Creating very slow optical gap solitons with a grating-assisted coupler

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We show that optical gap solitons can be produced with velocities down to 4% of the group velocity of light using a grating-assisted coupler, i.e., a fiber Bragg grating that is linearly coupled to a non-Bragg fiber over a finite domain. Forward- and backward-moving light pulses in the non-Bragg fiber(s) that reach the coupling region simultaneously couple into the Bragg fiber and form a moving soliton, which then propagates beyond the coupling region. Two of these solitons can collide to create an even slower or stopped soliton.

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There is great interest in slow light [1]. Spectacular slow light results have been achieved in Bose-Einstein condensates [2], but realizations in room temperature solid state materials are desirable for many applications. Two applications that motivate work on slow light are optical memory and buffering. For slow group velocities that are due to proximity to a resonance, the slowest achievable speeds and the greatest bandwidths are limited by the finite width of the resonance (even when measures are taken to cancel out dispersion from the resonance) [3]. Optical gap solitons (GSs) are an attractive alternative medium for optical memory or buffering because they can exist in a fiber Bragg grating, and the speeds may be arbitrarily slow (or zero) [4,5]. The length of the solitons is limited by the strength of the Bragg scattering and the damage threshold of the material. The solitons below are of cm length, but lengths less than a mm are accessible with current technology.

Suitable media for optical GS propagation are available, but it can be difficult to create the correct initial and/or boundary conditions in the first place. Methods proposed for producing slow optical GSs include: (1) apodized (gradually varying modulation depth) fibers [6], as was employed in [7], (2) growing a soliton in-place with distributed [8] or localized amplification [9], and (3) colliding faster moving GSs with each other [10] or with fiber defects [11]. The slowest solitons produced to date—16% of the speed of light in vacuum—have used apodized Bragg gratings [7]. The greatest limitation with the apodized Bragg grating approach is that the slowness depends on the strength of the Bragg scattering, which is limited by the maximum modulation depth of the refractive index. Optical GSs have heretofore not been grown in-place. Moreover, to get a quiescent soliton from an inelastic collision of faster GSs, the initial GS velocities must begin with speeds less than 10% or 20% of the group velocity [10], which is still beyond what has been achieved experimentally [7].

We propose a method to produce optical GSs using a fiber Bragg grating (FBG) and a non-Bragg fiber (or fibers) that are coupled over a finite distance, as illustrated in Fig. 1. Such a system is known as a grating-assisted coupler [12], and has been manufactured as long ago as 1994 [13]. We show that if light pulses of the right amplitudes, widths, phases, and synchronization times are sent into the non-Bragg fiber(s) in the forward- and backward-moving directions such that they reach the interfiber coupling region simultaneously, a slow GS can be created in the FBG.

A FBG may be coupled to a non-Bragg fiber by removing some of the cladding and bringing the fibers close together so that the evanescent waves of one fiber extend into the core of the other [12–15]. This results in linear coupling between the light in the two fibers. The closer the fibers, the stronger is the coupling. As shown in Fig. 1, our coupling region is finite and varies smoothly from uncoupled to maximally coupled regions.

The system dynamics are described by the equations

$$0 = ik_0' u_{1,t} + iu_{1,z} + \kappa v_1 + \lambda(z)\left(\frac{A_2}{A_1}u_2 + \frac{A_3}{A_1}u_3\right) + C(|u_1|^2 + 2|v_1|^2)u_1, \tag{1a}$$

$$0 = ik_0' v_{1,t} - iv_{1,z} + \kappa u_1 + \lambda(z)\left(\frac{A_2}{A_1}v_2 + \frac{A_3}{A_1}v_3\right) + C(2|u_1|^2 + |v_1|^2)v_1, \tag{1b}$$

$$0 = ik_0' u_{2,t} + iu_{2,z} + \lambda(z)u_1, \tag{1c}$$

$$0 = ik_0' v_{2,t} - iv_{2,z} + \lambda(z)v_1, \tag{1d}$$

$$0 = ik_0' u_{3,t} + iu_{3,z} + \lambda(z)u_1, \tag{1e}$$

$$0 = ik_0' v_{3,t} - iv_{3,z} + \lambda(z)v_1, \tag{1f}$$

where z is the spatial coordinate, t is time, u_1 (v_1) is the amplitude of the envelope of the forward-moving (backward-moving) electric field in the FBG, and $u_{2,3}$ and $v_{2,3}$ are the fields in the non-Bragg fiber(s). Subscripts in the independent variables t and z denote differentiation. The reciprocal of the group velocity is $k_0' = v_g^{-1} = \frac{d}{d\omega}[n(\omega)\omega/c]_{\omega_0}$, κ is the Bragg scattering coefficient,

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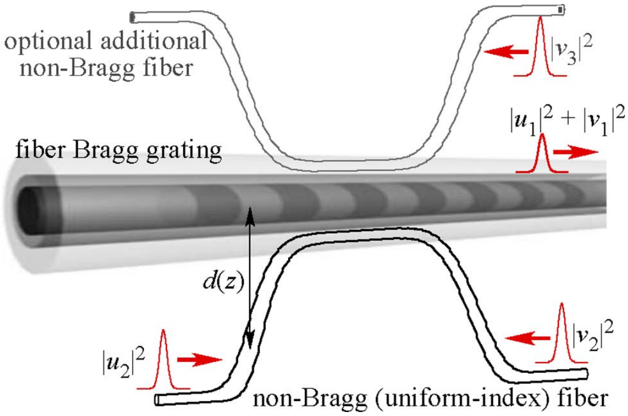

Fig. 1. (Color online) Schematic drawing of a Bragg fiber and a non-Bragg fiber that are brought close together so that their evanescent waves overlap and the light couples between the fibers. Light pulses are sent into both ends of the non-Bragg fiber and reach the coupling region at the same time. The shape and intensity of the pulses are adjusted such that they create a GS in the FBG, along with additional nonsoliton radiation. Alternatively, two non-Bragg fibers can be used, with counterpropagating pulses u_2 and v_3 input into opposite ends of these two fibers.

which scatters light back into the same fiber, $\lambda(z)$ is the interfiber codirectional coupling coefficient (contradirectional interfiber coupling is taken to be zero), $A_j = \int \mathrm{d}x\mathrm{d}y|u_j(x,y,z,t)|^2/|u_j(0,0,z,t)|^2 = \int \mathrm{d}x\mathrm{d}y|v_j(x,y,z,t)|^2/|v_j(0,0,z,t)|^2$ are the areas of the transverse light modes in the FBG and non-Bragg fibers [14,15], and $C = 2\pi\omega_0[n(\omega_0)c]^{-1}3\chi^{(3)}(\omega_0;\omega_0,-\omega_0,\omega_0)$ is a self-phase modulation coefficient. We used typical physical parameters for bulk fused silica at wavelength $0.8\,\mu$m [16]: The index of refraction is $n_0 = 1.45$, the Kerr coefficient is $C = n_2^I n(\omega_0)\omega_0/(2\pi)$, with $n_2^I = 2.8\times10^{-16}\,\mathrm{cm}^2/\mathrm{W}$, and the Bragg scattering coefficient κ is proportional to the modulation depth of the grating; we use $\kappa = 2.7\,\mathrm{cm}^{-1}$. The interfiber (codirectional) coupling, due to overlap of the evanescent fields with the cores of the adjacent fibers, depends on the distance $d(z)$ between the fibers. We take the coupling coefficient to be $\lambda(z) = A_{\mathrm{cpl}}\exp[-(z/z_{\mathrm{cpl}})^4]$, with $A_{\mathrm{cpl}} = 1\,\mathrm{cm}^{-1}$ and $z_{\mathrm{cpl}} = 0.2\,\mathrm{cm}$, i.e., a super-Gaussian, which is fairly flat in the middle and smoothly but quickly decreases to zero at the edges. The length of the interfiber coupling region was chosen so that pulses can switch once from the non-Bragg fiber(s) to the FBG, but not back again. Smooth interfiber coupling is due to the gradual bending of the non-Bragg fiber and ensures no backreflections.

Equations (1) omit the Kerr effect in the non-Bragg fiber, and coupling of light to the material density at either low wavenumbers (electrostriction) [17,18] or high wavenumbers (Brillouin scattering) [18]. The Kerr effect in the non-Bragg fiber and the Brillouin scattering can be reduced to negligible levels by (1) using short lead-ins to the interfiber coupled region, (2) choosing thicker non-Bragg than Bragg fibers, so that more energy can be delivered to the FBG with less intensity in the non-Bragg fiber(s), and (3) using *two* non-Bragg fibers (see Fig. 1) and sending one pulse into each in opposite directions [e.g., u_2 and v_3 (or v_2 and u_3)], so that Brillouin backscattering is not seeded. Low wavenumber acoustic waves are critical for optical GSs when the soliton velocity is less than or approximately equal to $v_g/300$ because the soliton has a momentum minimum near that velocity [18]. We did not attain such a slow velocity, so low wavenumber acoustic fields need not be included on these grounds unless yet slower solitons are produced (e.g., through collision [10]).

We choose pairs of input pulses to go into opposite ends of the non-Bragg fiber(s), and then optimized over parameters of the initial pulses in the non-Bragg fibers so as to obtain slow GSs in the FBG. We succeeded in creating GSs in the FBG with velocities as slow as 4% of the group velocity. Figure 2 shows such a simulation. Light pulses enter the non-Bragg fiber(s) from opposite ends [panel (a)], and reach the region with nonzero interfiber coupling simultaneously. These light pulses are initially at positions $z = \pm11\,\mathrm{cm}$, peak intensities $I_{\max} = 7.92\times10^8\,\mathrm{erg/cm}^3$ (corresponding to $1.64\times10^{12}\,\mathrm{W/cm}^2$), widths (FWHM intensity) of 5.00 cm, wavenumbers $k = 3.9\,\mathrm{cm}^{-1}$ and $k = -4.0\,\mathrm{cm}^{-1}$ (equivalent to frequencies $\omega = v_g k = 8.06\times10^{10}\,\mathrm{s}^{-1}$ and $-8.27\times10^{10}\mathrm{s}^{-1}$ relative to the carrier frequency), and relative phase (phases at the center of the right pulse minus the left) 0.885π. After a finite interaction time, light propagates into the

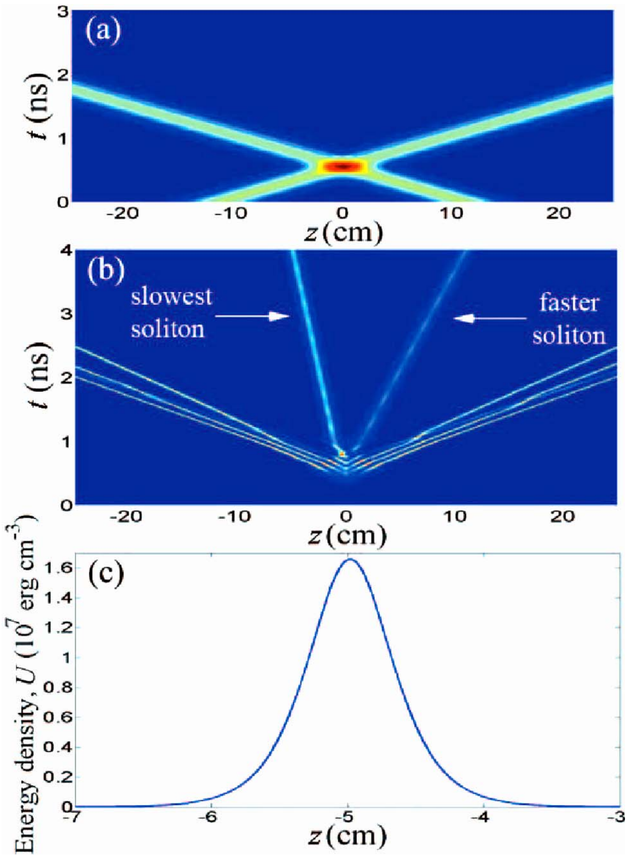

Fig. 2. (Color online) (a) Surface plot of the energy density in the non-Bragg fiber, as a function of distance (z) and time (t). (b) Surface plot of the energy density in the Bragg fiber propagated for 4 ns. The interactions occur over the first half ns because of the width of the input pulses. The output consists of one very slow GS, and the other pulses are dispersive radiation or faster GSs. (c) Light energy density at 4 ns, which is visibly indistinguishable in this figure from the exact analytic GS [5,17] with parameters $Q = 0.3\pi$ and speed $0.04v_g$.

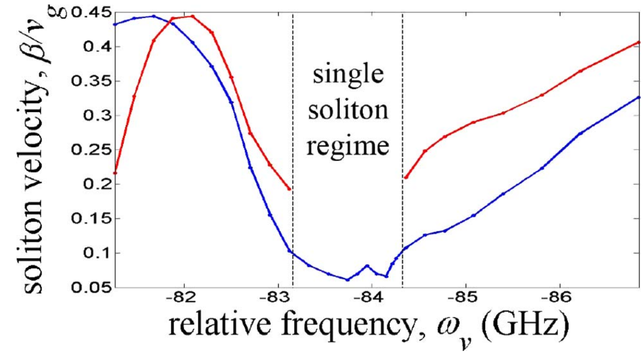

Fig. 3. (Color online) Plot of the velocities (β) of the slowest GSs as functions of the initial pulse frequencies. The abscissa shows the frequency ω_v (relative to the center of the bandgap) of the initial pulse moving to the left in a non-Bragg fiber. In this optimization, the average of the frequencies of the left- and right-moving initial pulses is held constant, $\omega_v = -\omega_u - 2.068$ GHz. In part of the range, one very slow GS is produced, and in another part, two. Each line corresponds to one GS. There is a break in one of the curves where the radiation fails to form a soliton but rather is dispersive. The initial pulses start at a separation of 22 cm and phase difference π.

uncoupled region of the FBG, some of it as a very slow GS (velocity $0.04v_g$), while other light propagates as faster GSs or as dispersive radiation [panel (b)]. The light energy density of the slowest GSs are shown in panel (c). At the peak of the soliton, the flux (energy density times soliton velocity) is 1.37×10^7 W/cm^2. Figure 3 shows the parameters of the slowest GSs versus frequencies relative to the center of the bandgap of the pulses in the non-Bragg fiber(s), i.e., it shows an optimization over frequency.

In summary, we proposed and numerically demonstrated a method for creating optical GSs in a fiber Bragg grating by side-coupling the light over a finite region from the non-Bragg fiber(s). Pulses of light are sent into opposite ends of the non-Bragg fiber(s). In the region where the fibers are coupled together by overlap of the transverse modes, a significant portion of the light switches to the Bragg fiber. The light in the Bragg fiber then escapes past the coupled region, and takes the form of GSs and dispersive light. The inputs can be adjusted so that one of the GSs that is produced in the fiber Bragg grating is quite slow—we achieved solitons with speeds down to 4% of the group velocity in the fiber. This is almost an order of magnitude slower than has been achieved to date experimentally [7]. GSs can also be produced with only a single input pulse in a non-Bragg fiber. However, this produced velocities no slower than half the group velocity.

GSs (or gap acoustic solitons, when electrostriction is included in the model, as required for very slow velocities) are subject to a supersonic instability [18] for speeds slower than that at which the soliton has a local momentum minimum. These acoustic effects become relevant in fused silica at or below approximately $0.005v_g$. This can provide another effect that can be used to bring the pulses of light to a complete stop. The solitons produced by this method can be made to collide inelastically to produce zero velocity optical GSs [10]. In fact, we succeeded, in numerical simulations, in making zero velocity optical GSs from inelastic collision of the solitons produced by our scheme (actually a collision of solitons and dispersive radiation, since we did not isolate or clean up the products of the interaction before colliding the light from opposite directions).

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