Robust optical control of an optical-amplifier-based flip–flop

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Abstract: We demonstrate new optical techniques for externally controlling the latchable output power of a semiconductor-optical-amplifier-based flip–flop. Optical 'set' and 'reset' signals increase and decrease the refractive index, respectively, via cross-phase modulation (XPM). Set signals, which deplete the carrier density, have wavelengths between 1533 and 1568 nm, and powers as low as 22 μW. Reset is performed with carrier-generating 'positive' optical pulses at 1306 and 1466 nm, and minimum powers below 1 mW. These techniques are useful for digital optical-processing functions such as bit-length conversion, retiming, and demultiplexing.

OCIS codes: (230.1150) All-optical devices; (250.5980) Semiconductor optical amplifiers; (200.4560) Optical data processing; (060.4510) Optical communications.

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1 Introduction

All-optical techniques for processing lightwave-communication signals have advanced considerably in recent years. Indeed, intensive research has produced practical all-optical devices for tasks such as routing [1], switching [2], demultiplexing [3], and data wavelength conversion [4]. The output from these devices, however, requires the continuous presence of an input signal, i.e. the output power does not *latch*. The latching capability of an optical flip–flop would allow the output to be maintained for processing at a later time; a digital, sequential means of processing would therefore be available for applications such as bit-length conversion, data-format change, demultiplexing, packet-header buffering, and retiming.

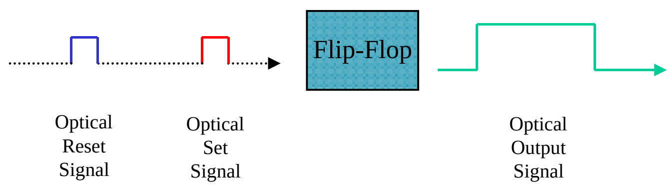

Fig. 1. All-optical flip–flop. Optical output is controlled by optical input signals.

The latchable output power of an all-optical flip–flop, as depicted in Fig. 1, is controlled by *optical* signals. The flip–flop can therefore be triggered directly by signals from other all-optical gates, allowing the creation of highly functional photonic circuits without electronic-conversion components. Since most opportunities for all-optical processing exist at data rates beyond those inexpensively accessible by electronic processing, the flip–flop should operate faster than 10 Gb/s. Furthermore, for practical use in optical communication systems, the device should operate at low power levels ($<$ 1 mW) over a flexible wavelength range, and be transparent to the control-signals' polarization.

A robust, high-speed, all-optical flip–flop applicable to optical communication systems has not yet been demonstrated, although many techniques come close. Flip–flop operation based on polarization bistability in semiconductor lasers is expected to be ultrafast ($\sim$100 Gb/s) [5], but requires orthogonally polarized control pulses that would be expensive to maintain in a fiber-optic system. Diode lasers with an integrated absorption-region have been used at submilliwatt powers over a 28-nm spectral range, but the carrier recombination lifetime is expected to limit repetition rates to a few GHz [6]. This lifetime has also limited the flip–flop operation of a holding beam undergoing dispersive bistability within a resonant-type semiconductor optical amplifier (SOA) [7], [8]. In addition, set and reset in these demonstrations occur either by varying the holding-beam input power (set [7, 8], and reset using a 'negative' optical pulse [7]), or by modulating the holding beam with a closely tuned (0.008 nm) auxiliary signal (reset [8]). Thus, these control signals have a very limited wavelength range.

Using a resonant-type SOA, we demonstrate optical-control techniques that do *not* rely on changing the holding-beam input power. Instead, set and reset are performed by auxiliary optical signals whose wavelengths can vary over a wide range. All-optical flip–flop operation was achieved using the experimental system described in the following section. In Section 3, we present experimental data and explain how set and reset can occur via two different kinds of cross-phase modulation (XPM). The broad wavelength range, low power, polarization dependence, and speed of these techniques are discussed in Section 4.

2 Experiment

We achieved all-optical flip–flop operation using the experimental system shown in Fig. 2. Within the flip–flop (central box), we used a commercial, multi-quantum well (MQW), distributed feedback (DFB) laser driven at about 97% lasing threshold as the resonant-type SOA. The dominant Bragg resonance of the device occurred near the center of the DFB stopband (determined by the grating phase at device facets); the stopband was located at 1547 nm, about 20 nm shorter than the gain peak. The holding beam was coupled into the DFB SOA using a polarization-maintaining (PM) lensed fiber connected to one branch of a 3-dB PM fiber coupler. The holding beam was fixed at a constant input power, tuned close to the DFB Bragg resonance, and its polarization was aligned with the transverse-electric (TE) mode of the SOA gain region.

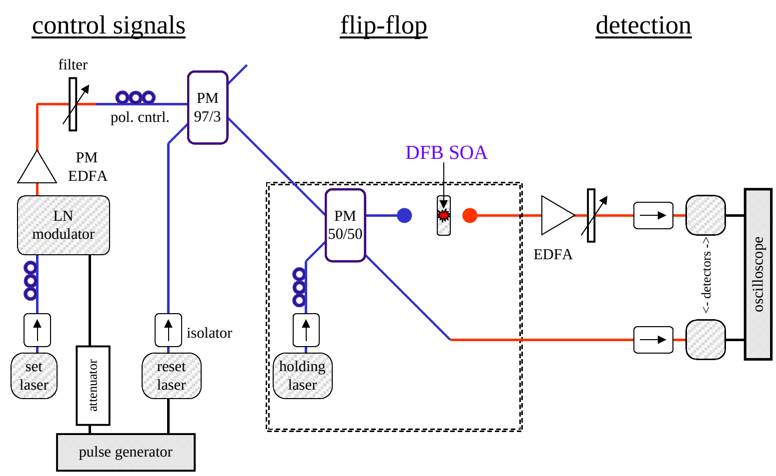

Fig. 2. Experimental system.

Optical-control signals entered the flip–flop via the other input branch of the fiber coupler. Set and reset pulse trains were generated using a single 3.5-GHz-bandwidth pulse generator, and separated in time by traversing different path lengths. 1.31-μm reset pulses were generated by direct modulation, and passed through the dominant port of a 97/3 PM fiber coupler. Using the 3% port for the set signals required an erbium-doped fiber amplifier (EDFA) to boost the optical pulses. [The EDFA is not required if, for example, a wavelength-division-multiplexing (WDM) coupler is used instead.] Set signals were created using a 5-GHz $LiNbO_3$ modulator. The polarization of both signals was controlled and preserved through PM fibers (drawn as blue).

The flip–flop output was amplified by an EDFA for accurate measurements. A tunable filter was used to remove the wideband EDFA amplified spontaneous emission (ASE) and to block the amplified set pulses. All signals were measured with detectors

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having bandwidths exceeding 20 GHz, and a 500-MHz real-time oscilloscope.

3 All-Optical Flip–Flop Operation

Control signals for a typical experiment are shown in Fig. 3(a). The 1567-nm set signals have a peak power of 22 μW, and pulse energy of 330 fJ. This power is measured in the reference arm and scaled to give the power within the tapered fiber before the DFB SOA. The set signal depletes the SOA charge carriers via stimulated recombination, thereby increasing the refractive index at the holding-beam wavelength. This kind of XPM is commonly used for SOA-based interferometric wavelength conversion [4]. We use XPM to shift the SOA Bragg resonance to longer wavelengths, and through the holding-beam wavelength. As a result, the upward-switching threshold of bistability passes through the CW holding-beam input power, forcing the holding-beam output power to switch to the higher state, as seen in Fig. 3(b).

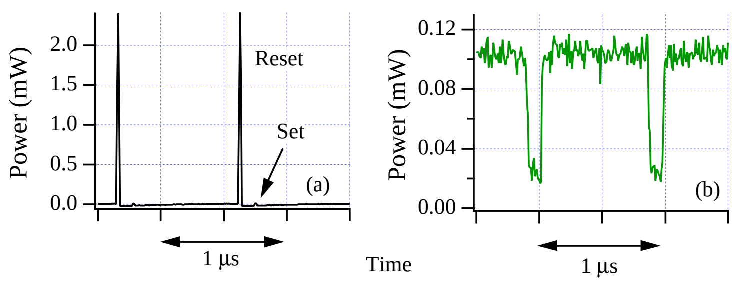

Fig. 3. All-optical flip–flop operation. (a)1567-nm set and 1306-nm reset signals controlling (b) the output power of the 1547-nm holding beam.

The holding-beam power of Fig. 3(b) is forced to return to the lower output state by a 1306-nm reset signal. The 36-pJ reset signals are absorbed by the SOA, thereby raising electrons to the conduction band and *decreasing* the refractive index experienced by the holding beam. (We verified this refractive-index change in a separate experiment by observing the DFB-SOA ASE spectrum shift to shorter wavelengths under the influence of a CW 1306-nm signal.) Reset to the lower state occurs as XPM shifts the Bragg resonance towards shorter wavelengths, forcing the downward-switching threshold of bistability through the holding-beam input power. The reset operation is remarkable not only because it is performed by a 'positive' optical pulse, but also because it changes the refractive index in the *opposite* way as the set pulse.

Control signals toggle the holding beam shown in Fig. 3(b) with a 6.2-dB contrast between 25- and 105-μW output states. This power is scaled to give the amount within the fiber, after the DFB SOA and before the EDFA. Since its input power was 65 μW, the holding beam experiences a small fiber-to-fiber set-state gain. The holding-beam wavelength was limited to a range of 0.004 nm to achieve flip–flop operation. We expect that this spectral range can be increased by using a chirped-grating DFB SOA [9]. Moreover, precise control of the holding-beam wavelength can be achieved by integrating the laser onto the same chip as the DFB SOA, writing both gratings with an electron beam.

The set state shown in Fig. 3(b) is maintained for 0.824 μs, a duration limited by our pulse generator. This demonstration of a long, static set is important because it shows unambiguous latching of the flip–flop, and not just a slow response of, for example, carrier recovery. Used as a bit-length converter, the all-optical flip–flop transforms the 15-ns input pulse to a 824-ns output pulse, simultaneously performing wavelength conversion from 1567 to 1547 nm. This downward bit-length conversion process may

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be useful for transferring data from high-speed, trunk lines to low-speed, local-access systems.

4 Robustness of Control Signals

XPM optical-control techniques allow flip–flop operation over a wide range of wavelengths. Using an external-cavity tunable diode-laser, we achieved set operation from 1533 to 1568 nm, as depicted in Fig. 4(a). The short-wavelength bound of this range is where the set signals loose their ability to saturate the gain. The upper bound was imposed by the poor amplification of the EDFA at long wavelengths. Since 1568 nm is near the peak of the SOA gain spectrum, we expect the set range to extend at least 20 nm to longer wavelengths [10]. This large (> 50 nm) wavelength range is ideal for WDM lightwave systems; signals from a wide range of communication channels can set the optical flip–flop.

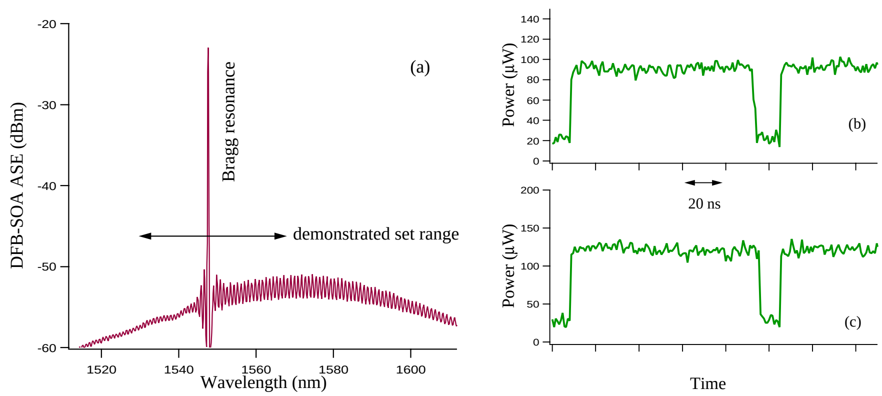

Fig. 4. Broad spectral range of control signals. (a) Demonstrated spectral range of set pulses compared to the ASE spectrum of the DFB SOA. Flip–flop operation using (b) 1537-nm set and 1306-nm reset signals, and (c) 1567-nm set and 1466-nm reset signals

The set-signal wavelength range extends on both sides of the Bragg resonance; flip–flop operation for 1537-nm set signals having a pulse power of 0.9 mW (and energy of 18 pJ) is shown in Fig. 4(b) [reset pulses are the same as for Fig. 3(a)]. Thus, the XPM-setting technique works for signals that interact with the carrier-density distribution at lower *or* higher energies than the holding beam. Although 1567-nm set signals could be as low as 22 μW (probably resulting from high amplification at that wavelength), the minimum allowable optical power at 1537 nm was about 85 μW. These powers are low enough to expect that optical signals directly from the communication system can set the flip–flop without pre-amplification.

The broad wavelength range demonstrated for the set signal is eclipsed by that of the reset signal. We reset the holding-beam power shown in Fig. 4(c) using an EDFA-pump laser at 1466 nm (with pulse widths of 15-ns, and energies of 1.98 and 0.77 pJ for the reset and set signals, respectively). We expect that reset occurs over the intermediate 160-nm spectral range between 1306 and 1466 nm, and extends down to much shorter wavelengths; any optical frequency that excites electrons to the conduction band can potentially reset the flip–flop. Most importantly, we expect that all signals within the 1310-nm communication band can perform the reset function. 1306-nm reset-signal powers were typically required to be above 0.7 mW.

Optical reset was found to be transparent to the polarization of the 1306- and 1466-nm signals. However, flip–flop operation was dependent on the polarization of the set

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pulses. The polarization dependence for gain-saturating pulses is well known, and can be significantly reduced by using techniques such as growing the gain-region depth to the same scale as its width [11].

Since the role of the control signals is only to change the carrier distribution, they are not required to enter the SOA in a co-propagating direction with the holding beam; XPM was observed for control pulses entering either SOA facet. We expect that control signals can even enter from an off-axis direction [6]. Transparency of incident direction allows flexibility in designing the control-signal input system, as well as in specifying the exiting direction of the amplified set pulses.

Our investigation into the high-speed limit of the all-optical flip–flop was limited by the low modulation bandwidth of the directly modulated reset laser (about 1 GHz). Using a pulse-generator rate of 3.44 GHz, we achieved pulse widths of 400 ps and 1 ns for the set and reset signals, respectively. Because of the wide reset pulses, clear flip–flop operation required a '10000000' data pattern, which resulted in a pulse-train period of only 2.4 ns.

The physical limit to the speed of SOA devices is often governed by the carrier recombination lifetime, which can be as low as 200 ps using a high carrier density [12]. High densities can be achieved in DFB SOAs by using spatially chirped gratings, because of an increase in the lasing threshold [9]. In addition, a strong, auxiliary, gain-saturating signal has been used in SOAs to reduce the lifetime to ∼10 ps [13]. We expect our optical-control techniques allow repetition rates faster than the carrier recombination lifetime; set and reset signals cause opposite changes in the refractive index, and may force the system to toggle back and forth at the rate of stimulated emission and absorption. The high-speed limit of this all-optical flip–flop remains to be demonstrated.

5 Conclusion

We have demonstrated robust optical techniques for controlling a resonant-type-SOA-based optical flip–flop. Set and reset are performed by XPM, rather than by changing the input power of the holding beam. Control signals operate at submilliwatt powers over wide wavelength ranges that intersect important communication bands centered near 1310 and 1550 nm. XPM is transparent to the direction of incidence, and reset is independent of polarization. We expect that the set-signal polarization dependence can be eliminated, and that repetition rates greater than 10 Gb/s can be achieved. The latching capability of such a fast, robust all-optical flip–flop would significantly advance the development of all-optical digital processing within communication systems.

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