Broadband time-reversal of optical pulses using a switchable photonic-crystal mirror

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Abstract

We propose a new time-reversal scheme for optical pulses which overcomes the limitations of existing schems. As examples, we demonstrate highly efficient and broadband reversal of pulses of 100 fs and 10 ps duration.

1. Introduction

Time-reversal is one of the most spectacular yet elusive wave phenomena. A time-reversed pulse evolves as if time runs backward, thus eliminating any distortions or scattering that occurred at earlier times. This enables applications in diverse fields such as medical ultrasound [1], communication systems and adaptive optics [2], superlensing [3], ultrafast plasmonics [4], biological and THz imaging [5] and quantum information and computing [6].

For low frequency waves (e.g., in acoustics, spin waves etc.), time-reversal is accomplished by electronic sampling and playing back. This is possible since in this frequency range, the pulse oscillates on a scale slower than electronic sampling speed. On the other hand, for high frequency (i.e., optical) electromagnetic waves, the carrier frequency, and even the pulse envelope, are too short to be sampled properly by even the fastest electronic detector. The standard solution in the optical regime is to use nonlinear processes such as Three-Wave or Four-Wave Mixing [2]. However, while such techniques routinely performed experimentally, they require fairly high intensities, thus, limiting on-chip integration; almost all existing schemes are narrowband whereas the schemes which are applicable to relatively short pulses are in general complex, requiring complicated setups and sometimes even cryogenic temperatures. Finally, some schemes may be difficult to apply to 2- and 3-dimensional systems.

2. The new reversal scheme

In this study, we offer an alternative approach which overcomes those limitations. In order to understand the principle at the heart of our scheme, recall that when a pulse is reflected by a (standard) mirror, its spatial components change their propagation direction *at different times*, i.e., the leading edge first and trailing edge last etc.. Thus, the pulse undergoes a *U-turn* whereby the leading edge remains the leading edge etc.. Now, imagine that one could change the direction of the pulse propagation *at all points in space at the same time*. Then, obviously, the leading edge will become the trailing edge, and vice versa, i.e., the pulse is (time-) reversed.

Such an extreme manipulation requires to reduce the transmissivity of the medium to zero uniformly and abruptly for *a spectral band as wide as possible*. One way to do that is to dynamically modulate the material properties in a periodic manner so that a frequency bandgap encompassing the pulse is opened. Then, heuristically, when the bandgap is turned-on, the wave cannot propagate in any direction. Instead,

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forward waves are repeatedly converted to backward waves, then to forward waves and vice versa. If one can re-establish the medium transmissivity once most of the energy of the forward wave has been converted to a backward wave, then the pulse is effectively time-reversed. In a sense, this procedure transforms a perfectly transmitting medium into a "volume" mirror for a brief moment, thus sending the pulse "in reverse".

Such techniques lie within the realm of dynamic photonic crystals (PhCs). Originally, the idea of using dynamically PhCs for the purpose of time-reversal was proposed in the pioneering work of Yanik and Fan [7]. However, despite being very effective, the design they proposed is still very challenging even with contemporary fabrication technology; in addition, it allows for reversal of relatively narrow pulses.

Following the heuristic explanation above, in this study, we show that efficient and broadband time-reversal of optical pulses can be obtained in very simple PhCs, such as layered structures or even a homogeneous, but periodically tunable material. This technique was independently studied theoretically by us in the context of optics, and experimentally demonstrated for microwave spin waves [8]. We perform a detailed analytical study of the reversal process and discuss the implementation in optics in detail [9, 10, 11].

For pulses as short as a few picoseconds, a 100% reversal efficiency can be easily obtained using index modulations on the scale of 10^{-3} (see Fig. 1(d)), accessible in a variety of materials. Importantly, the modulation can be slow enough so that it can be done electronically with standard linear modulators. The required energies are significantly lower than those required in wave-mixing based schemes. For shorter pulses, the index modulations can be performed with a short intense pulse. In this case, the required efficiencies are lower, see Fig. 1(c).

Our scheme has several advantages over existing ones for time-reversal of optical pulses [11]. The major advantages of our scheme are the superior reversal efficiency, the simplicity of the required structures (e.g., which are not complicated by the need for phase-matching) and the ability to use linear modulators or a single pump pulse etc.. Other advantages are that the reversal can be performed for any angle of incidence, for plane-waves as well as for beams, and for high dimensions. In that respect, our scheme, which requires only a periodic modulation, rather than complex optics-specific concepts, opens the way for time-reversal in many other systems for which time-reversal was not accessible before, such as quantum systems.

3. Theory and simulations

In order to demonstrate our scheme, we study wave propagation in a one-dimensional structure. In this case, the wave propagation is governed by the following wave equation

$$E_{xx}(x,t) = \frac{1}{c^2}\left[n^2(x,t)E(x,t)\right]_{tt}, \qquad n(x) = n(x+d). \tag{1}$$

For a discussion on the effects of dispersion, see [10]. Following an analysis similar to that performed in [12] for soliton propagation in PhCs, we derive the envelope equations describing the evolution of the forward and backward components. We further show that in the weak coupling limit, the envelope equations can be solved analytically. In this case, our analysis shows that the amplitude of the reversed pulse is given by

$$|b| = \sqrt{\pi}\, T_{mod}\, \omega_c\, m_{rev}\, \Delta n, \tag{2}$$

where ω_c is the carrier frequency of the incident pulse, T_{mod} is the modulation time, $m_{rev} \leq 0.5$ is a constant which depends only on the refractive index (indices), and Δn is the depth of refractive-index modulations.

In order to validate the analysis, we performed extensive numerical simulations. In Fig. 1(a), we plot the wave amplitude at the input side of the PhC as a function of time. The leading and trailing parts have clearly exchanged roles. We also show that the solutions of the wave equation (1) and the envelope equations are in excellent agreement. Fig. 1(b) shows a spatio-temporal contour map of the pulse propagation. A comparison of the reversal efficiencies as a function of the modulation strength is shown in Fig. 1(c)-(d). We employ realistic parameters corresponding to a Silicon PhC at $\lambda_c = 1550$nm. Fig. 1(c) shows reversal efficiency of $\sim$ 7-cycle pulses and verifies that the solutions of the wave equation (1), the envelope equations and the analytical solution are all in good agreement. The reversal efficiencies in this case are rather low, however, they are still somewhat higher than those of previous schemes. Fig. 1(d) shows simulations of longer pulses for which there is, again, very good agreement between the numerical and analytical solutions up to high efficiencies ($\sim 50\%$). At even higher efficiencies, the analytical approximation overestimates the reversal efficiency because at such high efficiencies, the forward wave amplitude is significantly decreased, thus providing a weaker source for conversion. Nevertheless, the solutions of the envelope equations show that a 100% reversal efficiency can be achieved in this configuration with index changes only slightly higher than those predicted analytically.

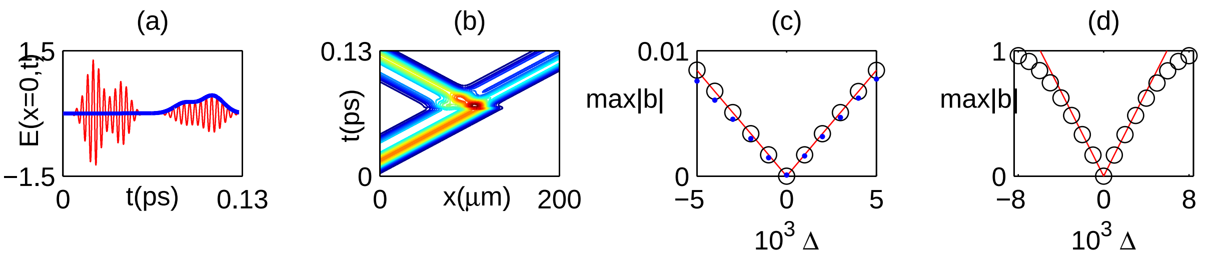

Fig. 1: (Color online) (a) Wave amplitude (red line) and the associated backward wave envelope (blue line) at the input side of the PhC as a function of time. (b) A spatio-temporal contour map of the pulse propagation in (a). (c) Reversal efficiency of a 30fs pulse as a function of the index change Δn. Shown are numerical solutions of the wave equation (blue dots) vs. the solution of the envelope equations (black circles) and the analytical solution (red solid line). (d) Same as (c) for 10ps.

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