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Demonstration of an Ultrafast Logic Gate by Interference of Coherent Transients

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Abstract—We demonstrate an ultrafast three-port all-optical Taffoli logic gate by using interference of femtosecond laser pulses with two-pulse photon echo in dye-doped polymer films at low temperatures. The gate performs an operation of "controlled controlled NOT" on the time scale of less than 1 ps, using one spatial spot. We show that important condition for this gate is causal nature of the coherent transient response. Relevant truth table is implemented only if pulses coming later in time do not influence the interference of the pulses applied earlier in time. The other special property of the gate is coherent phase memory about the input pulses. We suggest that if the excited electronic state coherence time is much longer that the duration of the pulses, then it is possible to implement a coherent logic gate with a large number of inputs.

INTRODUCTION

Possible implementations of ultrafast logic gates and switches are of great interest in the field of optical computing [1, 2], and most recently in quantum computing [3]. A variety of nonlinear optical phenomena, including soliton propagation in fibers [4], frequency conversion [5], Kerr effect [6] etc., have been proposed in the past to construct fast optical gates and switches. Coherent optical transients in frequency selective media such as photon echo [7] provide a means of constructing analog processing devices such as correlators [8–10], memories [11, 12] and delay lines [13, 14]. The nonlinear character of the coherent transients, if combined with proper thresholding procedures, can be used to construct logical processing elements [15]. Previously, interference between holograms recorded by persistent spectral hole burning was used to implement a XNOR gate [16]. In addition, interference between coherent transients has been controlled by external electric field [17, 18]. Superposition of spatial–spectral gratings, shifted by a half grating period, has been used to erase and address data by destructive interference in certain sections of time-domain data sequences [19–22].

Previously, interfering spatial–spectral gratings were produced either by persistent spectral hole burning or by some semitransient storage mechanism. Recording of such accumulated gratings requires a relatively long exposure time, which makes the previous techniques not applicable for fast optical logic operations. In this work, we use interference between true transient polarization, not associated with any permanent feature or grating. This allows us to demonstrate an all-optical logic gate operating in real time on subpicosecond scale. We implement a three input/three output "controlled, controlled NOT" gate, also known as Taffoli gate. This particular type of logic gate satisfies the conditions as a universal gate [23], and is relevant in recent discussions about quantum computing [24]. Although our present realization does not involve quantum mechanical entanglement, the transient photon echo phenomenon uses quantum coherence of individual molecules and is in this respect related to quantum computing. Such a gate is only possible because of the causal nature of coherent transients. To illustrate the essential role of causality, in the next section we discuss the causal interference of coherent optical transients. In the following section, we discuss our experiment on implementation of a logic gate by using femtosecond photon echo in dye-doped polymer at low temperature.

INTERFERENCE OF LIGHT PULSE WITH TWO-PULSE PHOTON ECHO

The phenomenon of photon echo can be described as scattering process from a transient spatial–spectral grating [25]. These gratings are created by nonlinear interaction of two or more light pulses illuminating an inhomogeneously broadened, spectrally selective resonantly absorbing medium. Nonlinearity reflects the fact that the interaction of the excitation pulses with a two-level resonant medium is a function of saturation and nonequilibrium polarization, which vanishes in the limit of low pulse intensity. The spectral selectivity is due to the inhomogeneous broadening of the resonance medium, which in turn is related to the fact that at low temperatures the homogeneous dephasing time T_2 can

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be orders of magnitude longer than the inverse value of the inhomogeneous band width, $T_2 \gg 1/\Gamma_{inh}$.

Two-pulse photon echo is generated by illuminating the resonance medium with two spatially overlapping laser pulses, propagating in unit vector directions, $\mathbf{n}_1$ and $\mathbf{n}_2$. Let us assume that the duration of the excitation pulses is short compared to the homogeneous dephasing time, but long compared to the inverse inhomogeneous line width, $T_2 \gg t_p \gg 1/\Gamma_{inh}$. The amplitudes of the pulses can be written as

$$E_1(\mathbf{r}, t) = \varepsilon_1(t - \eta_1)e^{i\omega(t - \eta_1)},$$
$$E_2(\mathbf{r}, t) = \varepsilon_2(t - \eta_2)e^{i\omega(t - \eta_2)}, \tag{1}$$

where ω is the carrier frequency, $\varepsilon(t)$ is the temporal amplitude profile of the pulses, the propagation phase factor is

$$\eta_i = \frac{\mathbf{n}_i \cdot \mathbf{r}}{c} + t_i, \quad i = 1, 2. \tag{2}$$

and the time delay between the pulses at the origin is $\tau_{12} = t_2 - t_1$. The delay between the pulses is assumed to be much less than the optical coherence time of the material T_2, but longer than the coherence time of the pulses. If the excitation pulses have sufficient intensity, then they will produce a macroscopic polarization of the medium, giving rise to coherent transient response or photon echo. In the usual approximation of moderate pulse intensity the polarization amplitude is

$$P_e(\mathbf{r}, t) \propto \varepsilon_e(t - \eta_e)e^{i\omega(t - \eta_e)}, \quad \eta_e = 2\eta_2 - \eta_1, \tag{3}$$

where,

$$\varepsilon_e(t) = \int_{-\infty}^{\infty} dt' \int_{-\infty}^{t'} dt'' \varepsilon_1(t - t' + t'' - \tau_{12})\varepsilon_2(t')\varepsilon_2^*(t''). \tag{4}$$

Now let us assume that a third pulse, with amplitude

$$E_3(\mathbf{r}, t) = \varepsilon_3(t - \eta_3)e^{i\omega(t - \eta_3)}. \tag{5}$$

is applied in direction $\mathbf{n}_3$, close to the direction of the echo, and is propagating through the sample. If a photodetector is placed behind the sample in the direction $\mathbf{n}_3 \approx \mathbf{n}_e$, then the intensity reaching the detector is a superposition of the third beam and the echo:

$$I_3 \propto |\varepsilon_3|^2 + |\varepsilon_e|^2 + [\varepsilon_3\varepsilon_e^* e^{i\omega(\eta_3 - \eta_e)} + \text{c.c.}], \tag{6}$$

where for simplicity we have assumed that all excitation pulses are essentially δ-pulses. Figure 1a shows the three excitation pulses. Let us consider now an idealized situation, where the propagation directions and also the wave fronts of the echo and the third beam coincide. We also assume that the amplitude of the third pulse is equal to the amplitude of the echo polarization, $\varepsilon_3 = \varepsilon_e = \varepsilon$. Then the intensity at the detector will be given by a simple cosine function of the delay between the pulses:

$$I = 2|\varepsilon|^2(1 + \cos\omega(t_e - t_3)), \tag{7}$$

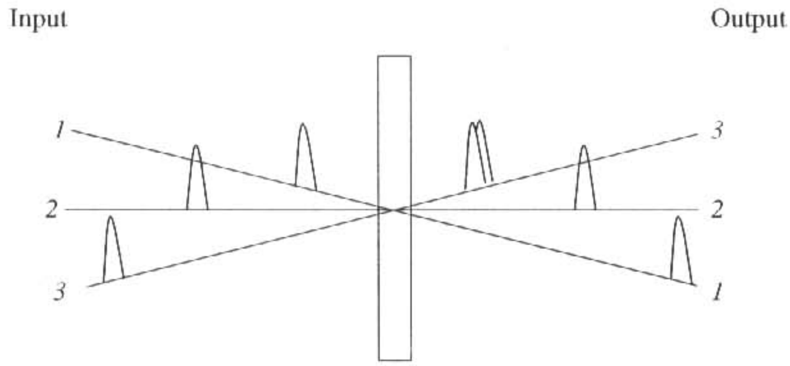
If the delay difference is an odd number of half wavelengths, then destructive interference occurs, and the intensity will be zero. In the opposite case, when the delay difference is an even number of half wavelengths, there will be constructive interference. In both cases the interference affects only the third beam and does not influence the first two beams. This is a direct consequence of causal nature of coherent transients in spectrally selective medium.

To further illustrate this point, note that the arrangement in Fig. 1a would give an essentially different result, if all three pulses would arrive at the medium at the same time. In that case, they would create a conventional spatial grating, which will scatter light in direction 1 and 2 as well as in direction 3, and interference will influence all beams practically on the same level. The operation of the causal interference on the three output beams, as a function of the three input beams, is summarized in the truth table shown in Fig. 1b. On the input side, "1" corresponds to excitation pulse in given direction, while "0" corresponds to no pulse. On the output side, "1" corresponds to finite intensity seen by detector in given direction and "0" corresponds to zero intensity. By comparing the input and output tables, we see that the first two inputs (1 and 2) control the output of channel 3: if the status of both channels 1 and 2 is nonzero, then the status of the third channel is inverted. Such logic gate is called Taffoli gate and it corresponds to "controlled controlled NOT" operation. The interesting property of Taffoli gate is that it constitutes a universal gate for reversible quantum computation [24]. Since classical computations are not reversible, any classical computation can be performed with an array of NAND gates. Similarly, any quantum, and therefore reversible, computation can be performed with an array of Taffoli gates.

The shaded cell on the output side of the truth table represents this single bit, whose status would be opposite, if the scattering from the grating would be symmetrical like described above for temporally coinciding pulses. The causal coherent response described in our experiment has a built-in "time arrow," which facilitates the implementation of Taffoli gate.

An important practical problem, which is often encountered in constructing interference-based optical elements, is how to ensure sufficient spatial uniformity of the interacting wave fronts. In many cases, a rather sophisticated set of methods to compensate for spatial wave front distortions is needed to make interference a practical device. In our present case, we need to ensure not only the spatial interference, but also the temporal

(a)



(b)

Input

pulse 1	pulse 2	pulse 3
0	0	0
0	0	1
0	1	0
0	1	1
1	0	0
1	0	1
1	1	0
1	1	1

Output

pulse 1	pulse 2	pulse 3
0	0	0
0	0	1
0	1	0
0	1	1
1	0	0
1	0	1
1	1	1
1	1	0

Fig. 1. Principle scheme of the three-port logic gate. (a) Two noncollinear pulses propagating in directions 1 and 2 excite two-pulse photon echo, propagating in direction 3. Pulse 3 is directed through the sample, at the time and in the direction of the echo pulse. (b) Truth table showing all six different possibilities for input and out put pulses. Ideal destructive interference between the echo and the third pulse is assumed.

and spectral shapes uniformity of the pulses. Perfect interference between the echo and the third pulse is possible only if the temporal and spatial wave fronts of the echo and third beam overlap exactly. Below we will investigate to which degree this condition can be fulfilled by using relatively simple means.

EXPERIMENTAL

Figure 2a shows the constituent parts of the experimental arrangement. The laser source was a regenerative-amplified Ti : sapphire femtosecond laser system (Clark MRX CPA 1000), which delivered at 1 kHz repetition rate pulses with average power 800 mW. The laser beam was expanded and the central portion of the wave front was selected with an iris diaphragm. Next, the beam was passed through a 50% beam splitter cube, BSC. The transmitted beam and the reflected beam were passed through optical delay lines DL1 and DL2, respectively. These two beams were crossed at an angle $\theta \sim 1°$ on the sample, which was immersed in liquid helium inside optical cryostat (CR) at temperature T = 2K. A thin beam splitter plate (BSP) was used to reflect a small fraction (2% energy) of the first beam. This third beam was directed at a corresponding double angle $\theta \sim 2°$ through the sample, in a direction roughly coinciding with the expected direction of the two pulse photon echo signal produced by the first two-pulses. The delay lines DL1 and DL2 were adjusted in such a way that the arrival time of the second pulse was about 1 ps after the first pulse and the third pulse arrived an equal interval after the second pulse. All three beams were spatially overlapped in the sample plane, and emerge on the output side of the cryostat, where they were captured with a CCD camera.

A pinhole PH was placed in the path of the laser beam, in order to select the central portion of the beam, providing for a relatively smooth spatial wave front of the excitation pulses. The beam spot size on the sample was ~3 mm^2. Average power in the first two excitation beams was on the order of 5 mW/cm^2. The power of the third beam was about 10^2 times lower than that of the first two beams, basically in order to match the power of the echo signal generated by the first two pulses. Absolute efficiency of the echo was about 0.1%.

The absorption spectrum of the sample is shown in Fig. 2b. The sample consists of a 50 μm thick polyvinyl butyral film doped with phthalonaphthaloanthracenocyanine molecules (Ciba HW 1009) [26] at a concen-

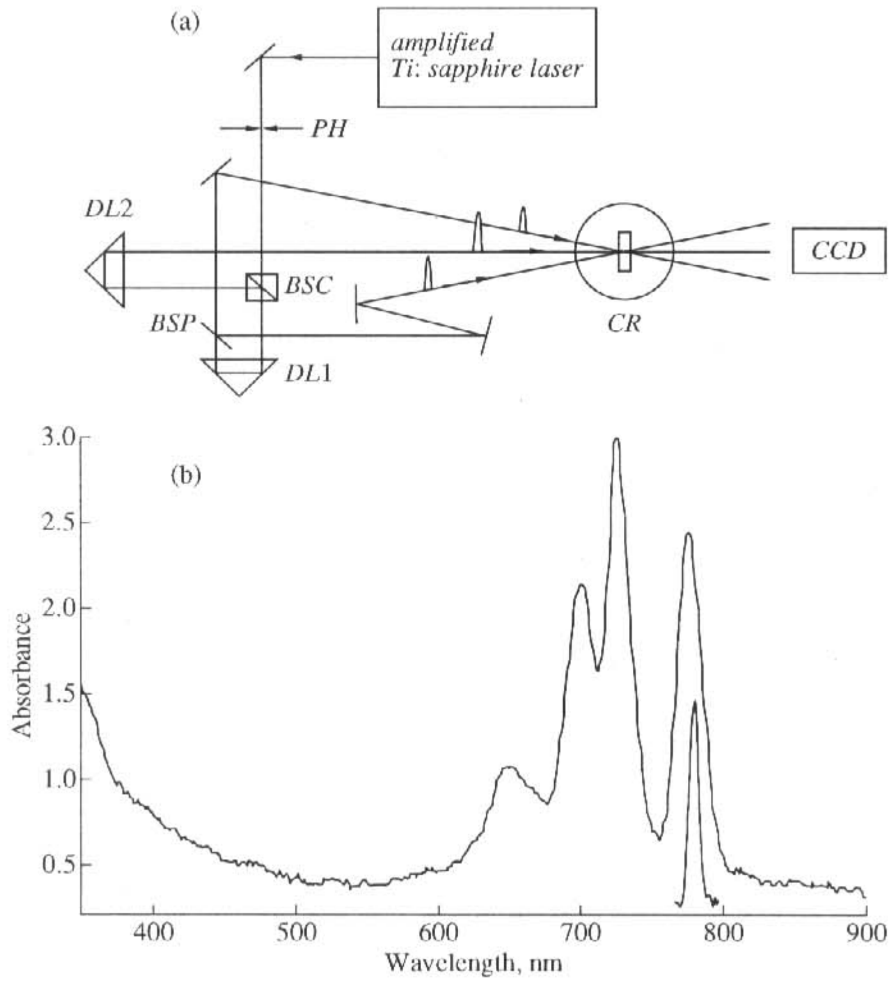


Fig. 2. Experimental arrangement. (a) Scheme of the optical setup: BSC, 50% beam splitter cube; BSP, 2% beam splitter plate; CR, cryostat; DL1, DL2, optical delay lines; CCD, video camera; PH, pinhole. (b) Absorption spectrum of phthalonaphthalocyanine molecules in PVB film (solid line) overlapping with the intensity spectrum of the excitation pulses (dashed line).

tration 10^{-3} mol/liter. Figure 2b also shows the intensity spectrum of the excitation pulses, which overlaps with the inhomogeneous band at 780 nm, corresponding to the transition from the ground state singlet S_0 to the first excited singlet state S_1. The inhomogeneous band width Γ_{inh} for this transition is on the order or broader than the 6 nm spectral width of the pulses, while the homogeneous line width at T = 2°K. was Γ_{hom} ~ 360 MHz [27].

RESULTS AND DISCUSSION

Figure 3 shows the spatial intensity distribution in the third output beam measured with the CCD camera for different combinations of input pulses. In these negative images, darker shading corresponds to higher image intensity. If either input pulse 1 or 2 (or both) was absent, then no photon echo was produced in the 3rd beam direction. Correspondingly, the recorded image was simply the transmitted 3rd beam or zero if this beam was also closed (Fig. 3a). The spatial intensity distribution of other two pulses was similar to that shown in Fig. 3a. If, on the contrary, the input pulse 3 was absent, but both other input pulses 1 and 2 were present, then the detected signal was the photon echo excited by pulses 1 and 2 (Fig. 3b). By comparing (a) and (b) we see that the echo wave front had a narrower width than the excitation pulses. This can be expected, because the echo signal is, at least in the first approximation, proportional to the third power of the excitation pulses. If we assume that both excitation pulses have a gaussian profile with the same half-width, then the spatial half-width of the echo signal should be less by a factor of 0.6. In our experiment this factor is about 0.8, which can be explained by relatively high optical density of the media, which can influence the apparent diameter of the beams at the output of the sample. Figure 3c shows the pattern, which was observed when all three input pulses were present. We see a clear interference pattern, with destructive interference taking place in the center of the beam and constructive interference

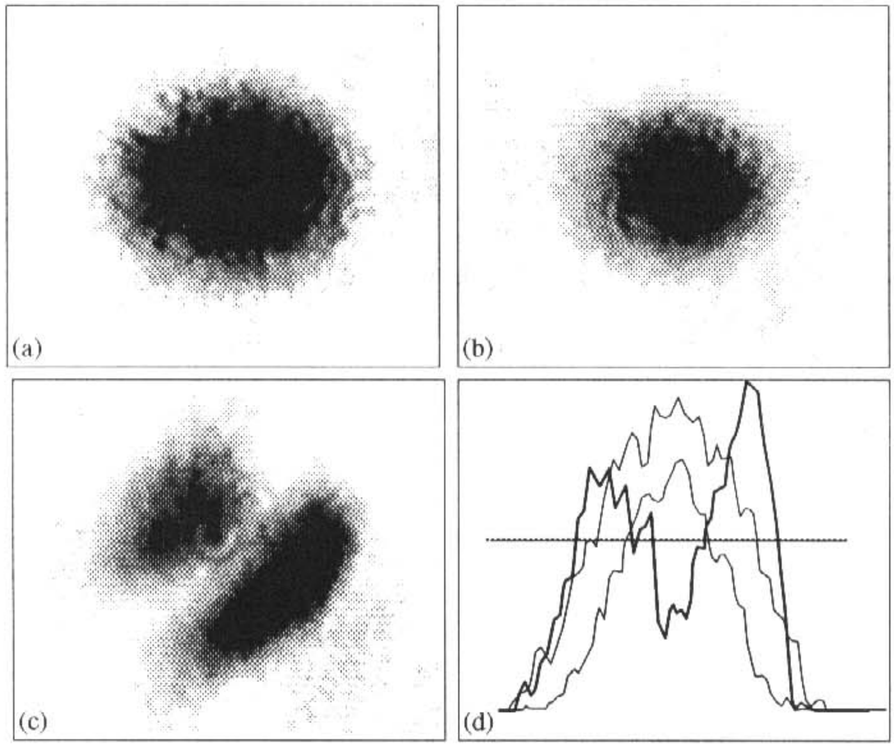


Fig. 3. Two-dimensional spatial intensity measured in the direction of the third beam for different input pulse combinations. Darker color corresponds to higher intensity. (a) Input pulses 1 and 2 are present while input pulse 3 is absent; (b) input pulse 1 or 2 (or both) is absent and input pulse 3 is present; (c) all three input pulses are present. Dashed horizontal line indicates where the intensity profile is measured; (d) one-dimensional intensity distribution in horizontal direction for image (a) dashed line, (b) solid line, and (c) bold solid line.

occurring on its sides. The observation of simultaneously both, constructive as well as destructive interference indicates that the spatial phase of the echo amplitude did not match exactly the phase of the third beam. In our experiment no special measures were taken (except one pinhole positioned in the laser beam) to guarantee that all pulses have a perfectly plain wave front. In this case, one can expect considerable phase distortions to occur, especially because of the known fact that the phase front of two-pulse echo is a phase conjugated replica of the first pulse [28]. In the situation, where the second pulse has a nonideal profile, the conjugation will strongly increase the distortion of the phase of the echo. This in its own turn will influence badly the shape and contrast of the interference fringes. Nevertheless, our results show that at least for a limited portion of the beam profile, a nearly perfect destructive interference is possible. Figure 3d shows one-dimensional cuts in horizontal direction through the spatial intensity distribution of images (a)–(c). If we set the threshold to distinguish between "0" and "1" as indicated by the dashed line in Fig. 3d, then the destructive interference in the center of the beam will give output value "0", while the other two lines, corresponding to (a) and (b) in Fig. 3 will give value "1". This is in correspondence with the functions, needed to accomplish the rows 2, 4, 6, 7, and 8 of the truth table Fig. 1a. The remaining three operations, corresponding to rows 1, 3, and 5, are essentially transmitted beams, which is trivial in the context of the present experiment.

In the following we will shortly discuss further points regarding the nature of the interference phenomenon. The first question is how fast can the logic operation be performed, or in other words, how much time does it take for the destructive interference tp occur. Here we concentrate on the microscopic properties of the effect and will exclude purely technical issues such as methods of generating, modulating and detecting of ultrashort light pulses. One should note that the echo phenomenon is itself a result of constructive interference between coherent polarization amplitudes of molecules (atoms). These oscillating microscopic polarization amplitudes are result of a special superposition state, excited by first two pulses between the ground and excited electronic states. In our experiment, we apply the third laser pulse, which depending on its relative phase brings the molecules into a different superposition state. Destructive interference takes place if, at a given time of the echo, the third pulse leads to decreased (or zero) interference between the coherent polarization amplitudes. Constructive interference, in turn, means that at the time of the echo there is more rephasing between the polarization amplitudes at different frequencies. The time needed to perform interference is then given by the overall duration of the sequence of three pulses, which in our case was on the order of 1–2 ps. This duration can be decreased further by using shorter pulses. However, since temporal overlap between the excitation pulses must be avoided for the reasons discussed earlier, perhaps the fastest operation is achieved within about three times the pulse duration.

A further interesting question to consider is what role energy conservation can have in the interference between coherent transients. In conventional optics, ideal interference can radically change the direction in which optical energy is routed, but cannot change the total balance between incoming and outgoing energy. For example, in the case of a simple beam splitter or diffraction grating illuminated by coherent monochromatic beams, the energy in one reflection or diffraction direction can be enhanced at the expense of reducing the energy in other directions. In our case, however, constructive or destructive interference does not appear to lead to an obvious redistribution of energy. One possibility to resolve this apparent contradiction is to consider higher order echoes, which are diffracted at larger angles relative to the first-order echo. In particular, it can be easily shown that coherent interaction between the third pulse and the first two pulses gives rise to echoes propagating at two- and threefold angles, and at correspondingly higher order time delays. In our present experiment, these higher order signals were rather weak, especially because we chose the third pulse to be considerably weaker than the first two pulses. From energy conservation rule one can conclude that if constructive (destructive) interference takes place in the third beam direction, corresponding increase (decrease) of the signal intensity should take place in the higher order echo directions. Another possibility is to consider energy redistribution, which takes place within the diffraction angle of the third beam itself, like that shown in Fig. 3d. To clarify this point, we will need in future more precise quantitative energy measurements of all emerging beams.

The optical coherence lasts in our resonant material for about 1 ns, which is by several orders of magnitude longer than the duration of the excitation pulses. This leads to a possibility of using higher order echoes to construct a coherent causal optical gate with many parallel inputs and outputs. As an extension of the scheme discussed above, we can think about a multiport optical switch, where channels are linked together by interference. Because many pulses can interact coherently within time T_2, we can estimate that the number N of input pulses can be tens, or, theoretically even thousands. If we would map all possible input and output pulse combinations, then we would get a truth table similar to that shown in Fig. 1b, but with 2^N rows and N columns. The question if such a multiport coherent gate has practical applications, e.g., in computing with large numbers, will be left open for future discussion. We only note here that although our present experiment does not involve quantum-mechanical entanglement other than superposition of molecule's ground and excited electronic state, the availability of long coherence time makes it possible coherent interaction between multiple data inputs.

CONCLUSIONS

We have proposed and implemented an all-optical logic gate, which makes use of interference between coherent transients in two-pulse photon echo excitation regime. The property of this interference is that it acts selectively, depending on the relative time delay between the excitation pulses. We showed that the optical coherence transfers the phase information about the pulses applied earlier in time to the pulses applied later in time but, due to causality, the reverse is not true—pulses applied later in time do not influence the interference of the pulses applied earlier in time. Based on this asymmetry we have demonstrated a Taffoli gate, which is a universal gate for certain quantum algorithms. Further, because we excite the photon echoes with femtosecond pulses, our gate is operating on ultrafast time scale. Finally, we have suggested that because the optical coherence time T_2 of the resonance medium is much longer than the duration of the excitation pulses, a coherent gate can be constructed with many input and output channels.

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