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Experimental observation of superluminal pulse reflection in a double-Lorentzian photonic band gap

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We report on the experimental observation of superluminal reflection of picosecond optical pulses at 1.5 μm using a specially designed 30-cm-long fiber Bragg grating (FBG) that realizes a spectral reflectivity profile given by the superposition of two closely spaced Lorentzian lines. Probing pulses of 380 ps duration tuned midway between the two Lorentzian lines are reflected without appreciable distortion with a measured peak pulse advancement of $\simeq 60$ ps. The achievement of the *negative* group delay is due to the interference of the two resonance modes of the FBG structure and has a close connection to the phenomenon of negative group velocity for pulse propagation in an inverted medium possessing a doublet line.

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It is well known that a light pulse can travel at a group velocity exceeding the speed of light in vacuum in regions of anomalous dispersion or evanescent propagation. Anomalous dispersion is usually achieved by exploiting the dispersive properties of absorptive [1] or inverted [2–4] atomic media near resonances; in particular, by exploiting the transparent anomalous dispersion of a gain doublet [3], pulse propagation at a negative group velocity without appreciable pulse distortion or attenuation has been recently reported in cesium vapor [4]. A different but closely related issue is that of photon tunneling through photonic barriers, in which superluminal effects are associated with evanescent wave propagation (for recent reviews on this subject see [5,6] and references therein). As opposed to superluminal pulse propagation in atomic media, evanescent wave propagation in photon tunneling is accompanied by the generation of an antievanescent (reflected) wave, which propagates backward. Although accurate measurements of superluminal tunneling times have been reported in a series of experiments in different kinds of photonic barrier, including undersized waveguides [7,8], one-dimensional photonic band gaps (PBGs) [9,10], and frustrated total internal reflection [11], little attention has been devoted to the study of superluminal effects of *reflected* waves. In the case of lossless and *symmetric* barriers, one can prove on the basis of general grounds that the transmission and reflection times are equal (see, e.g., [12]); since the transmission (tunneling) time in opaque barriers saturates to a constant value and becomes independent of barrier width (Hartman effect), the reflection time from lossless symmetric barriers is thus expected to be independent of their length. An experimental demonstration thereof has been recently given for microwaves in [13]. A different and intriguing question is whether it is possible for a pulse reflected by a photonic barrier to appear *earlier* than if it were reflected by an ideal mirror placed at the entrance plane of the barrier. A positive answer to this question has been given recently in a few theoretical works [14,15] by considering either an active system or a passive (lossless) but *asymmetric* photonic barrier. In Ref. [14], superluminal peak advancement of the reflected pulse was predicted to occur in optical phase conjugation, but solely in the unstable (self-oscillatory) regime, which makes it a difficult experimental observation. In Ref. [15], one of the present authors has shown quite generally that superluminal pulse reflection may occur in a broad class of asymmetric one-dimensional PBGs. In particular, it was shown that a negative group delay *in reflection* can be achieved by a PBG structure possessing *two* resonant modes, for which the spectral reflectivity profile is given by the interference of two closely spaced complex Lorentzian lines. The dispersion curve in reflection of such a structure, which we call a double-Lorentzian PBG, is analogous to that produced in an inverted medium with a gain doublet [3,4], where a negative group delay in transmission is achieved by exploiting the interference of the two Lorentzian lines of the homogeneously broadened atomic transitions.

In this Rapid Communication we report on what we believe to be the first experimental observation of superluminal optical pulse reflection. A double-Lorentzian fiber Bragg grating (DL FBG) at the wavelength of 1550 nm has been used to achieve a negative group delay with measured peak pulse advancements of $\simeq 60$ ps. The use of a FBG as a photonic barrier is a key point for the achievement of unambiguous experimental results for two important reasons. On the one hand, the recent technological progress in FBG writing techniques, in conjunction with efficient inverse scattering methods of FBG design, allows the synthesis and fabrication of complex FBG structures, such as that required in a DL FBG. On the other hand, as we recently demonstrated in Ref. [16], the weak modulation depth of the refractive index along the fiber core permits one to perform experiments with barrier widths several orders of magnitude larger than the wavelength of the probing pulse, thus leading to a drastic increase of the time scale involved in tunneling processes; for probing pulses in the optical region, the use of a FBG instead of multidielectric quarter-wave PBG structures [9,10] enables us to reduce the temporal resolution required in pulse

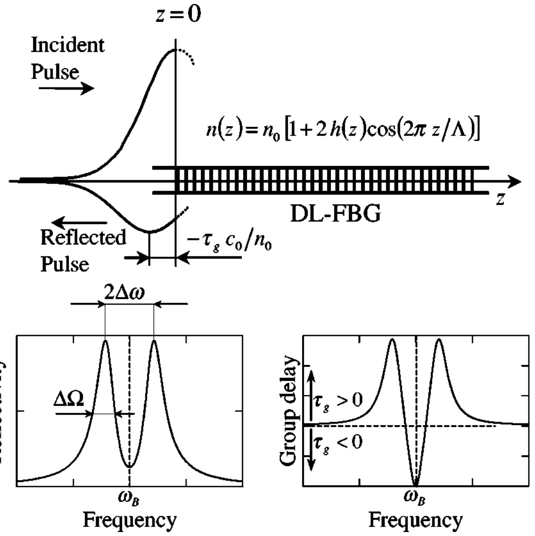

FIG. 1. Principle of superluminal pulse reflection in a DL FBG. When the peak of the incident pulse enters the grating at input plane $z=0$, the peak of the reflected pulse has already left the grating in advance and traveled backward the distance $2|\Delta L|=-\tau_g c_0/n_0$. For the sake of clarity, the intensity scale for the reflected pulse is expanded as compared to that of the incident pulse. The lower pictures show schematically the spectral power reflectivity and group delay of a DL FBG.

delay measurements from the femtosecond to the picosecond time scale.

The principle of superluminal pulse reflection in a DL PBG structure is schematically shown in Fig. 1 [15]. A monochromatic electromagnetic field at frequency ω incident upon the input plane $z=0$ undergoes Bragg scattering in the optical fiber, and the amplitude and phase of the reflected wave depend on the frequency of incident wave according to the spectral reflectivity function $r(\omega)$ of the structure. For a spectrally narrow optical pulse with a carrier frequency ω incident upon the fiber, the reflected pulse emerges with a time delay $\tau_g=\partial\arg(r)/\partial\omega$ from the entrance plane, as if the pulse were reflected at an ideal plane inside the barrier at a distance $\Delta L=c_0\tau_g/(2n_0)$ from the entrance plane (n_0 is the average refractive index of the FBG and c_0 the speed of light in vacuum). Superluminal pulse reflection thus occurs for a negative group delay, i.e., for $\tau_g<0$. The DL FBG structure schematically shown in Fig. 1 is a periodic FBG with a refractive index profile $n(z)=n_0[1+2h(z)\cos(2\pi z/\Lambda)]$, where Λ is the Bragg period and $h(z)$ is the apodization profile, which is specially designed to provide two closely spaced resonant modes at frequencies $\omega_B\pm\Delta\omega$, $\omega_B=\pi c_0/\Lambda$ and $2\Delta\omega$ ($\ll\omega_B$) being the Bragg reference frequency of the FBG and the frequency separation between the two resonances, respectively. The explicit form of the spectral reflectivity of a DL FBG is

$$r(\omega)=i\sqrt{R_0}\left[\frac{1}{(\omega-\omega_B-\Delta\omega)/(\Delta\Omega/2)+i}+\frac{1}{(\omega-\omega_B+\Delta\omega)/(\Delta\Omega/2)+i}\right] \tag{1}$$

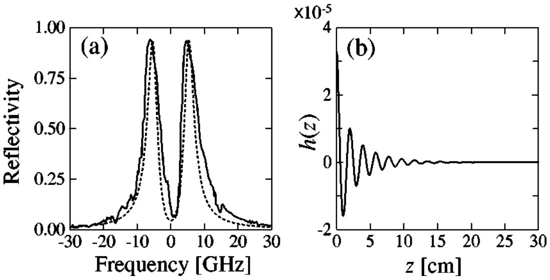

FIG. 2. (a) Measured spectral power reflectivity of the DL FBG used in the experiment (solid line) and corresponding theoretical curve (dashed line). Parameter values are $n_0=1.452$, $\omega_B=1.2161\times10^{15}$ rad/s, $\Delta\omega=33.93\times10^9$ rad/s, $R_0=0.92$, and $\Delta\Omega\simeq0.74\Delta\omega$. (b) Apodization profile $h(z)$ of refractive index for the DL FBG as obtained by the Gel'fand-Levitan-Marchenko inverse scattering method.

where $\Delta\Omega$ is the full width at half maximum (FWHM) and R_0 the peak power reflectivity of each Lorentzian line. The qualitative behavior of power spectral reflectivity $R(\omega)=|r(\omega)|^2$ and group delay $\tau_g(\omega)$ is shown in Fig. 1. The minimum of the group delay is attained at $\omega=\omega_B$, i.e., in correspondence with the minimum of spectral reflectivity $R(\omega)$, and is given by $\tau_g(\omega_B)=(2/\Delta\Omega)[(\Delta\Omega/2)^2-\Delta\omega^2]/[(\Delta\Omega/2)^2+\Delta\omega^2]$. Superluminal peak pulse advancement in reflection is thus expected for a spectrally narrow optical pulse with a carrier frequency $\omega=\omega_B$ when $2\Delta\omega>\Delta\Omega$, i.e., when the frequency separation between the two Lorentzian lines is larger than their FWHM. The apodization profile $h(z)$ that realizes the spectral reflectivity given by Eq. (1) can be analytically determined by use of the Gel'fand-Levitan-Marchenko inverse scattering method; the explicit expression of $h(z)$ is rather cumbersome to be given here, and we refer the reader to Ref. [15] for technical details.

The FBG used in the experiment consists of a 30-cm-long single-mode deuterated fiber with a Bragg resonance at 1550 nm; the separation of the Lorentzian lines is $2\Delta\omega\simeq2\pi\times10.8$ GHz, the FWHM and peak power reflectivity of each line being $\Delta\Omega\simeq2\pi\times4$ GHz and $R_0\simeq0.92$, which yield a negative group delay $\tau_g\simeq-62$ ps and a minimum power reflectivity $R\simeq5\%$ at $\omega=\omega_B$. The calculated (dashed curve) and measured (solid curve) spectral power reflectivity R of the FBG are shown in Fig. 2, together with the apodization profile $h(z)$ computed by the inverse scattering technique. The FBG was fabricated using a continuous writing technique in which the UV beam from a frequency doubled Ar-ion laser is focused onto the fiber through a phase mask and strobed using an acousto-optic modulator. With this writing technique, the fiber is continuously translated in front of the phase mask, and the fiber position is monitored by an interferometer, with subnanometer precision, which triggers the acousto-optic modulator with period corresponding to the desired grating pitch. This allows for an accurate exposure on a grating plane by grating plane basis [17]. By suitably delaying adjacent exposures with respect to each other, the desired apodization profile shown in Fig. 2(b) is achieved, with a spatial resolution of ~1 mm.

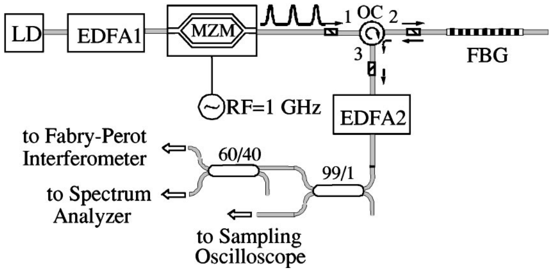

FIG. 3. Schematic of the experimental setup. LD, tunable laser diode; MZM, Mach-Zehnder waveguide modulator; OC, optical circulator; EDFA1 and EDFA2, erbium-doped fiber amplifiers; RF, radio-frequency synthesizer.

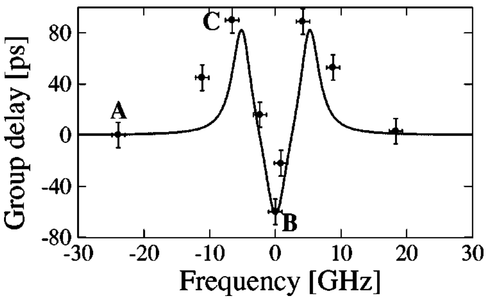

FIG. 4. Measured (circles) and predicted (solid curve) group delay versus frequency detuning from Bragg resonance. In the experimental measurements, the group delay for the redshifted off-resonance pulse (point *A* in the figure) has been taken equal to zero (see [18]).

Group delay measurements were performed in the time domain by analyzing the reflection of picosecond optical pulses from the FBG at different tuning conditions of probing pulses. The experimental setup for time delay measurements is shown in Fig. 3. The pulse train was generated by external modulation of a single-frequency continuous-wave tunable laser diode (Santek model ECL-200/210). A high-power erbium-doped fiber amplifier (FiberTek model EAD-2-PM; EDFA1 in Fig. 3) was used to increase the average power level up to ~ 0.5 W. External modulation was achieved by a LiNbO$_3$ Mach-Zehnder modulator, sinusoidally driven at a repetition frequency $f_m = 1$ GHz by a low-noise radio-frequency (RF) synthesizer. The bias point of the modulator and the RF modulation power level were chosen to generate a train with a pulse duration (FWHM) of $\simeq 380$ ps and a spectral extent of ~ 3 GHz, i.e., slightly narrower than the 4 GHz FWHM of each Lorentzian line. The pulse train was then sent to the FBG through a three-port optical circulator, and the reflected signal was retrieved at port three of the circulator. A low-noise erbium-doped fiber amplifier (OptoCom model OI LNPA; EDFA2 in Fig. 3) with a low saturation power ($\simeq 30$ μW at 1550 nm) was connected to the output port to maintain the average power level of reflected optical signal at a constant level ($\simeq 18$ mW). In this way, the power levels of reflected pulses, for the laser tuned close to or far from the two peaks of the Lorentzian lines, were equalized. The reflected pulse train was detected in the time domain by a fast sampling oscilloscope (Agilent model 86100A), with a low jitter noise and an impulsive response of $\simeq 15$ ps, and simultaneously in the frequency domain by using both an optical spectrum analyzer (Anritsu model MS9710B) with a resolution of 0.07 nm, and a plane-plane scanning Fabry-Pérot interferometer (Burleigh model RC1101R) with a free-spectral range of $\simeq 80$ GHz and a measured finesse of ~ 180. The oscilloscope traces of reflected pulses were recorded for different tuning conditions of the laser emission spanning the entire reflectivity spectrum of the FBG. With this aim, by disconnecting the laser diode from the input port of EDFA1 and sending to the FBG the broadband ($\simeq 30$ nm) amplified spontaneous emission signal of the optical amplifier, the FBG spectral reflectivity $R(\omega)$ was first measured using the Fabry-Pérot interferometer and recorded on a digital oscilloscope. This trace was then used as a reference to tune the pulse spectrum across the recorded FBG reflectivity spectrum. Time delays were estimated by measuring on the sampling oscilloscope the change of the peak pulse position for the different tuning conditions, assuming as a reference the pulse corresponding to off-resonance operation [18]. The time delay measurements are summarized in Fig. 4 and compared to the expected group delay curve of the DL FBG. Repeated measurements showed that, owing to slow thermal drifts of the FBG spectrum and to uncertainty in tuning of the semiconductor laser wavelength, the experimental data are accurate within ± 1 GHz for the frequency tuning condition and ± 10 ps for time delay measurements. Notice that, within the experimental uncertainties, the agreement between theoretical curve and experimental points is satisfactory. Superluminal pulse reflection, with a peak pulse advancement of $\simeq 60$ ps, is apparent when comparing time delays for a pulse tuned off resonance (e.g., point *A* in Fig. 4 [18]) and at resonance midway between the two Lorentzian peaks (e.g., point *B* in Fig. 4). Conversely, for a pulse spectrum tuned at one of the two Lorentzian peaks (e.g., point *C* in Fig. 4), the group delay is positive and reflection is subluminal, with a peak pulse delay of $\simeq 90$ ps. Typical traces of reflected optical pulses, averaged over 128 acquisitions and corresponding to the three different tuning conditions *A*, *B*, and *C* of Fig. 4, are shown in Fig. 5. Notice that a slight pulse distortion is apparent for both advanced and delayed traces, which is probably ascribable to residual ripples in the spectral response of the grating due to fabrication imperfections [see Fig. 2(a)] as

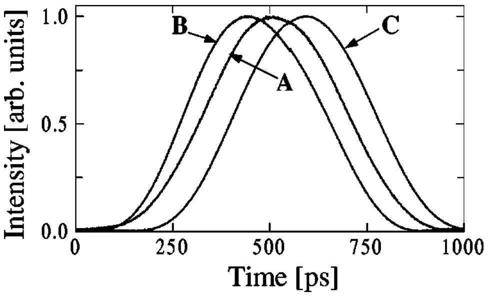

FIG. 5. Pulse traces recorded on the sampling oscilloscope corresponding to the reflected pulses for the three tuning conditions *A*, *B*, and *C* of Fig. 4.

well as to the relative spectral extent of the pulses as compared to the width and separation of Lorentzian lines. As a final remark, we note that the observed superluminal peak pulse advancements can be explained as a reshaping phenomenon by means of which the leading edge of the pulse is reflected preferentially to the trailing edge, leading to an effective advancement of the pulse ‘‘center of mass;’’ however, no true violation of ‘‘Einstein’s causality’’ occurs, as stressed by several authors (see, e.g., [5]), since any discontinuity in the wave front that carries new information is reflected exactly at $z=0$.

In conclusion, we have experimentally demonstrated superluminal reflection of picosecond optical pulses by the synthesis of a DL FBG that simulates in reflection the causal response of a medium with two closely spaced resonances. Peak pulse advancements of $\simeq 60$ ps, corresponding to $\sim 1/6$ of pulse duration, were observed when the probing optical pulses were tuned at the center between the two Lorentzian peaks. These results represent what is believed to be the first experimental observation of superluminal reflection by photonic barriers and may be of particular importance in the fields of superluminal pulse propagation and dynamics of tunneling processes.

[1] C.G.B. Garret and D.E. McCumber, Phys. Rev. A **1**, 305 (1970); S. Chu and S. Wong, Phys. Rev. Lett. **48**, 738 (1982); B. Segard and B. Macke, Phys. Lett. **109A**, 213 (1985).

[2] R.Y. Chiao, Phys. Rev. A **48**, R34 (1993); E.L. Bolda, J.C. Garrison, and R.Y. Chiao, *ibid.* **49**, 2938 (1994).

[3] A.M. Steinberg and R.Y. Chiao, Phys. Rev. A **49**, 2071 (1994).

[4] L.J. Wang, A. Kuzmich, and A. Dogariu, Nature (London) **406**, 277 (2000); A. Dogariu, A. Kuzmich, and L.J. Wang, Phys. Rev. A **63**, 053806 (2001).

[5] R.Y. Chiao and A.M. Steinberg, Prog. Opt. **37**, 345 (1997).

[6] G. Nimtz and G.W. Heitmann, Prog. Quantum Electron. **21**, 81 (1997).

[7] A. Enders and G. Nimtz, Phys. Rev. B **47**, 9605 (1993), and references therein; G. Nimtz, A. Enders, and H. Spieker, J. Phys. I **4**, 565 (1994); H.M. Brodowsky, W. Heitmann, and G. Nimtz, Phys. Lett. A **222**, 125 (1996).

[8] A. Ranfagni, D. Mugnai, P. Fabeni, and G.P. Pazzi, Appl. Phys. Lett. **58**, 774 (1991).

[9] A.M. Steinberg, P.G. Kwiat, and R.Y. Chiao, Phys. Rev. Lett. **71**, 708 (1993).

[10] Ch. Spielmann, R. Szipöcs, A. Stingl, and F. Krausz, Phys. Rev. Lett. **73**, 2308 (1994).

[11] Ph. Balcou and L. Dutriaux, Phys. Rev. Lett. **78**, 851 (1997); see also A.A. Stahlhofen, Phys. Rev. A **62**, 012112 (2001); A. Haibel, G. Nimtz, and A.A. Stahlhofen, Phys. Rev. E **63**, 047601 (2001).

[12] J.P. Falck and E.H. Hauge, Phys. Rev. B **38**, 3287 (1988); see also A.M. Steinberg and R.Y. Chiao, Phys. Rev. A **49**, 3283 (1994), Sec. III.

[13] G. Nimtz and A. Haibel, e-print quant-ph/0103073.

[14] M. Blaauboer, A.G. Kofman, A.E. Kozhekin, G. Kurizki, D. Lenstra, and A. Lodder, Phys. Rev. A **57**, 4905 (1998).

[15] S. Longhi, Phys. Rev. E **64**, 037601 (2001).

[16] S. Longhi, M. Marano, P. Laporta, and M. Belmonte, Phys. Rev. E **64**, 055602(R) (2001).

[17] W.H. Loh, M.J. Cole, M.N. Zervas, S. Barcelos, and R.I. Laming, Opt. Lett. **20**, 2051 (1995); A. Asseh, H. Storoy, B.E. Sahlgren, S. Sandgan, and R.A.H. Stubbe, J. Lightwave Technol. **15**, 1419 (1997).

[18] The theoretical cuve of group delay versus frequency (see Fig. 1; see also solid curve in Fig. 4) shows that, for a pulse with a carrier frequency ω far from the two resonance peaks by a few times the Lorentzian width, the group delay approaches zero, which means that in Fig. 1, $\Delta L \simeq 0$. Off-resonance pulses are thus reflected close to the entrance plane of the FBG structure, thus providing an important reference in the experimental measurements.