop has similar properties to that based on two coupled Mach-Zehnder interferometers [4]. However this implementation is easy to realise using commercially available pigtailed components and shows stable operation without photonics integration. We demonstrate the feasibility of the concept and we show that the contrast ratio between output states of flip-flop is 20 dB while the switching power is <3 dBm.
wave (CW) probe beam at wavelength $\lambda_1$ that is fed into an SOA. The SOA output is sent into a PBS. The system contains two polarisation controllers. The first is used to adjust polarisation of the input signal with the orientation of the PBS layers, while the second is used to adjust the polarisation of the amplified SOA output with the orientation of the PBS. The SOA can be saturated by injection of a high intensity pump (control) signal. The solid curve in Fig. 2 shows the typical (experimental) PBS output against intensity of the saturating control light. It follows that a control beam of sufficient intensity can suppress the PSW output. This effect is caused by the additional birefringence introduced in the SOA by the control light [6], which causes the TE and the TM modes of the probe beam to experience a different refractive index. At the PBS, the two modes combine coherently, if the phase difference between the two modes is an odd multiple of $\pi$, the PSW output is suppressed. Note that the curve of Fig. 2 is similar to that presented in [4] in which the suppressed output of an active Mach-Zehnder interferometer is discussed.

![Fig. 1 Configuration of all-optical flip-flop based on two polarisation switches](image1)

Similarly as in [4], an optical flip-flop can be realised by coupling two identical PSWs as shown in Fig. 1. The first PSW, hereafter called PSW1, outputs light that is injected into the second PSW (called PSW2). Hence, the light that outputs PSW1 acts as a saturating control signal that can suppress PSW2 and the light that outputs PSW2 can act as a saturating control signal to suppress PSW1. The solid curve in Fig. 2 represents the intensity $P_{out,1}$ of the light that outputs PSW1 as a function of the intensity $P_{out,2}$ of the light that outputs PSW2. The system is set in such a way that the maximum output intensity $P_{out,1}$ equals the intensity of the control light $P_{out,2}$ that is required to suppress PSW1. Since the PSWs are identical, the solid curve is complementary to the dashed curve that represents the intensity of the light that outputs PSW2. At point A, PSW1 is dominant and PSW2 is suppressed while at point B, PSW1 is suppressed and PSW2 is dominant. Both A and B can be shown to be stable states of the system and point S can be shown to be an unstable point [3].

The system of two coupled PSWs can function as an optical flip-flop as follows. The state of the flip-flop can be determined by observing the amount of light at the PSW outputs. In state 1, PSW1 dominates and suppresses PSW2, while in state 2 PSW2 dominates and suppresses PSW1. To switch the flip-flop between the states, light can be injected in the PSW that dominates (that is the one injecting the most light into the other PSW) via the set and reset ports. The injected light reduces the light exiting the dominant PSW, which allows the suppressed PSW to increase its light output and become the dominant PSW.

The steady state PSW output intensity against the intensity of the input light is shown in Fig. 2 as discussed in the previous Section. The two states of the flip-flop are shown as point A and point B. The dynamic operation of the flip-flop is demonstrated by toggling the state of the flip-flop by injecting a regular sequence of optical pulses into the PSW that was previously the master. The pulses had a wavelength of 1552.52 nm and a duration of 120 ns. The pulses were injected in the master once every 1.85 µs through the set and reset port (see Fig. 1). Fig. 3 shows the oscilloscope traces of the optical output power of flip-flop for each state. The optical peak power for the set and reset pulses were $-3.91$ and $-3.35$ dBm, respectively. In Fig. 3, regular toggling between the flip-flop output states every 1.85 µs is visible. Furthermore, it can be observed that the flip-flop state is stable in the time between changing states. Also the contrast between state 1 and state 2 was investigated by using an optical spectrum analyser. It turned out that contrast ratio between the two states of the flip-flop is over 20 dB.

![Fig. 2 Intensity $P_{out,1}$ of light that outputs PSW1 against intensity $P_{out,2}$ of light that outputs PSW2](image2)

![Fig. 3 Regular toggling between two flip-flop states by injecting set or reset pulse every 1.85 µs](image3)

**Conclusion:** An all-optical flip-flop memory based on two coupled polarisation switches has been demonstrated. The contrast ratio between output states of the flip-flop is $>20$ dB and the optical switching power is $<-3$ dBm. The speed of this flip-flop is determined by the speed of the PSW and the propagation distance between two SOAs. In the experimental setup, ~12 m of fibre is used between the two SOAs, which implies that at least 100 ns are required for the states of the flip-flop to change. However, integrated versions of the flip-flop could reduce the distance between two SOAs to several millimetres. In this case, the speed of the flip-flop is dominated by the speed of the PSW. It has been demonstrated that the PSW can operate at 10 GHz [7], thus we expect the flip-flop can reach similar speeds. Finally, we remark that the curves in Fig. 2 are similar to those in [3] which reveals that a PSW acts as a Mach-Zehnder interferometer where the role of the different light paths is now realised by independently operating TE and TM modes of the optical field.
Data transmission using GaAs-based InAs-InGaAs quantum dot LEDs emitting at 1.3 mm wavelength

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Vertical emission light-emitting diodes (LEDs), based on long-wavelength, self-assembled InAs-InGaAs quantum dot (QD) grown on GaAs substrate, are used to demonstrate up to 1 GBit/s digital data transmission. The devices are characterised in terms of small-signal modulation, showing bandwidths beyond 1 GHz.

Introduction: There is an increasing interest in the development of GaAs-based active materials emitting at 1.3 and 1.55 mm wavelength for telecommunication applications. Since the first realisation of lasing using self-assembled InAs-InGaAs quantum dots on GaAs substrate, great advances have been made yielding laser diodes with remarkably low threshold current densities [1-4]. QD-based LEDs may represent efficient and cheap sources for low data rate links at 1.3 mm [5]. To our knowledge, this Letter presents the first demonstration of data transmission using 1.3 mm QD LEDs.

Device structure: In this experiment we use single-mirror QD LEDs operating at around 1.3 mm wavelength. The detailed device structure is described in [5]. In brief, devices are grown on Si-doped (001)-oriented GaAs substrate using solid source molecular beam epitaxy. A 2/3/2/2 layer of AlGaAs is grown first for carrier confinement, followed by a GaAs spacer layer. For the active QD region InAs is deposited directly on the GaAs surface and covered by an InGaAs layer. A successive low-index AlGaAs layer is intended for wet oxidation to serve as a current aperture. It is sandwiched between two AlGaAs barriers and forms a single Bragg period with the following high-index GaAs layer. To phase-match the reflection from the gold layer deposited on top, a highly p-doped GaAs cap layer is grown, serving as a contact layer as well. Layer thicknesses are chosen such that radiation reflected by the top mirror constructively interferes with emission from the QD region, resulting in a fourfold increase in optical output at the substrate side [6]. Device fabrication consists of mesa etching, lateral wet oxidation of the AlGaAs layer, contact evaporation and annealing. Using this structure we previously demonstrated an external quantum efficiency of 1% at low current densities [5].

DC characteristics: In Fig. 1 the output power is plotted against the injected current for three different device sizes denoted by their oxidised aperture size. The inset shows electroluminescence (EL) spectra taken for CW operation of an 84 mm size device. As the injection density increases, ground state emission at 1285 nm saturates due to state filling in the QDs, and two peaks corresponding to emission from excited states are observed. Total output power also saturates since carriers on excited states are more easily lost due to escape to the wetting layer and nonradiative recombination.

Small-signal modulation: We use a scalar network analyser for the small-signal modulation measurements. The modulation signal out of the 50 Ω impedance source is combined in a bias-T with the DC-bias current and fed to the LED. The device is contacted by a ground-signal-ground configuration high-frequency probe head to ensure signal integrity during on-wafer testing. The optical signal is collected using a microscope objective with a numerical aperture of 0.4 and focused onto an InGaAs PIN detector of 100 μm diameter using another objective. All optical components are anti-reflection coated for the emission wavelength. The electrical signal is amplified by 25 dB prior to detection. The bandwidth of the setup is limited to 1.5 GHz by the photodiode (PD). All measurements have been performed at room temperature with no temperature stabilisation of the device.

Fig. 2 shows the modulation response curves of an 84 mm device for different bias currents, normalised to the value at 20 MHz. Periodic modulations in the curves are caused by reflections on the feeding lines due to the impedance mismatch between the LED and the driving source. The electrical modulation power was set to −1 dBm out of the 50 Ω system for all currents. The 3 dB decay is indicated by a horizontal line. We observe the modulation depth to increase with bias current up to about 4 mA, while for higher currents it decreases. Furthermore we observe a continuous increase in bandwidth with increasing bias, leading to rather flat response curves for high driving currents. The maximum bandwidth reached for 20 mA of bias is 860 MHz.

This behaviour can be attributed to state filling, as observed in the DC characteristics. The modulation depth is related to the slope of the light-current curve, which is seen to decrease at high currents in Fig. 1.