Optical group-velocity control in a phase-shifted narrowband filter

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(Received 27 January 2011; accepted 15 May 2011; published online 17 June 2011)

We demonstrate group-velocity control with an optically reconfigurable narrow-band filter at 1550 nm based on a volume-holographic Bragg grating. The filter is dynamically addressed to obtain different tunable magnitude and phase function by modification of the length, coupling strength, apodization, and phase discontinuities. We characterize the switching behavior, group-delay, electro-optical tuning, and Gaussian pulse propagation. © *2011 American Institute of Physics*. [doi:10.1063/1.3600646]

Volume-holographic gratings offer low insertion loss, narrow bandwidth selectivity and high sidelobe suppression making them candidates for optical filters.[1] Additionally, $LiNbO_3$ filters are in most cases insensitive to photo-induced damage in the C- and L-band, thus they have been proposed for telecom applications, e.g., filters for wavelength division multiplexing.[2] It has already been shown that reflection type gratings in photorefractive $LiNbO_3$ can be used to produce slow-light for a single photonic band gap (PBG) in the visible wavelength range.[3] To modify the spectral response of narrowband filters most techniques rely on mechanical strain or temperature changes but are limited to modification of the central wavelength of static gratings and tend to be anisotropic. Compared to in-fiber grating filters, $LiNbO_3$ allows indefinite write erasure cycles of nearly arbitrary filter configurations based on multiple phase-shifts and superstructure profiles. Spatial phase-shift keying in photorefractive media with electrical fields has been demonstrated by Petrov and co-workers[4] to reconfigure the filter transfer function. We use optical phase-shift-keying to manipulate the group-velocity properties of a one-dimensional PBG with broken symmetry. This tuning mechanism does not induce strain or wear on the device, spectral characteristics are highly repeatable and also allow control of the magnitude or phase response. In this letter, a method to obtain a tunable delay is experimentally demonstrated by utilizing an active $LiNbO_3$ crystal. Both superluminal and subluminal pulse propagation can be observed as the PBG shows the inverse behavior as in gain media with atomic transitions.[5] Group-velocity reduction with static phase-shifted gratings have previously been studied by Longhi *et al.*[6,7] In this system the emphasis is not on the maximum delay which can be achieved, but more on the quick, computer controlled reconfiguration of different grating states to study e.g., optical effects with quantum analogies.

The principle of operation is diffraction from a volume phase Bragg grating in x-cut $LiNbO_3$:Fe, read out in transmission with one or more phase discontinuities. We estimate the reflection, dispersion, and delay properties of our system transfer matrix calculations, see e.g. Ref. 8. Figure 1 shows qualities of a typical phase grating in $LiNbO_3$ centered at 1542.000 nm, 16 mm long with a refractive index modulation of $\Delta n = 10^{-5}$ and a π phase-shift placed in the middle of two adjacent grating sections. The phase shift of the grating phase opens a narrow transmission resonance with a full width at half maximum of 5 pm at the central wavelength. Due to normal dispersion in the passband, the group-delay exhibits a narrow peak with high transmission and an adjustable signal bandwidth.

The grating is pumped with two expanded plane wave fronts of a 487.5 nm optically pumped semiconductor laser (Fig. 2). The beams are overlapped with an angle of 44.29° and the end-facets of the crystal are antireflection coated for 1.5 μm to suppress resonances in transmission. To dynamically induce phase-shifts into the grating, a computer controlled, phase only spatial light modulator (CRC 128P) in combination with polarizers is used in one beamline of the interferometer. Polarization of the writing beams before the crystal is extraordinary with respect to the c-axis of the crystal. For changing the grating strength profile we employ a second laser and a modulator (Holoeye LC2002) in amplitude mode perpendicular to the writing face of the crystal. By addressing a raised cosine amplitude transmission on the modulator, sidelobe suppression is achieved, but it also allows for superstructured modification filter gratings during or after recording. The phase during the recording process is stabilized by a piezoelectric mirror with interferometric feedback.[9]

The filter spectrum is characterized by a fiber coupled tunable laser source (HP8168E) with a grin fiber collimation package to achieve a beam diameter off approximately 1.6 mm and low divergence. To measure the group velocity with high spectral resolution we use the modulation phase-shift method.[10] The narrowband signal from the tunable laser is

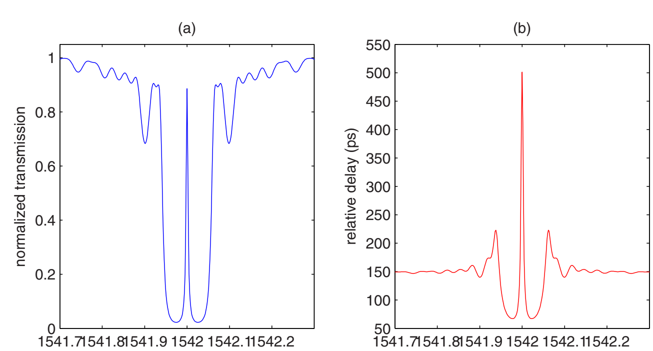

FIG. 1. (Color online) Calculated, normalized transmission, and delay properties of a 16 mm long grating in $LiNbO_3$. Base refractive index of 2.212 at 1550, a phaseshift in the middle of the grating section and a refractive index contrast of 10^{-5} with 0.5 mm raised cosine apodization.

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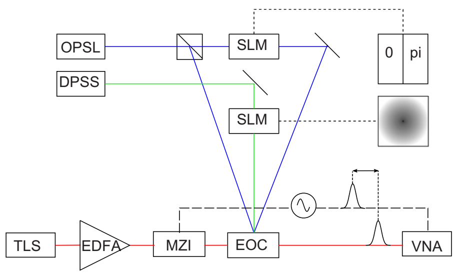

FIG. 2. (Color online) Schematic setup for dynamic filter recording; OPSL: optically pumped semiconductor laser; DPSS; TLS: tunable laser source; SLM: spatial light modulator; EDFA: erbium doped fiber amplifier; MZI: Mach-Zehnder modulator; EOC: electro-optic crystal; VNA: vector network analyzer.

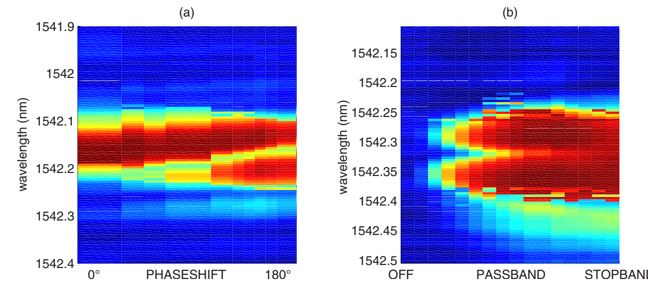

FIG. 4. (Color online) (a) Gradual increase in a single phasejump from 0 to π. (b) Switching of the filter from OFF-state to passband- and stopband-configuration.

RF modulated with a signal by a Mach-Zehnder modulator and the signal is increased by an erbium-doped fiber amplifier. The phase shift allows determination of the of the relative group delay. The signal in transmission and reflection is fed back into a vector network analyzer (HP 8753B) for phase-locking.

Figure 3 shows the magnitude response in transmission for different phase code configurations. With no phase-code applied, recording results in a single stopband comparable to a fiber grating filter (a). Addressing a phasecode with a single π shift, the material adapts to the pump light and a passband filter is achieved (b). The reflectivity of the single grating without phase-shifts is more than 99 percent but since recording is reversible, any coupling strength and group-delay below saturation is possible without tilting. The half-width of the symmetric stop bands is approximately 90 pm and the passband in between is 36 pm. By changing the ratio of the two grating sections or by applying more asymmetric phasecodes with multiple phase shifts, the transfer function allows modification of the group delay bandwidth as well. However, the tradeoff between signal bandwidth and delay remains constant.

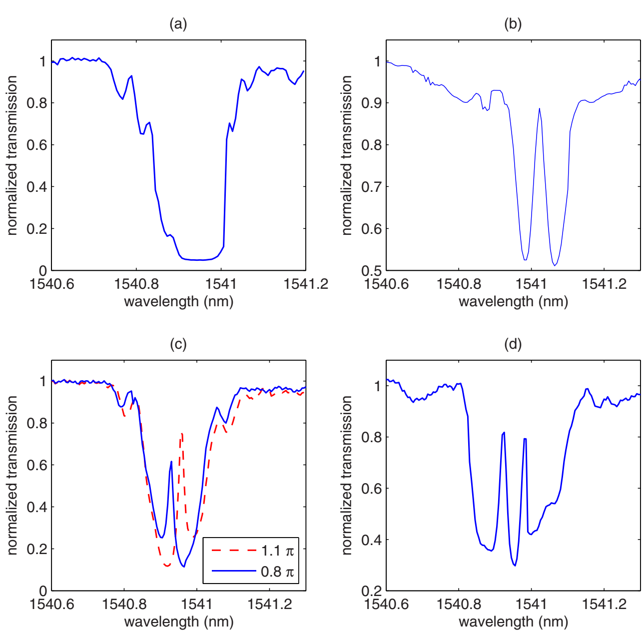

FIG. 3. (Color online) Magnitude filter response in transmission: (a) Single homogeneous grating; (b) a phasecode with a single π shift in the middle; (c) detuned phasecodes with 0.8π and 1.1π leading to an asymmetric filter response and with two π defects (d).

In Fig. 3(c) the phase discontinuity is detuned to 0.8π and 1.1π, respectively, which leads to an asymmetric response and a shift of the central transmission dip. This allows continuous optical adjustment of the passband without mechanical reconfiguration with picometer precision. Multiband configurations for several wavelength division multiplexing channels with more complex magnitude and phase responses are easily obtained. In our experiment we were able to use up to 128 individual phase-shifts.

Figure 4 shows a time plots at different configuration states of the filter. This behavior is exclusively controlled by the optical phase-keyed hitless tuning. In Fig. 4(a), the phase jump is gradually increased from 0–180 degrees and the passband observed in reflection is shifted from the short wavelength side to the center of the resonance. On the left-hand-side in Fig. 4(b), the pump is switched on with a $[0;\pi]$-phasecode and the passband filter builds up. If the [0;0]-phasecode is applied the filter reconfigures to the stopband-configuration. This demonstrates the optical switching capability of the system when the previous grating is erased and a new one is recorded. In general, continuous tuning between grating spectra is possible with approximately 0.002 π within the dynamics of the phase-modulator. Although $LiNbO_3$ has a time constant that does not allow very fast switching times between two transfer functions at low light intensities, in general other electro-optic, e.g., photorefractive semiconductors can be employed to reduce reconfigurations in less than a microsecond.[11]

The magnitude of the group-delay is modified by the second diode pumped solid state laser (DPSS) by modification the coupling strength during the recording process or subsequent weakening. Grating length can be changed continuously by the second pump laser to adjust the effective coupling length of propagating signals. The linearity of the measurement was tested using different modulation frequencies ranging from 100 MHz to 1 GHz. Larger delays can be achieved by increasing the refractive index change in a different type of photorefractive material or by increasing the overall interaction length in a waveguided structure.

Figure 5(a) shows a plot of the group-delay if 16 averaged signal traces launched into the grating structure. The group-delay is calculated from the wavelength dependent phase-shift and exhibits the anticipated central maximum. The phase-stability in the phase-locked loop is approximately 0.1 degrees, so that at a modulation frequency of 1 GHz we are able to measure the group delay with a resolution of 0.278 ps and a maximum delay of 1 ns. The group-delay inside the transmission gap is approximately 43 ps at point B. At point A the relative group-delay is negative and

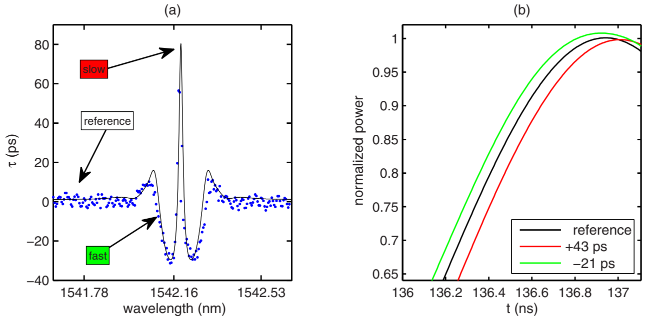

FIG. 5. (Color online) Delay measurements: (a) Delay measured by the modulation phase-shift method at 125 MHz; (b) time-of flight delay of 2.6 ns pulses at points A and B compared to a reference signal.

superluminal propagation with −21 ps is observed. However, the latter case this is only feasible if the coupling strength of the filter is reduced to achieve sufficient signal-to-noise ratio in the stopband region. Figure 4(b) shows the time-of-flight traces of single 2.6 ns long pulses at both points relative to an off-resonance reference.

Since $LiNbO_3$ has electro-optical properties, the refractive index can be tuned by an external electric field. A similar method has been proposed by using an inverted domain grating in periodically poled $LiNbO_3$. Using indium-tin-oxide-electrodes on the pump surface of the crystal and therefore the r_{22} electro-optic coefficient, values from $0-0.88\ \mathrm{V}\ \mu\mathrm{m}^{-1}$ were applied. The measure refractive index increase at 6 kV external electric field was 3.5×10^{-5} which yields an experimental value of $r_{22}=6.9\ \mathrm{pm/V}$ and the spectrum can be shifted 25 pm to the longer wavelength side. Hence, the group-delay at a fixed probe wavelength can be tuned in the nanosecond timescale with high precision. Figure 6(a) shows group delay traces for different applied fields and Fig. 6(b) the quantitative group-delay at a fixed wavelength of 1541.810 nm. The shift in this experiment is limited by the crystal thickness due to sparkover at the electrodes when using higher fields. In general, a wavelength can be chosen to electro-optically tune the pulse from sub- to superluminal velocity and vice versa.

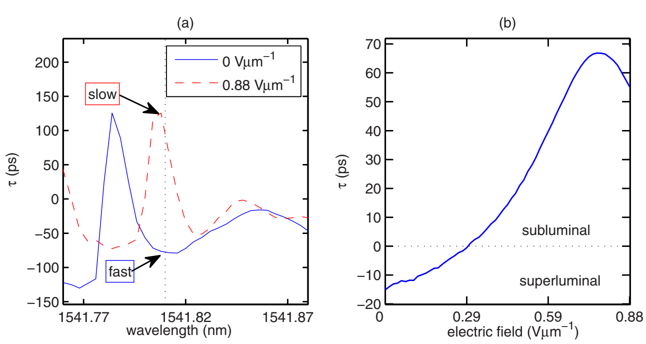

FIG. 6. (Color online) Delay measurements: (a) Delay measured with and without an external fields; (b) Delay vs electric field at a fixed wavelength of 1541.810 nm.

In contrast to slow-light in static phaseshifted fiber gratings as demonstrated in Refs. 12 and 13 and in approaches using gap-solitons (Refs. 14 and 15) the delay performance is worse. This is due to the finite structure length that is technically limited to less than 2 cm coupling length compared to 40 cm interaction length in the fibers and the amount of phaseshifts induced between grating sections. Additionally, the coupling strength that can be achieved in hydrogen loaded fibers is a magnitude higher than refractive index change induced by the photorefractive effect. Finally, the loss at 1540 nm of iron-doped $LiNbO_3$ can be as high as 0.7 dB/cm with additional holographic scattering. This has a significant impact on the bandwidth and dispersion of the narrow transmission region.

In summary, we have demonstrated a slow light system where the group-velocity is modified by a phase-shift-keyed, reconfigurable one-dimensional index structure. The system allows for optical and electro-optical reconfiguration of the reflection and transmission properties with multiple gaps and superstructures and may therefore be interesting for the efficient study of different spectral distributions for dispersion compensation and optical filtering as a moderate group delay and dispersion can be achieved anywhere in the C- and L-band wavelength range.

[1]G. A. Rakuljic and V. Leyva, Opt. Lett. **18**, 459 (1993).
[2]S. Breer and K. Buse, Appl. Phys. B: Lasers Opt. **66**, 339 (1998).
[3]S. H. Lin, K. Y. Hsu, and P. Yeh, Opt. Lett. **25**, 1582 (2000).
[4]C. Heinisch, S. Lichtenberg, V. Petrov, J. Petter, and T. Tschudi, Opt. Commun. **253**, 320 (2005).
[5]A. M. Steinberg and R. Y. Chiao, Phys. Rev. A **49**, 2071 (1994).
[6]S. Longhi, M. Marano, P. Laporta, O. Svelto, and M. Belmonte, J. Opt. Soc. Am. B **19**, 2742 (2002).
[7]S. Longhi, M. Marano, P. Laporta, and P. Crespi, Phys. Rev. E **65**, 045602 (2002).
[8]T. Erdogan, J. Lightwave Technol. **15**, 1277 (1997).
[9]S. Breer, K. Buse, K. Peithmann, H. Vogt, and E. Kratzig, Rev. Sci. Instrum. **69**, 1591 (1998).
[10]K. Daikoku and A. Sugimura, Electron. Lett. **14**, 149 (1978).
[11]G. Gheen and L. J. Cheng, Appl. Opt. **27**, 2756 (1988).
[12]S. Longhi, D. Janner, G. Galzerano, G. Della Valle, D. Gatti, and P. Laporta, Electron. Lett. **41**, 1075 (2005).
[13]D. Janner, G. Galzerano, G. Della Valle, P. Laporta, S. Longhi, and M. Belmonte, Phys. Rev. E **72**, 056605 (2005).
[14]J. T. Mok, C. Martijn de Sterke, and B. Eggleton, Opt. Express **14**, 11987 (2006).
[15]Joe T. Mok, C. Martijn de Sterke, I. Littler, and B. Eggleton., Nat. Phys. **2**, 775 (2006).