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All-optical delay line using semiconductor cavity solitons

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An all-optical delay line based on the lateral drift of cavity solitons in semiconductor microresonators is proposed and experimentally demonstrated. The functionalities of the device proposed as well as its performance is analyzed and compared with recent alternative methods based on the decrease of group velocity in the vicinity of resonances. We show that the current limitations can be overcome using broader devices with tailored material responses. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2828458]

Future photonic networks will include all-optical routers (e.g., Refs. 1 and 2) for high-speed switching of data packets. As a consequence, the possibility of all-optical buffering of information is needed, if several packages of data are impinging simultaneously onto a router.[1,2] The appealing solution is to "park" one of the data streams in an all-optical delay line until the router is available again (see, for example, Ref. 2 and references therein for a review). This delay should be continuously tunable. The state-of-the-art techniques for achieving all-optical delays are based on a slowing down of the light, i.e., they rely on *dispersion* modifying the (longitudinal) *group velocity*. Nearly all proposed systems use some kind of resonance (electromagnetically induced transparency,[3] stimulated Brillouin scattering,[4] Raman scattering,[5] quantum dots and quantum wells,[6,7] fiber Bragg gratings,[8] and microresonators[9]) though a promising recent scheme uses wavelength conversion.[10]

In this letter, we propose a different approach to all-optical delay lines and we give a proof-of-principle demonstration based on single pulse operation. This approach is based on injecting an optical bit stream into an optical resonator, creating cavity solitons (CSs) (see, e.g., Ref. 11 and references therein for a recent review) that drift *transversely* with a controllable velocity. CSs are miniature beams of light, self-localized through the material nonlinearity and stored within an optical cavity. They have robust shape and can be very small. Those in our experiment (see the inset of Fig. 1) have diameter around 10 μm, in a cavity a few microns thick.

A CS can be created by a single pulse of light, and remains fixed at the point of addressing in a transversely homogenous system. To make a delay line, we take advantage of the fact that a CS couples easily to any perturbation of the translational symmetry and will, therefore, drift transversely on any parameter gradient.[11,12] The CS, thus, behaves like a particle, but with non-Newtonian dynamics: its *velocity*, rather than its acceleration, is proportional to the applied "force." Although unavoidable inhomogeneities provide pinning centers for the CS (see inset of Fig. 1), appropriate externally imposed parameter gradients allow full control of both the position[13] and motion of a CS in the transverse plane. In particular, a CS can be induced to drift away from the point where it was created, thus clearing the way for the addressing of a new CS. A succession of drifting CS can, thus, be formed, creating a spatial replica of an input bit stream, say from an "input fiber." Since the CS continuously emits light, a time-delayed version of the input bit stream can be read out, say by an "output fiber," at any point downstream. The duration of the delay is controllable by selecting different pick-off points (see Fig. 2 below), or by changing the gradient and, hence, the drift speed. The latter can be done optically and fast.

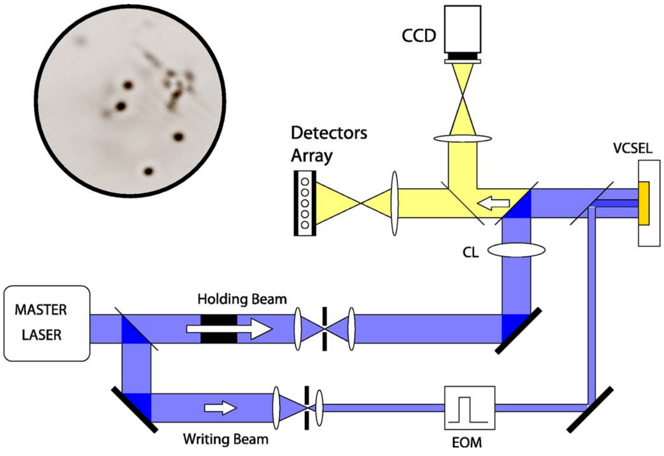

FIG. 1. (Color online) Experimental set-up. vertical cavity surface emitting laser (VCSEL). cylindrical lens (CL). Electro-optic modulator (EOM). tunable master laser (ML). Inset: Transverse profile emission (negative image) of a 200 μm section VCSEL, in the regime of CS existence under injection by a broad holding beam. Four CS are present.

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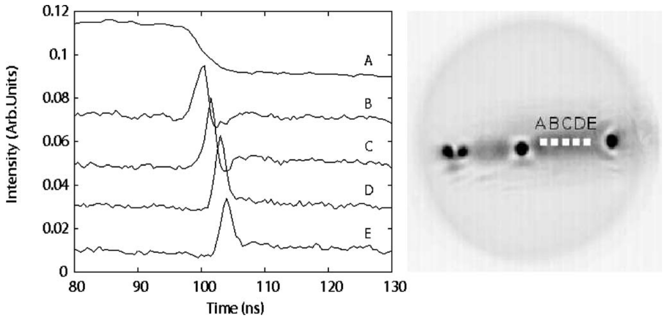

FIG. 2. Passage of a cavity soliton in front of a linear array of five detectors (A–E). Left panel: time traces of these detectors, displaced vertically by 0.02 units for clarity. Detector A monitors the point addressed by the writing beam, applied at time $t=0$. Right panel: positions of the detectors in the transverse plane (indicated by squares). The area monitored by each detector has a diameter of less than 7.2 μm and the separation between neighboring detectors is 8.9 μm. Also shown is a time-averaged output image of the VCSEL during the CS drift (charge coupled device camera exposure time of about 1 ms).

Since telecom applications require fast, robust, and compact systems, we implement a CS delay line in semiconductor devices. CS existence and individual addressing have been demonstrated in broad-area vertical-cavity surface emitting lasers (VCSEL).[14]

The experimental set-up, as shown in Fig. 1, is similar to that of Ref. 14. A broad-area (200 μm diameter) VCSEL is injected with a collimated holding beam. System control parameters are: detuning between the frequencies of the cavity resonance and of the injected signal; intensity of the injected field; VCSEL pumping current. These parameters are set in the region where the CS exists.[15] A cylindrical lens is used to shape the holding beam in the form of a stripe, which channels the CS sequences and their movement onto a line. A line of five fast (350 MHz bandwidth) avalanche photodiode detectors is placed in a plane imaging the VCSEL output, in order to monitor the dynamics at several points along the delay line. To induce CS drift along the line, a phase gradient is introduced by tilting one of the mirrors that aligns the holding beam with respect to the optical axis of the VCSEL. We implement, as a first approximation to a "1," a perturbation in the form of an optical beam [writing beam (WB)] with a waist of about 10 μm, switched on and off by an electro-optic modulator (EOM). This perturbation has fast ($\approx$0.6 ns) rise and extinction times but, due to technical limitations of the EOM driver, a fixed duration of around 100 ns. In fact, in Ref. 15 we show that CS switching occurs when the writing pulse overcomes a critical energy and the overall switching time can be shortened down to less than one nanosecond.

In the left panel of Fig. 2 we show the sequence obtained when addressing the point A (see the right panel of Fig. 2) with the writing pulse. The relevant dynamics occurs at the end of the WB pulse, when a CS is emitted from the address point A and drifts along the delay line under the influence of the phase gradient. Its optical emission is successively picked up by detectors B–E, registering at E after a delay of 7.5 ns. The distance between points A and E is 36 μm, so the CS average speed is about 4.7 μm/ns. This drift length of 36 μm is the largest obtainable in our current devices, because of the presence of defects such as those which trap the stationary CS visible in the right panel of Fig. 2. Noting that the detector array could be replaced by a read-out fiber array, these measurements provide a proof-of-principle demonstration of an all-optical delay line based on drifting cavity solitons in semiconductor amplifiers.

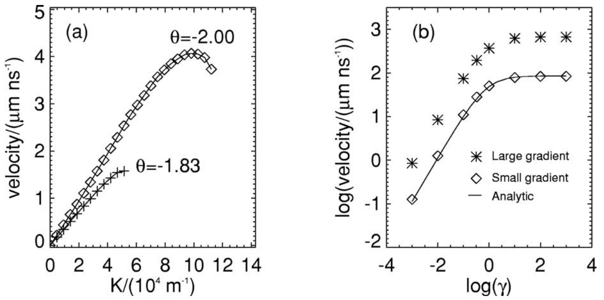

FIG. 3. (a) Drift speed vs phase gradient (wavevector tilt of holding beam) for $\gamma=0.01$ and two cavity detuning values. Here, $\kappa \approx 100\times 10^9$ s^{-1}. (b) Log-log plot of CS drift speed vs γ for a fixed detuning ($\theta=-2$) and for two values of the gradient: (stars) $K=2.38\times 10^4$ m^{-1}; (diamonds) $K=1.91\times 10^5$ m^{-1}. Here, $\kappa \approx 650\times 10^9$ s^{-1}.

The performance of a delay line is commonly assessed by two criteria: the delay-bandwidth product M or, for digital signals, the ratio between delay and the bit period and the bandwidth itself. M corresponds to the maximum number of bits which can be stored in the delay line.[16] In our system, the delay Δt is given by $\Delta t = L/\nu$ where L is the drift length and ν is the CS drifting speed. Delay tunability is obtained straightforwardly by choosing the position of the read out point of the bit stream along the length L. Δt depends also on ν which is a function of the gradient strength. Though ν could be decreased in order to increase the delay, it turns out that ν limits the writing rate of the CSs, i.e., the system bandwidth. This can be understood when considering that the incoming bit stream is addressing a single point of the device and that a CS, once written, must clear out the addressing point before the next bit can be written. Numerical simulations indicate that a CS should have drifted around five diameters between one writing pulse and the next [i.e., during the "return to zero" (RZ) stage of the bit stream], in order to avoid interactions which might introduce timing jitter and, hence, bit errors. Calling τ_0 the RZ time of the incoming signal, the above condition reads $\tau_0 > 5a/\nu$, where a is the CS width. In our proof-of-principle demonstration, $\tau_0 > 10.6$ ns. In Ref. 15 we show that a CS can be written in around 1 ns, then we infer that the total bit interval cannot be less than 11.5 ns, which limits the bandwidth to about 90 Mb/s and leads to $M \approx 0.7$. Larger values of M can be straightforwardly obtained in our scheme using resonators of larger transverse dimension and improved homogeneity. Although this is challenging, there are in principle no barriers to manufacturing delay lines several millimeters long, gaining more than two order of magnitude on the value of M. On the other hand, the bandwidth can be improved by increasing the CS drifting velocity.

Using spatiotemporal equations describing the dynamics of the optical field and of the carriers inside the VCSEL cavity,[17] we are able to calculate the CS drift speed both perturbatively and numerically as a function of the system parameters and material characteristics. For a holding beam phase gradient of the form $P(x,y)=P_0\, exp(iKx)$, the velocity of the CS maximum is plotted in Fig. 3(a) as a function of the phase gradient strength K and for different cavity detunings θ. The drift speed at first increases linearly with K while for larger gradients the (numerically obtained) velocity eventually saturates. Beyond the displayed range the CS becomes unstable. Figure 3(a) is obtained for parameter values appropriate for the experimental system[14] and it is worthwhile to note that calculated CS drift speeds are in agreement with the experimental findings.

For semiconductor microcavities, the carrier lifetime is considerably longer than the photon lifetime and, hence, it is expected to limit the CS drift speed[18] and CS writing time.[15] We explore theoretically the dependence of CS drift speed on carrier lifetime. Figure 3(b) shows v as a function of γ, defined as the ratio between the carrier decay rate and the field decay rate κ. CS speed increases roughly linearly when $\gamma < 1$, and then it reaches a limit value, where photon lifetime becomes the limiting factor. This holds for the small speed perturbative limit (lower curve) as well as for the large speed case (upper curve). Figure 3(b) has been calculated with a larger κ than in Fig. 3(a). This leads to an improvement of the figure of merit, since CS size a scales with the square root of κ. According to Fig. 3(b), operating the device at $\gamma \approx 0.33$ ($\log \gamma \approx -0.5$) would lead to a reduction of the CS writing time down to 5 ps, while drift speed would become $v \approx 200\ \mu\text{m/ns}$. In these conditions, the limit for τ_0 is less than 0.1 ns, taking the system bandwidth to 10 Gbit/s. Adjustment of γ is possible by known methods to shorten carrier lifetime (see, e.g., Refs. 19 and 20). We mention that very fast gain recovery times compatible with 200 GHz modulation bandwidth have recently been demonstrated in quantum dot amplifiers.[21]

In terms of functionalities, our system provides robust all-optical pulse reshaping of the incoming optical pulse. Because of the threshold response of the CS excitation, amplitude fluctuations of the incoming signal will be eliminated, improving the quality of the output signal. Moreover, the bit length will also be formatted to the same value fixed by the ratio between the CS size a and the drift speed v. This reshaping of the bit stream can be useful in a telecom network to avoid deterioration of the signal. Thus, this functionality may be implemented as an alternative method to all-optical pulse restoring.[1,22,23]

On the other hand, we point out that our scheme cannot be used straightforwardly for delaying analogue signals or binary signals where information is stored in the bit length (NRZ coding, for example).

Summarizing, the measurements and simulations presented in this report provide clear evidence of controllable drift of cavity solitons in semiconductor-based devices and open a promising approach to all-optical delay line applications.

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