Remote optical control of an optical flip-flop

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We experimentally demonstrate control of a holding-beam-enabled optical flip-flop by means of optical signals that act in a remote fashion. These optical-control signals vary the holding-beam power by means of cross-gain modulation within a remotely located semiconductor optical amplifier (SOA). The power-modulated holding beam then travels through a resonant-type SOA, where flip-flop action occurs as the holding-beam power falls above and below the switching thresholds of the bistable hysteresis. Control is demonstrated using submilliwatt pulses whose wavelengths are not restricted to the vicinity of the holding beam. Benefits of remote control include the potential for controlling multiple flip-flops with a single pair of optical signals and for realizing all-optical control of any holding-beam-enabled flip-flop.

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All-optical signal-processing devices promise to be essential ingredients for the future of data and communication networks [1]. All-optical *sequential* signal processing—in which the digital output from a device depends on the input signals *and* memory of past signals—is a means of realizing key applications such as data-format conversion, memory, and buffering, as well as core functionalities such as counting and clock division. Performing sequential logic directly within the optical domain—as opposed to converting between optical and electrical signals—has several potential advantages. Processing can occur for signal pulses shorter than 10 ps and can achieve a high-speed repetition rate greater than 40 Gbits/s [2]. For high-capacity, wavelength-division multiplexed systems [3], in particular, avoiding optical-to-electrical-to-optical conversion promises a significant reduction in physical footprint and equipment cost. Moreover, all-optical sequential processing would boost the capabilities of photonic integrated circuits and planar light-wave circuits, whose on-chip, integrated geometry seeks to improve reliability and cost in digital optical networks [4].

A fundamental building block of optical-domain sequential processing is the all-optical flip-flop, whose optical output power is turned "on" and "off" by means of optical set and reset control signals, respectively. Several flip-flop investigations have employed a semiconductor optical amplifier (SOA) [5–10]—a compact (~0.1 to 1 mm) device that exhibits optical gain and a strong nonlinear refractive index (commonly expressed as the linewidth enhancement factor), as well as the capacity for integration into photonic integrated circuits [11] and for supporting switching at 40 Gbits/s and above [2]. Flip-flop operation of a resonant-type SOA (RT-SOA), in which a holding beam undergoes dispersive bistability due to the strong nonlinear refractive index and resonator-based optical feedback, was first realized using an optical modulator to increase and decrease the holding-beam power above and below the switching thresholds of the bistable hysteresis [5–7]; such control does not originate from optical signals. The first reset technique based on optical signals was demonstrated using a closely tuned (within 0.008 nm) optical beam that interfered with the holding beam within the bistable RT-SOA [7]. Set and reset techniques have also been demonstrated using widely detuned (>30 nm) pulses that entered the bistable RT-SOA and varied the optical-power hysteresis by means of cross-phase modulation (XPM) [8,9].

In this paper we demonstrate set and reset techniques in which optical control pulses do not enter the RT-SOA flip-flop but instead act in a remote fashion on the holding beam. The principle of operation is shown in Fig. 1. A continuous-wave (cw) holding beam is fed through an SOA on its way to an all-optical flip-flop. Control signals act on the SOA and vary the holding-beam power by means of cross-gain modulation (XGM). The modulated holding beam then passes through the RT-SOA, where it undergoes flip-flop action as its power falls above and below the switching thresholds of the bistable hysteresis.

Remote optical control has several potential benefits over control techniques whose optical signals enter the flip-flop directly. Fan-out of the holding beam can result in the control of multiple flip-flops with a single pair of set and reset signals. In addition, independent design and optimization can be undertaken for the waveguide paths that feed the remote SOA and flip-flop. Remote optical *reset* was previously

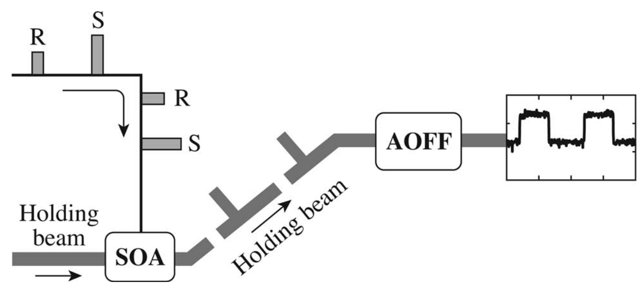

Fig. 1. Principle of operation for remote optical control of an optical flip-flop. Set (S) and reset (R) pulses act on the holding beam via XGM within a remotely located SOA; the modulated holding beam then turns the all-optical flip-flop (AOFF) on and off.

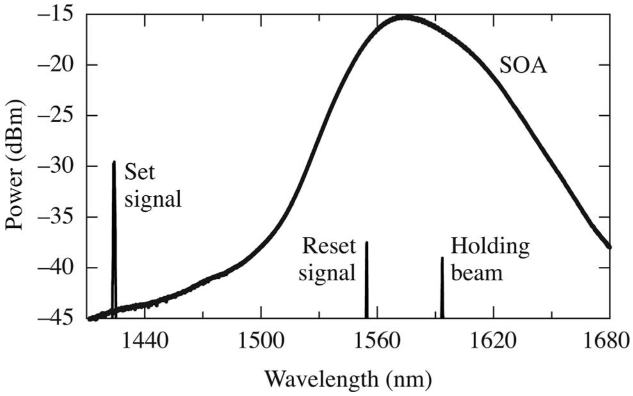

Fig. 2. Spectral overlap of the control-signal, holding-beam, and SOA ASE. The gain experienced by the 1594 nm holding beam is increased by the 1424 nm set signals and decreased by the 1555 nm reset signals by means of gain pumping and gain saturation, respectively.

demonstrated using a different nonlinear process (XPM) to reduce the holding-beam power passing through a dye-filled Fabry–Perot cavity [12]. Our work directs both the *reset* and *set* signals away from the flip-flop and into an integratable SOA, whose optical gain can support large-scale fan-out.

The impact of the control signals on the holding beam can be understood by viewing the spectral overlap of these signals with the SOA-gain spectrum, depicted in Fig. 2. The 1594 nm holding beam falls within the gain spectrum, represented in this figure by the SOA's amplified spontaneous emission (ASE) spectrum; the holding beam therefore experiences a change in power for any change in the SOA gain. The 1424 nm set pulses fall to the short-wavelength side of the gain spectrum and have sufficiently high photon energy to be absorbed and generate charge carriers that provide additional gain for the holding beam. The 1555 nm reset pulses, on the other hand, fall inside the SOA gain spectrum and thus reduce the holding-beam power by saturating the SOA gain.

The experimental setup used to demonstrate remote optical control is shown in Fig. 3. The pulse-generation scheme provided equipment-bandwidth-limited 2 ns set signals and 1 ns reset signals, which entered the SOA with peak powers of 0.43 and 0.02 mW, respectively; these pulses have energies of ~0.9 pJ and 20 fJ, respectively, and are shown in Fig. 4(a). The reset signals required substantially less power because they experienced gain within the SOA, whereas the set signals experienced absorption. Control pulses were combined using a 1420/1550 nm WDM coupler and sent through the SOA in a counterpropagating fashion to demonstrate their flexibility in injection geometry with respect to the holding beam.

A cw holding beam originating from a tunable laser was injected into an SOA with an input power of 0.008 mW. The SOA was a commercial, high-speed 1 mm device from the Center for Integrated Photonics, driven at 86 mA to provide ~18 dB gain. The cross-gain modulated holding beam, having passed through the SOA, is shown in Fig. 4(b). The holding beam injected into the flip-flop exhibited a baseline power of 0.39 mW and was increased by 0.02 mW and decreased by 0.22 mW by the set and reset signals, respectively.

The wavelength of the holding beam was tuned 0.13 nm from a strong resonance of the RT-SOA; this close proximity is required for dispersive bistability. The control-signal wavelengths, however, are not restricted to the close vicinity of the holding-beam wavelength. The set and reset wavelengths were tuned 170 and 39 nm from the holding beam, respectively, and are each expected to have a wavelength range of operation exceeding 40 nm.

The bistable output from the all-optical flip-flop is shown in Fig. 4(c). The particular bistable device used was a Fabry–Perot SOA (FP-SOA) driven at 98% lasing threshold by an injection current of 63.3 mA. The set-signal-increased portion of the holding beam switched the flip-flop "on," and the output power remained latched in the "on" state until the reset-signal-reduced portion of the holding beam entered the flip-flop.

The measured all-optical flip-flop operation was sufficient to demonstrate these remote control techniques, but the flip-flop speed and output-power performance were limited by our experimental equipment. The power switched on and off with a rise and fall time of 1.5 and 0.6 ns, respectively. These times were comparable with the available control-signal pulse widths and to the oscilloscope bandwidth of 1.5 GHz. XGM-induced changes in the holding-beam power are governed by the SOA's effective carrier lifetime, which can be as small as 5 ps in commercial devices [2], and which can be reduced by increasing the holding-beam power because of stimulated recombination [13]. The repetition rate ("on" to "off" to "on") is limited by the SOA recovery time between control signals as well as by the response time of the particular flip-flop. Nonlinear SOAs have been used for experiments at 40 Gbits/s and beyond [2], and future work will aim at high-speed demonstrations.

The measured on/off switching contrast of 2 dB was impaired by the lack of an optical bandpass fil-

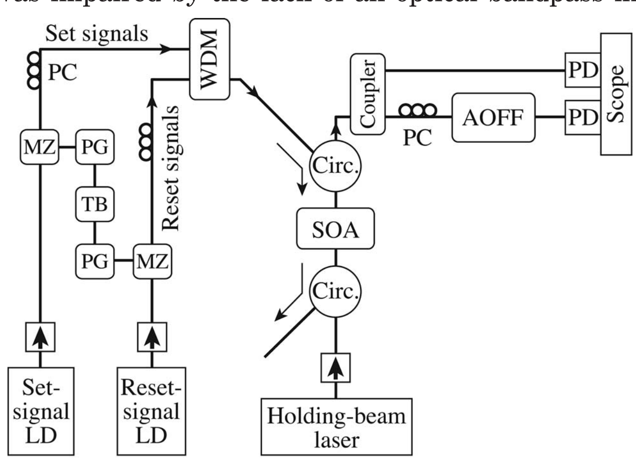

Fig. 3. Experimental setup: LD, laser diode; MZ, Mach–Zehnder modulator; PG, pulse generator; TB, trigger box; WDM, wavelength-division multiplexing coupler; Circ, circulator; PC, polarization controller; SOA, semiconductor optical amplifier; AOFF, all-optical flip-flop; PD, photodiode.

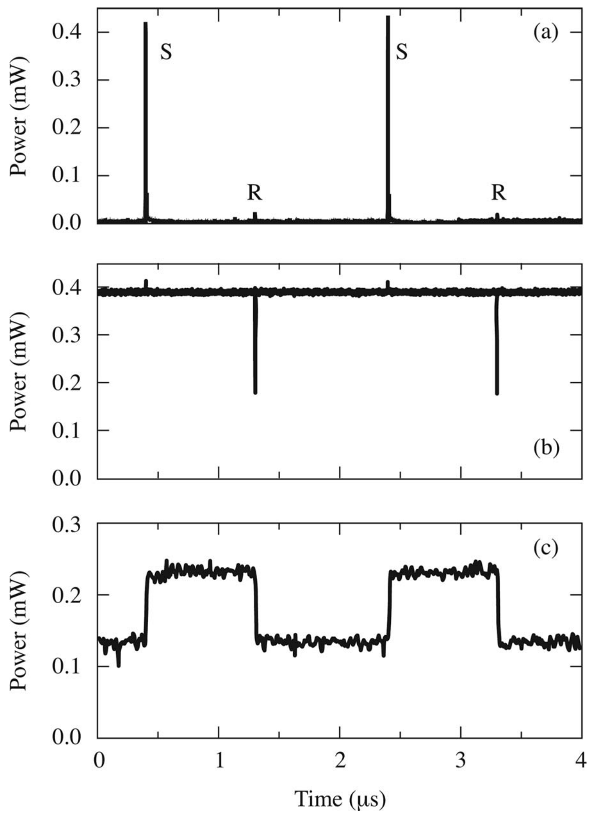

Fig. 4. All-optical flip-flop operation. (a) Control signals injected into the remote SOA, (b) XGM holding beam injected into the flip-flop, (c) optical power transmitted through the flip-flop.

ter; an ASE-filtered contrast ratio of 3 dB was estimated based on spectral measurements. Spectral measurements also revealed an optical signal-to-noise ratio of 38 and 32 dB for the set and reset states, respectively (using a noise-measurement bandwidth of 0.1 nm). The set-state power of 0.24 mW exiting the FP-SOA was substantially impacted by a nonoptimal 9 dB output-coupling loss.

Flip-flop operation occurred for any polarization state of the optical control signals but was sensitive to the state of the holding beam. The latter polarization state alters the amount of light coupled into the nonlinear resonator mode and thus changes the injected optical power with respect to the bistable switching thresholds. The holding-beam power was set close ($\sim 10\ \mu$W) to the upward switching threshold to accommodate the small, 20 μW increase in power [as seen in Fig. 4(b)] effected by the equipment-limited 0.43 mW set pulse. We expect that an increased set power, while remaining below 1 mW, would relax the polarization dependence on the holding beam.

Since the control signals act in a remote fashion, the particular flip-flop used in our experiment can be replaced with, in principle, *any* holding-beam-enabled flip-flop. Using a distributed-feedback SOA instead of an FP-SOA, for example, would have several advantages, including the capacity for integration into a monolithic photonic circuit and the ability to improve the switching contrast by introducing grating nonuniformities [14,15].

In conclusion, we have demonstrated all-optical flip-flop operation using optical control signals that act in a remote fashion, outside the bistable flip-flop. Control signals have submilliwatt power and wavelengths that are not restricted to the vicinity of the holding beam. Remote action allows for the potential of controlling multiple flip-flops with a single pair of control signals; this fan-out is supported by the SOA gain. Moreover, the remote nature of these control techniques allows set and reset operations to be performed in the optical domain for, in principle, any holding-beam-enabled optical flip-flop.

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