All-optical flip-flop operation of VCSOA

A.M. Kaplan, G.P. Agrawal and D.N. Maywar

An all-optical flip-flop, the memory of which is based on dispersive bistability in a single vertical cavity semiconductor optical amplifier, is demonstrated experimentally. Flip-flop control is achieved using two mechanisms: cross-phase modulation to set the flip-flop and cross-gain modulation of the holding beam within a remote SOA to reset it. Optical control signals are sub-milliwatt in power and derived from a single 5 ns, 1539 nm initial pulse. Flip-flop operation at 1542 nm is polarisation insensitive to control signals and achieved with an on-off contrast greater than 3 dB.

Introduction: All-optical signal-processing devices are expected to play an essential roll in future optical-data networks [1]. Bistable optical devices have been widely studied for their use in all-optical processing and recent research has focused on bistable vertical cavity semiconductor optical amplifiers (VCSOAs), which are advantageous over in-line amplifiers for some applications owing to their compact, symmetrical, surface-emitting design [2–6]. Bistable optical devices can be used as the basis of all-optical flip-flops, a switch whose bistable output power is set and reset by optical pulses. To date, a VCSOA-based flip-flop has been demonstrated; however, this flip-flop was dependent on the polarisation state of the control signals, based on coupled VCSOAs, and used long 850 nm control signals of 1 s duration [7]. We demonstrate an all-optical flip-flop that is independent of the polarisation state of the control signals, exhibits memory based solely on the dispersive bistability of a single VCSOA and uses 1539 nm pulses of 5 ns duration. To achieve both the set and the reset functionalities using signal wavelengths within the C-band, two unique control mechanisms are employed: cross-phase modulation (XPM) to set the flip-flop [8], and cross-gain modulation (XGM) to reset it [9].

Experimental setup: The experimental setup is illustrated in Fig. 1. Each injected pair of set and reset pulses is derived from a single 5 ns-wide initial pulse generated using a 1538.73 nm DFB diode laser, a Mach-Zehnder modulator and an electrical pulse generator. This 61 μW initial pulse is split via a 3 dB splitter: one output is the set signal and the other is used to imprint the reset signal onto the holding beam as follows. The 1542.12 nm holding beam is generated by a DFB diode laser and passes through a travelling-wave SOA. Through a circulator from the opposite direction arrives a portion of the initial pulse from the 3 dB splitter. The initial pulse acts on the holding beam by XGM, saturating the gain of the SOA and thereby decreasing the power of the holding beam [9]. The imprinted holding beam then passes through a bandpass filter (BPF) to reduce the broadband ASE from the SOA and is recombined with the set signal by a 3 dB coupler for injection into the VCSOA. A circulator is used between the holding-beam laser and the SOA to prevent the counter-propagating, amplified initial pulse from reaching the holding-beam laser.

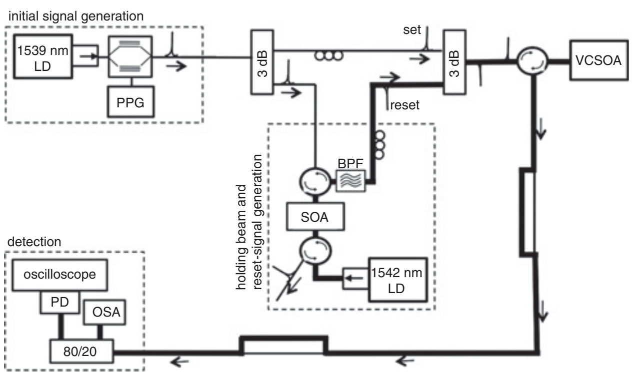

Fig. 1 *Experimental setup*

Thick lines indicate 1542.12 nm holding beam VCSOA input and reflected signals

A circulator is used to inject the holding beam and control signals into the VCSOA and to direct the reflected VCSOA output towards the photodiode and optical spectrum analyser. The VCSOA is a commercially available 1550 nm VCSEL from Vertilas™ biased at 1.79 mA with a measured lasing threshold of 1.77 mA at 1541.9 nm. A lensed fibre is used to couple the VCSOA to an optical fibre with an estimated coupling loss of 6 dB.

Experimental results: Fig. 2*a* shows the single initial pulse at 1538.73 nm. In general, two separate pulses can be used provided that the set and reset pulses are within the gain bandwidth of the VCSOA and travelling-wave SOA, respectively. Fig. 2*b* shows the optical power injected into the VCSOA. Clearly distinguishable are the 0.19 mW baseline of the holding beam, the 0.48 mW set signal riding on top of the holding beam and the temporary reduction in power to 0.05 mW is the reset signal. The holding beam wavelength is detuned from the dominant VCSOA resonant wavelength by 0.22 nm towards the red.

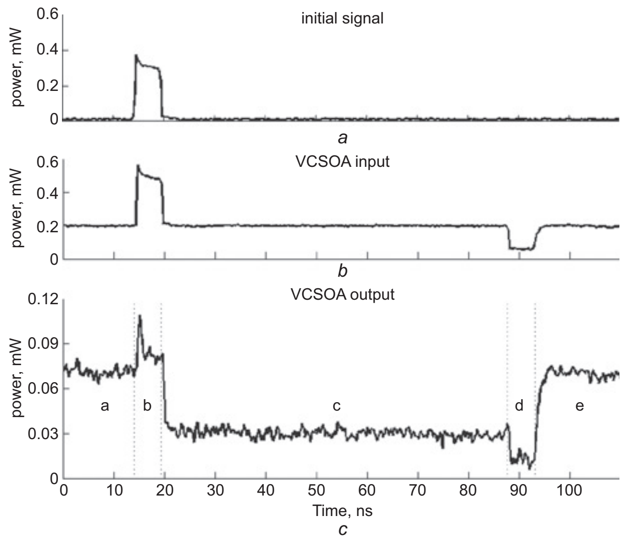

Fig. 2 *All-optical flip-flop operation*

a Initial signal
b Holding beam, set and XGM-induced reset signals injected into VCSOA
c VCSOA reflected optical power

Fig. 2*c* shows the VCSOA reflected power demonstrating inverted flip-flop operation. At time ‘a’ the bistable VCSOA is in the higher of its two stable output states. At time ‘b’ the set signal arrives; the measured reflected power is the combination of the VCSOA output and a portion of the set signal being reflected. The VCSOA’s output power remains in the set state, lower output power, ‘c’, until time ‘d’ when the reset signal arrives. The reset signal momentarily decreases the input power and resets the flip-flop into the high output state ‘e’. Flip-flop operation is achieved with an on-off contrast of 3.31 dB. Flip-flop operation is dependent on the polarisation of the holding beam but is not dependent on the polarisation of the control signals; therefore, the flip-flop will work with lightwave-system pulses with uncontrolled polarisation states.

Discussion: The effects of the holding beam, set, and reset signals on the VCSOA hysteresis curve have been simulated and are shown in Fig. 3 where each sub-figure corresponds to a time marked in Fig. 2*c*. In Fig. 3*a* the holding-beam input power intersects the bistable region of the hysteresis and exhibits an output power corresponding to the higher branch. In Fig. 3*b*, the set pulse saturates the VCSOA gain within the resonator, increasing the refractive index and, temporarily shifting the hysteresis of the resonator by XPM [8]. This action allows for the holding beam to experience positive feedback; the internal power increases, latching the resonant wavelength onto the holding beam such that the VCSOA relaxes into the lower output power of the bistable portion of the hysteresis, as shown in Fig. 3*c*. The XGM-induced reset signal lowers the VCSOA optical input power below the bistable portion of the hysteresis, as shown in Fig. 3*d* [9], after which the cavity relaxes into its initial state. This is the first time these XPM and XGM processes have been used in tandem to set and reset the flip-flop, respectively, allowing both control signals to be within the C-band.

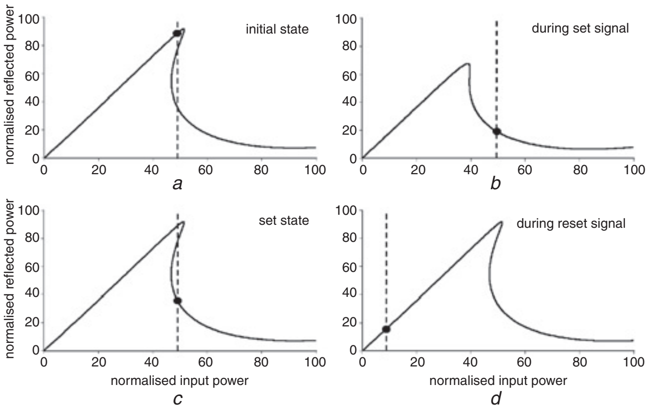

Fig. 3 *Simulation of VCSOA hysteresis*

a Initial state, having high reflected power
b XPM-induced shift in hysteresis during set signal
c Set state, having low reflected power
d Decrease in input power of holding beam during reset signal

The hysteresis curves in Fig. 3 were calculated by modelling the VCSOA as a Fabry-Perot cavity with an effective cavity length $L_c = 2.8598\ \mu m$ that incorporates optical penetration into the multilayer cavity mirrors, an approach described in [4]. Using (3) and (4) of [4], we have calculated the reflected power and the input power (both normalised by the saturation power P_s) by parameterising each in terms of the averaged internal power P_{av}, while expanding the expressions for the normalised gain gL_c and the single-pass phase Φ to explicitly show the relation to the modal gain g_m, based on [10], and to include the internal set-pulse power P_{set} as follows:

$$gL_c = \Gamma g_m L_c - \alpha_i L_c = \frac{\Gamma g_0 L_c}{1 + (P_{av} + P_{set})/P_s} - \alpha_i L_c$$

$$\phi = \phi_0 + \frac{\alpha}{2}(g_0 L - g_m L) = \frac{\Gamma g_0 L_c \alpha}{2} \frac{(P_{av} + P_{set})/P_s}{1 + (P_{av} + P_{set})/P_s}$$

where $\alpha L_c = 0.0252$ is the normalised internal loss, $\Gamma = 0.1$ is the confinement factor, $g_0 L_c = 0.2962$ is the normalised unsaturated modal gain, $\Phi_0 = -16.93 \times 10^{-4}\pi$ is the initial phase detuning, and $\alpha = 2.1$ is the linewidth enhancement factor. The active area of $9.42\ \mu m^2$, upper DBR reflectivity of 99.37%, lower DBR reflectivity of 99.77%, wavelength of 1542.12 nm, and injection current of 1.79 mA were all chosen to match the experimental conditions. The remaining parameter values are given in [4]. The equations above make the role of the set pulse clear; the set-pulse power adds to the saturation of the VCSOA gain. As a result, the phase of the holding beam is altered; it is this phase change that has the most significant effect on the hysteresis curve shown in Fig. 3*b*, shifting its multi-valued region to lower holding-beam input powers. For Fig. 3*b*, a constant set-signal power $P_{set} = 0.02\ P_s$ was assumed. These steady-state calculations are an acceptable way to demonstrate the behaviour of the flip-flop because they describe the states that persist for time scales longer than the sub-nanosecond carrier dynamics.

Conclusion: We have demonstrated an all-optical flip-flop based on the dispersive bistability of a single VCSOA. This experiment is the first demonstration of a hybrid control scheme which allows both control signals to fall within the C-band. C-band operation and polarisation independence of the control signals are important features for use in lightwave systems.

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