Dispersionless and Tunable Slow Light in Bragg Gratings

Joe Mok, Martijn de Sterke, Ian Littler and Benjamin J. Eggleton

The ability to slow and delay optical pulses is intriguing, and has significant applications for telecommunications and other areas. Slow light is usually obtained by having large dispersion over a narrow frequency band. The bandwidth of these systems is therefore limited, leading to pulse broadening in addition to the delay—which imposes a tradeoff between the delay and the system's bandwidth. We have shown that, by introducing nonlinearity in the slow-light system, a soliton can be formed. The pulse can then travel slowly over arbitrarily long distances without broadening, permitting the generation of arbitrarily large delays.

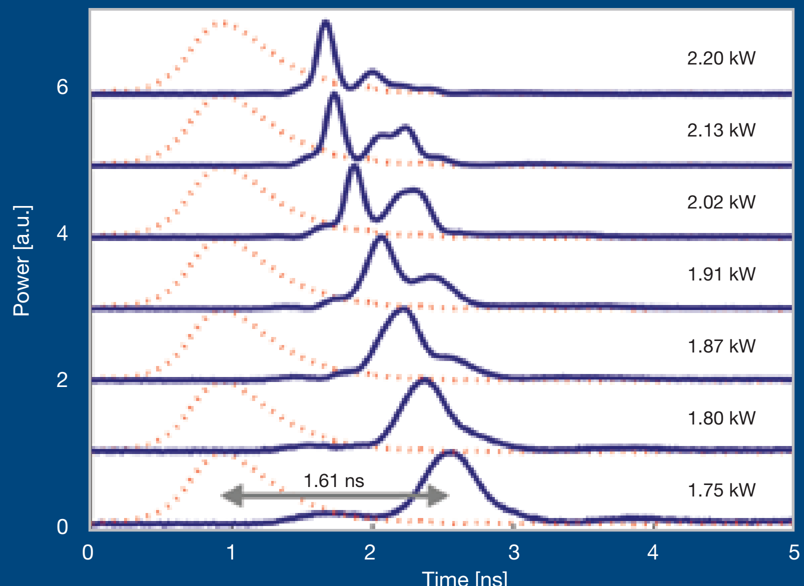
We implement this in a Bragg grating, written in the core of a silica optical fiber. Bragg gratings have a spectral bandgap where light cannot propagate and is strongly reflected. Just outside the bandgap, light propagation is allowed, but the group velocity is drastically reduced, and varies in a narrow spectral window between zero and the normal speed of light (c/n), allowing large, tunable pulse delays.

Slow propagation arises because light is constantly reflected back-and-forth inside the grating, leading to a path length much longer than the grating length. However, as in most slow-light systems, the strongly wavelength-dependent group velocity implies large dispersion, which, at low intensities, results in severe pulse broadening, thereby limiting the pulse delay.

We sent high-intensity pulses through the Bragg grating.[1] In addition to retaining the desired features just mentioned, high intensities led to the formation of gap solitons.[2] Like all solitons, gap solitons retain their shape upon propagation and do not suffer from dispersive broadening. Here this is so because energy in the wings of the pulse is constantly Bragg reflected by the grating toward the high-intensity pulse center. The distance over which the soliton can propagate without broadening is, in principle, limited only by the grating length.

The figure shows the time-resolved output intensity when 0.68-ns pulses were launched into a 10-cm fiber Bragg grating at peak powers around 2 kW. The largest delay we obtained was 1.6 ns, or 2.4 × the input pulse width, corresponding to a group velocity of 0.23 c/n. As the peak power is varied, the delay is tuned because the bandgap wavelength shifts relative to that of the pulse due to nonlinear effects, thereby varying the pulse's group velocity. The output pulse is narrower than the input pulse, consistent with simulation, indicating dispersion being canceled.

Our vision is to implement such a slow-light system in a chalcogenide waveguide. Chalcogenide is a highly nonlinear material that can lower the peak power requirement to a few watts. Chalcogenide glasses also exhibit large photo-induced index changes,[3] which permit longer delays in shorter device lengths.[4] Furthermore, thermal poling of chalcogenide glass can induce a significant second-order susceptibility[5] that leads to the possibility of electrically tunable delay via the electro-optic effect.[6] Since this is a planar geometry, all these features can be implemented in an integrated environment, making the device more compact and easier to control.



Solid lines show the delayed output pulses measured at a range of incident peak powers. The dotted line shows the undelayed output pulse having traveled at a group velocity of c/n and acting as a reference.

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Slow-Light Signals Travel at Sonic Speed Across Micro-Laser Arrays

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Closely packed micro-laser cavities such as vertical cavity surface-emitting laser (VCSEL) arrays can interact through their evanescent fringe-fields, whereby radiation confined in one cavity causes stimulated emission and carrier depletion in neighbor cavities.[1] Active coupling differs from optical interference in "passive" photonic lattices, as here the radiation in one cavity modulates the complex gain of nearby cavities. Such nonlinear cross-cavity interactions endow active photonic lattices with a rich, multifaceted behavior.

When a constant, identical bias is applied to all cavities, a spontaneous settling into a phase-locked steady state occurs, where the phase difference ("phasing") among neighbor cavities is fixed in time. The dynamic properties of phase-locked arrays are of particular interest. Since each cavity possesses a characteristic (slow compared to optical) oscillation frequency, the array behaves as a coupled oscillator lattice.

Our numerical simulations demonstrate that driving one of the cavities generates periodic variations in amplitude and phase around the steady-state values, propagating over the entire array. The dispersion for such lattice waves has been derived for small amplitude variations around the steady state.[2,3] Stable, low-frequency (GHz) optical waves exist in a wide region of coupling strengths and line-width factor values. For parameters near the stability boundary, the decay constant approaches zero, and these waves propagate over a long range. (Beyond that stability boundary, the lattice breaks into self-excited oscillations and steady state does not exist.)

Part (c) of the figure shows the group velocity vs. propagation wavenumber κb for waves on an in-phase locked array. Although the group velocity becomes zero at the band edges, the decay constant has a maximum there, prohibiting practical applications. The minimum useful group velocity occurs along the stability boundary corridor.

Typical propagation speeds of km/s show a 5-orders-of-magnitude reduction from the vacuum light speed *c*. Although the group velocity decreases with the coupling strength *Y*, the coupling cannot go to zero in order to maintain coherence. Because such waves involve oscillations in the coupled fermion-boson gas (carrier and photon densities) near the material sound speed, they are characterized as photonic sound.[2]

Part (d) shows wave propagation vs. time from a 1 × 49 VCSEL array simulation. The central cavity is driven by a current $I_D = 1.25\ I_{th}$ on top of the common bias current $I_o = 3.15\ I_{th}$. The Mach cone slope yields $v_{gr} = 4.9$ km/s for cavity separation b = 2 μm. The parameters are typical for narrow aperture VCSELs. Recently, 9 × 9 photonic defect arrays with μm cavity separation have been reported.[4]

Part (e) shows waves radiating from the center of a 2D array driven at frequency $\kappa b=\pi$.

Spreading of the imposed modulation from one cavity over an entire array promises many applications in optical processing. All-optical functions, such as signal multiplexing and wavelength switching, can occur naturally in a photonic fabric of coupled micro-lasers. Slowing down the speed of the input optical signal also increases the information density and allows parallel bit processing on a micro-chip size scale. Electronic bias control applied to a phased array can also lead to fast optical beam steering without micro-mechanical parts.

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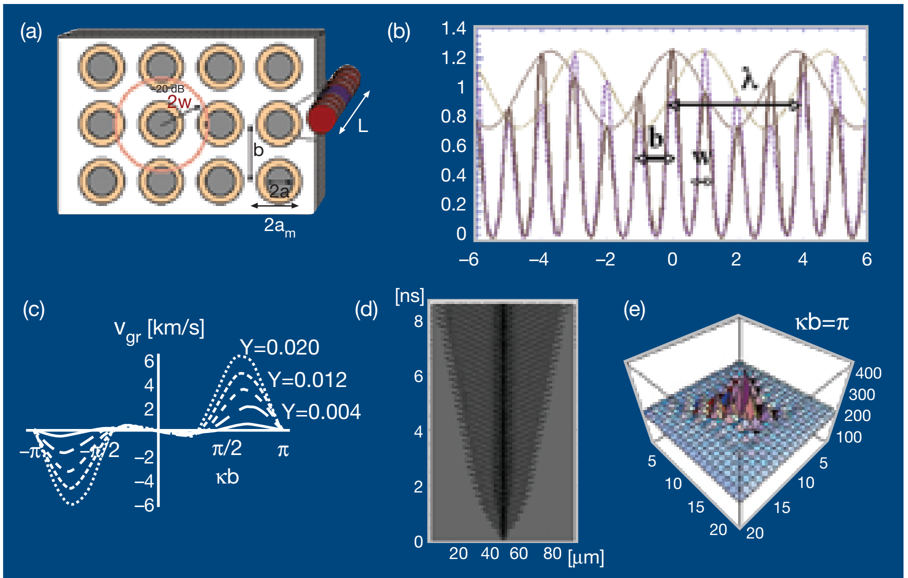

(a) An in-plane 2D VCSEL array. (b) Coherent oscillations of the amplitude of the Gaussian mode envelope in each cavity, propagating over a 1D array. (c) Slow light group velocity vs. wave number. (d) Contour plot of waves in an array cavity power as they spread in time over a 1D array driven at the middle cavity. Numerical simulation uses the coupled-cavity rate equations. (e) Snapshot of power waves propagating over a 2D array driven at the center.