PHYSICAL REVIEW E, VOLUME 64, 055602(R)

# Superluminal optical pulse propagation at 1.5 $\mu$m in periodic fiber Bragg gratings

S. Longhi, M. Marano, and P. Laporta
*Istituto Nazionale per la Fisica della Materia, Dipartimento di Fisica, Politecnico di Milano, Piazza L. da Vinci 32, I-20133 Milano, Italy*

M. Belmonte
*Corning-Optical Technologies Italia, Viale Sarca 222, 20126 Milano, Italy*

(Received 19 March 2001; published 16 October 2001)

We report on the experimental observation of superluminal tunneling of picosecond optical pulses in a periodic fiber Bragg grating. Optical pulses of 380-ps duration, generated by an externally-modulated single-frequency erbium-ytterbium laser operating near 1.5-$\mu$m wavelength, were propagated at a group velocity greater than ~1.97 times the speed of light in vacuum across a 2-cm long fiber grating. Owing to the very large ratio between the thickness of the barrier (2 cm) and the wavelength of probing optical pulses (~1.5 $\mu$m), our experiment allows for the observation of superluminal tunneling in the optical region by direct optoelectronic time-domain measurements.

DOI: 10.1103/PhysRevE.64.055602 PACS number(s): 42.25.Bs, 42.70.Qs, 03.65.Xp

The longstanding question of tunneling times of electromagnetic or matter wave packets across a barrier [1,2] and the related issue of superluminality [2–6] have received, in recent years, an increasing and renewed interest both from a fundamental as well as from a technological viewpoint. There are by now several experiments, performed at either microwave or optical wavelengths, which report on superluminal tunneling of photons in waveguides, periodic dielectric structures, or in two side-by-side prisms (frustrated total internal reflection); a detailed account on these experimental studies and extended references can be found, e.g., in recent review papers on the subject [2,5]. A common feature of all the tunneling experiments reported so far is the relatively low value achieved for the ratio $r = L/\lambda$ between the thickness of the barrier, $L$, and the photon wavelength, $\lambda$. In the recent experiments on photon tunneling using one-dimensional photonic band gaps at optical wavelengths (Berkeley and Vienna groups [7,8]), as well as in undersized waveguides in the microwave region (Florence and Cologne groups [9,10]), the barrier thickness $L$ is in fact few times larger than the wavelength of the probing pulse. Since for an opaque barrier the advancement of the tunneled wave packet is of the order of $L/c_0$, where $c_0$ is the speed of light in vacuum, a relatively low value of $r$ implies a time resolution for detection of the flight time of the order of (or few times larger than) the single-cycle period of the probing wave packet. In the microwave region, temporal advancements fall in the nanosecond time scale, which are easily accessible by electronic measurements. Conversely, in the optical region a time resolution down to few femtoseconds or even less is required, which is possible solely by means of some kind of indirect measurement, such as interference of twin-photon beams for single-photon tunneling [7] or interferometric autocorrelation techniques of ultrashort femtosecond pulses for "classical" wave packets [8]. Larger advances in time, in the picosecond or nanosecond scale, would be of major interest making accessible with standard optoelectronic measurements the detection of tunneling times and superluminal group velocities for classical wave packets at optical wavelengths. In addition, superluminal tunneling in the picosecond time scale may be of interest for the technologically important field of optical communications, where picosecond optical pulse trains at high repetition rates are typically used instead of femtosecond pulses.

In this work we report on the tunneling of optical pulses at 1.5 $\mu$m, i.e., in the third transmission window of optical fibers, across the long barrier provided by a 2-cm long periodic fiber Bragg grating (FBG), with measured superluminal peak pulse advancements up to a few tens of picoseconds. The use of a FBG [11] as a photonic barrier at the optical wavelengths is similar, in principle, to the multilayer dielectric mirror configuration previously employed by Steinberg *et al.* and Spielmann *et al.* [7,8]; however, owing to the weaker modulation of the refractive index achieved in the fiber core, the FBG offers the advantage of realizing a relatively long barrier (up to several centimeters) with a transmission coefficient sufficiently high (>~1%) to permit detection of the transmitted pulse at a reasonable power level.

Let us consider a single-mode optical fiber with a weak and periodic modulation of refractive index $n(z) = n_0[1+2h\cos(2\pi z/\Lambda+\phi)]$, $0<z<L$, where $z$ is the propagation axis, $L$ is the grating length, $n_0$ is the average refractive index of the structure, $\Lambda$ is the Bragg modulation period, and $h(z)$, $\phi(z)$ are the slowly-varying amplitude and phase profiles of the refractive index ($|h(z)| \ll 1$). If we consider the propagation of a monochromatic field $E(z,t)$ at the optical frequency $\omega$ close to the Bragg frequency $\omega_B = c_0\pi/(n_0\Lambda)$, where $c_0$ is the speed of light in vacuum, we may write $E(z,t) = u(z,\delta)\exp(-i\omega t + ik_B z) + v(z,\delta)\exp(-i\omega t - ik_B z) + \text{c.c.}$, where $k_B = \pi/\Lambda$ is the Bragg wave number and $u, v$ are the envelopes of counterpropagating waves that satisfy the following coupled-mode equations [11,12]:

$$du/dz = i\delta u + iq(z)v, \tag{1a}$$

$$dv/dz = -i\delta v - iq^*(z)u. \tag{1b}$$

 

In Eqs. (1), $q(z)\equiv k_B h(z)\exp[i\phi(z)]$ is the scattering potential, whereas $\delta\equiv k-k_B=n_0(\omega-\omega_B)/c_0$ is the detuning parameter between the wave number $k=n_0\omega/c_0$ of counterpropagating waves and the Bragg wave number $k_B$ of the grating. Equations (1) have the form of the Zakharov-Shabat system encountered in problems of inverse scattering [13]. The general solution to Eqs. (1) is $(u(L,\delta),v(L,\delta))^T=\mathcal{M}(u(0,\delta),v(0,\delta))^T$, where the elements of the scattering matrix $\mathcal{M}=\mathcal{M}(\delta)$ satisfy the conditions $\mathcal{M}_{22}=\mathcal{M}_{11}^*$, $\mathcal{M}_{21}=\mathcal{M}_{12}^*$, and $\det\mathcal{M}=1$. The spectral transmission coefficient of the grating is given by $t(\delta)=[u(L,\delta)/u(0,\delta)]_{v(L,\delta)=0}=1/\mathcal{M}_{22}$. Owing to Bragg scattering of counterpropagating waves, the transmission spectrum $T(\delta)=|t(\delta)|^2$ shows a band gap at around the zero-detuning $\delta=0$, where propagation is forbidden and superluminal tunneling of optical pulses is expected. An estimate of the tunneling time for a wave packet transmitted through the FBG is provided by the group delay (or phase time) $\tau_g$, which is given by the derivative of the phase of $t$ with respect to $\omega$. Though different tunneling times, such as the Büttiker-Landauer (semiclassical) time or the Larmor time [1,2] might be considered, our choice for the phase time is mainly motivated by its consistency with tunneling time measurements, previously reported in photonic band-gap structures [7,8]. For a periodic FBG ($\phi=0$) with uniform modulation depth ($q=q_0$ constant), which corresponds to the FBGs used in our experiments, a simple analytical expression for spectral transmission $t$ and group delay $\tau_g$ can be derived and read:

$$t(\delta)=\frac{1}{\cosh(\Omega L)-i\dfrac{\delta}{\Omega}\sinh(\Omega L)}, \tag{2a}$$

$$\tau_g(\delta)=\frac{n_0 L}{c_0}\frac{q_0^2}{\Omega^2+\delta^2\tanh^2(\Omega L)}\left[\frac{\delta^2}{q_0^2}\tanh^2(\Omega L)+\frac{1}{\Omega L}\tanh(\Omega L)-\frac{\delta^2}{q_0^2}\right], \tag{2b}$$

where $\Omega\equiv(q_0^2-\delta^2)^{1/2}$. Notice that both $T(\delta)=|t(\delta)|^2$ and $\tau_g(\delta)$ show a minimum at the center of the gap, i.e., for $\delta\sim 0$, and one has $T\sim 1/\cosh^2(q_0L)$ and $\tau_g\sim(Ln_0/c_0)\tanh(q_0L)/(q_0L)$ near $\delta=0$. In this case, a spectrally-narrow pulse centered at $\delta=0$ can cross the barrier without appreciable distortion of its shape, albeit attenuated, with a group velocity $v_g$ given by

$$v_g\equiv\frac{L}{\tau_g}=\frac{c_0}{n_0}\frac{\operatorname{arctanh}\sqrt{R}}{\sqrt{R}}, \tag{3}$$

where $R=1-T$ is the power spectral reflectivity at the band-gap center. Superluminal tunneling, corresponding to $v_g>c_0$, occurs for a sufficiently opaque barrier such that $\operatorname{arctanh}\sqrt{R}>n_0\sqrt{R}$ [14].

In Fig. 1 we show the measured spectral power transmission $T$ and group delay $\tau_g$ versus frequency detuning $\nu=(\omega-\omega_B)/(2\pi)$ for one of the periodic FBG used in the experiments; in the figure are also shown the theoretical curves as given by Eqs. (2a) and (2b). Parameter values are $L=2$ cm, $h_0=0.2345\times10^{-4}$, $n_0=1.452$, and $\omega_B=2\pi\times195.58$ THz, which correspond to a band gap of $\sim$12 GHz full width at half maximum (FWHM) near $\lambda_B=1533.8$ nm (in vacuum) and to a minimum power transmission of $T\sim1.5\%$ at the gap center. The group delay was measured using a modulation phase shift technique [15], which is a commonly used method for the characterization of FBGs. Notice that the experimental curves for both spectral transmission and group delay show a slight asymmetric behavior around the Bragg resonance; this is probably ascribable to local change of average refractive index $n_0$ along the 2-cm fiber and to imperfections in the fabrication process, which introduce some residual chirp. Despite this asymmetry, the spectral measurement of group delay clearly shows that superluminal tunneling should occur for an optical pulse tuned inside the band gap.

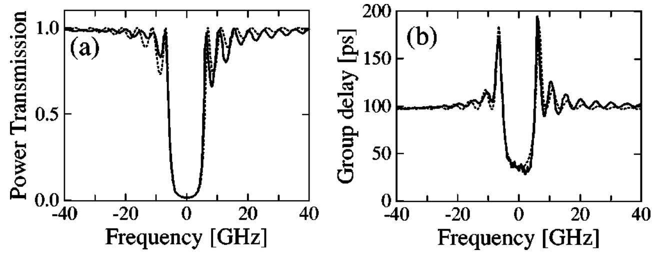


FIG. 1. Spectral power transmission (a) and group-delay (b) for the periodic 2-cm-long FBG used in the experiment. Solid and dashed lines refer to measured and predicted spectral curves, respectively.

The tunneling experiments were performed using pulses with $\sim$380-ps duration, corresponding to a spectral pulse bandwidth about one-fifth of the grating band gap. A schematic diagram of the experimental setup is shown in Fig. 2. A pulse train, at a repetition frequency $f_m=1$ GHz, was generated by external modulation of a single-mode stabilized Er-Yb laser [16]. The 18-cm long laser cavity is end-pumped at 980 nm by an InGaAs laser diode and comprises a 300-$\mu$m thick BK7 etalon that allows for a tuning of the emission laser wavelength by few nanometers at around 1533 nm; a finer tuning ($<$800 MHz) of the laser frequency, when necessary, was achieved by a submicrometric control of the laser cavity length using a piezoelectric transducer mounted on the output laser mirror. The pulse train

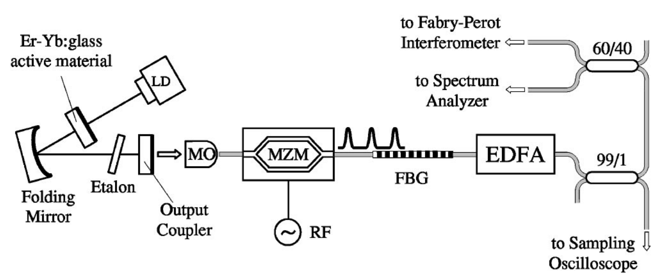


FIG. 2. Schematic of the experimental setup. LD, pump laser diode; MO, microscope objective; MZM, Mach-Zehnder waveguide modulator; EDFA, erbium-doped fiber amplifier.

was generated by sending the laser output to a $LiNbO_3$-based Mach-Zehnder modulator sinusoidally driven at a frequency $f_m$ by a radio-frequency (RF) synthetizer. For a waveguide modulator with chirp compensation, which applies to our case, the frequency chirping introduced by the modulator may be neglected and the output optical field envelope $E$ is given by

$$E(t)=E_0 \cos[\delta_0+\delta_m \sin(2\pi f_m t)]\exp(i\omega_0 t), \quad (4)$$

where $E_0$ is the amplitude of the electric field at the input of waveguide, $\omega_0$ is the carrier frequency of the laser, and $\delta_0$, $\delta_m$ define the bias point and modulation depth impressed to the modulator by the sinusoidal RF voltage. Different pulse durations and pulse shapes can be achieved in this way by varying both bias point $\delta_0$ and amplitude modulation $\delta_m$. In our experiments, the bias voltage and modulation depth were typically chosen to give $\delta_0 \sim 0.74\pi/2$ and $\delta_m \sim 0.29\pi/2$. For these parameters, a train of pulses, with a pulse duration (FWHM) of $\sim 380$ ps and 1-ns periodicity, was generated with an average optical power of $\sim 2$ mW. The pulse train transmitted across the FBG was sent to a low-noise erbium-doped fiber amplifier, with a saturation power of $\sim 30$ $\mu$W, that maintains the average output power level of the optical signal at a constant level, equal to $\sim 18$ mW, for an average input power signal larger than $\sim 30$ $\mu$W. In this way, the power levels of the transmitted pulse trains, for the laser emission tuned either inside or outside the band gap of the grating, were comparable. We notice that, since the pulse bandwith ($\sim 2$–3 GHz) used in the experiment is very narrow as compared to that of erbium (a few tens of nanometers), pulse reshaping effects introduced by the optical amplifier are fully negligible as compared to those provided by the FBG. The pulse train transmitted across the FBG was characterized in the frequency domain using both a scanning Fabry-Perot interferometer (Burleigh Mod. RC1101R) with a free-spectral range of $\sim 27$ GHz and a finesse of $\sim 90$, and an optical spectrum analyzer (Anritsu Mod. MS9710B) with a resolution of 0.07 nm. The pulse train was simultaneously detected in the time domain by sending a fraction of the transmitted optical signal to a fast photodiode connected to a sampling oscilloscope (Agilent Mod. 86100A), with a low jitter noise (less than 1 ps) and an impulsive response of $\sim 15$-ps width; the sensitivity of this apparatus to phase shifts is of the order of 1 ps. The electrically-converted signal at the sampling oscilloscope was triggered by the low-noise sinusoidal RF signal that drives the Mach-Zehnder modulator, thus providing a precise synchronism among successive pulses in the train. By a proper tuning of the laser wavelength, we recorded the trace of transmitted pulses, as measured on the sampling oscilloscope, for different tuning conditions (see Fig. 3). We first detuned the pulse spectrum far away from the center of the FBG gap by about 120 GHz, and the transmitted pulse train was recorded on the sampling oscilloscope [trace 1 in Fig. 3(a)]. In this case Bragg scattering inside the grating is negligible and the pulse travels across the barrier with a velocity equal to $c_0/n_0$. By looking at the spectrum analyzer and Fabry-Perot interferometer, we then tuned the laser spectrum close to the center of the band gap [see Fig. 3(b)], and recorded the trace of transmitted pulse [curve 2 in Fig. 3(a)]. A temporal advancement of the transmitted pulse peak of $\sim 63$ ps *without appreciable pulse distortion* is clearly observed. Notice that the measured pulse advancement is in rather good agreement with the value predicted by the phase time analysis, and corresponds to a velocity for barrier crossing equal to $v_g \sim 1.97c_0$, very close to the theoretical value $v_g \sim 1.94c_0$. We finally detuned the spectrum of the pulse apart from the band-gap center by $\sim 7$ GHz, i.e., close to the first side peak of transmission curve at the band-gap edge, as shown in Fig. 3(b). In this case, the behavior of group delay [see Fig. 1(b)] indicates a peak pulse delay, as compared to off-resonance propagation, of $\sim 65$ ps, i.e., pulse slowing down occurs for such a tuning condition. The pulse trace in this case [curve 3 in Fig. 3(a)] clearly shows pulse slowing down with a pulse peak delay of $\sim 60$ ps, close to the expected value. Notice that in this case a slight pulse distortion is appreciable, which is due to spectral pulse reshaping produced by the rapidly-varying spectral

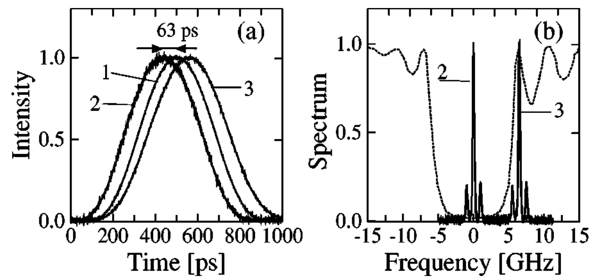


FIG. 3. (a) Pulse traces (in arbitrary units) recorded on the sampling oscilloscope corresponding to transmitted pulses for off-resonance (curve 1) and on-resonance (curve 2) propagation. Curve 3 is the pulse trace measured when the pulse spectrum is tuned close to the right-side edge of the FBG. (b) Spectrum of the probing pulse train, as measured by the scanning Fabry-Perot interferometer, corresponding to on-resonance (curve 2) and band-gap edge (curve 3) tuning conditions. The dotted curve is the measured spectral power transmission of the FBG. The tuning condition corresponding to 120 GHz off-resonance operation falls outside the frequency window shown in the figure.

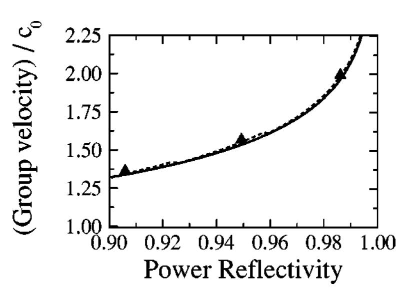


FIG. 4. Behavior of group velocity $v_g$ for barrier crossing, normalized to the speed of light in vacuum $c_0$, as a function of power reflectivity $R$ at the band-gap center for a uniform FBG with $q_0 = 140$ m$^{-1}$. The solid curve is the theoretical behavior as predicted by numerical propagation of pulse train (4) with $\delta_0 \sim 0.74\pi/2$, $\delta_m \sim 0.29\pi/2$, and $f_m = 1$ GHz; the dashed curve is obtained by the phase time analysis [Eq. (3)]; triangles refer to measured traversal velocities for three FBGs.

transmission and group delay near the band-gap edge (see Fig. 1). We checked that the observed superluminal tunneling time is easily reproducible and persists by changing the operational conditions of the Mach-Zehnder modulator, i.e., pulse duration and modulation frequency. In further experiments, we measured the group velocity corresponding to pulse propagation across FBGs with different lengths, i.e., barrier thickness, designed and fabricated to have the same Bragg wavelength and comparable bandwidth, i.e., the same value of $q_0$. According to Eq. (3), the group velocity is in turn a function of the peak power reflectivity $R$ solely, which depends on the barrier thickness $L$ according to $R=\tanh^2(q_0L)$. For a refractive index $n_0=1.452$, $v_g/c_0$ becomes larger than one for $R>\sim 70\%$ and tends to infinity as $R$ approaches unity. The experimental results, corresponding to three FBGs with lengths of 1.3 cm, 1.6 cm, and 2 cm, are shown in Fig. 4 (triangles), together with the theoretical curves obtained by either numerical propagation of the pulse train [Eq. (4)] through the FBG or by phase time analysis [Eq. (3)].

In conclusion, we have reported on the experimental observation of superluminal tunneling of picosecond optical pulses at 1.5-$\mu$m wavelength across the photonic barrier provided by a periodic FBG. The large barrier thickness ($\sim 2$ cm) as compared to the wavelength of tunneled photons ($\sim 1.5$ $\mu$m) enabled us to reach superluminal peak pulse advancements in the picosecond time scale, which are easily detectable using direct time-domain optoelectronic measurements. We envisage that the use of FBGs as photonic barriers may be of potential interest in the field of optical communications to either accelerate or slow down the propagation of picosecond optical pulses.

S.L. gratefully acknowledges fruitful discussions with E. Recami.

[1] V.S. Olkhovsky and E. Recami, Phys. Rep. **214**, 339 (1992).
[2] R.Y. Chiao and A.M. Steinberg, Prog. Opt. **37**, 345 (1997).
[3] E. Recami, F. Fontana, and R. Garavaglia, Int. J. Mod. Phys. A **15**, 2793 (2000).
[4] J. Marangos, Nature (London) **406**, 243 (2000).
[5] G. Nimtz and G.W. Heitmann, Prog. Quantum Electron. **21**, 81 (1997).
[6] Workshop on superluminal velocities, Ann. Phys. (Leipzig) **7**, 591 (1998).
[7] A.M. Steinberg, P.G. Kwiat, and R.Y. Chiao, Phys. Rev. Lett. **71**, 708 (1993).
[8] Ch. Spielmann, R. Szipöcs, A. Stingl, and F. Krausz, Phys. Rev. Lett. **73**, 2308 (1994).
[9] A. Ranfagni, D. Mugnai, P. Fabeni, and G.P. Pazzi, Appl. Phys. Lett. **58**, 774 (1991); D. Mugnai, A. Ranfagni, and L. Ronchi, Phys. Lett. A **247**, 281 (1998).
[10] A. Enders and G. Nimtz, Phys. Rev. B **47**, 9605 (1993); W. Heitman and G. Nimtz, Phys. Lett. A **196**, 154 (1994).
[11] See, for instance, T. Ergodan, J. Lightwave Technol. **15**, 1277 (1997), and references therein.
[12] J.E. Sipe, L. Poladian, and C. Martijn de Sterke, J. Opt. Soc. Am. A **11**, 1307 (1994).
[13] M.J. Ablowitz, Stud. Appl. Math. **58**, 17 (1978).
[14] The fact that the group velocity $v_g$ of a pulse exceeds $c_0$ does not imply violation of the principle of causality. Indeed, for a smoothly varying pulse, infinitely extended in time, $E(t-L/v_g)$ is just an analytic continuation of the input pulse, and a very small leading edge of the pulse enables one to predict the entire pulse. Conversely, the front of any wave form $E(t)$ that starts at $t=0$, i.e., for which $E(t)=0$ for $t<0$, propagates in any linear and causal medium at a velocity equal to $c_0$, not $v_g$. These points have been extensively discussed by several authors, and hence we refer the reader to previous works for more details [see, e.g., [2]; see also L. Brillouin, *Wave Propagation and Group Velocity* (Academic, New York, 1960); J.D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1975), pp. 315 and 316; G. Nimtz, Eur. Phys. J. B **7**, 523 (1999); M. Mojahedi, E. Schamiloglu, F. Hegeler, and K.J. Malloy, Phys. Rev. E **62**, 5758 (2000)]. Here we just point out that, for the model given by Eqs. (1a) and (1b), causality is ensured because $t(\delta)\exp(-i\delta L)$ is an analytic function of $\delta$ in the upper half plane $\mathrm{Im}(\delta)>0$ (see [13]) and because $n_0\to 1$ and $q\to 0$ as $\omega\to\infty$ when material dispersion of the fiber is properly taken into account.
[15] B. Costa, D. Mazzoni, M. Pulseo, and E. Vezzoni, IEEE J. Quantum Electron. **QE-18**, 1509 (1982); S. Ryu, Y. Horiuchi, and K. Mochizuky, J. Lightwave Technol. **7**, 1177 (1989).
[16] P. Laporta, S. Taccheo, S. Longhi, O. Svelto, and C. Svelto, Opt. Mater. **11**, 269 (1999).