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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 microresonators9) 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 homogeneous 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 position13 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 down-stream.

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The drift speed at first increases linearly with \( t \), while \( \tau \) eventually saturates. Beyond the displayed range the CS becomes unstable. Figure 3(a) shows \( \tau \) as a function of the phase gradient strength \( K \) and for different cavity detunings \( \theta \). 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 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 and CS writing time. We explore theoretically the dependence of CS drift speed on carrier lifetime. Figure 3(b) shows \( \nu \) as a function of \( \gamma \), defined as the ratio between the carrier decay rate and the field 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 orders 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, 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 \( \theta \). 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 and it is worthwhile to note that calculated CS drift speeds are in agreement with the experimental findings.

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decaying rate $\kappa$. 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 $\kappa$ 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 $\kappa$. According to Fig. 3(a), operating the device at $\gamma \approx 0.33$ ($\log \gamma = -0.5$) would lead to a reduction of the CS writing time down to 5 ps, while drift speed would become $v \approx 200 \mu$m/ns. In these conditions, the limit for $\tau_p$ is less than 0.1 ns, taking the system bandwidth to 10 Gbit/s. Adjustment of $\gamma$ 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 restorers.\(^{1,22,23}\)

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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17. See EPAPS Document No. E-APPLAB-92-010801 for theoretical model and numerical simulations details. This document can be reached through a direct link in the online article’s HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html).