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Slowdown of group velocity of light in PPLN by employing electro-optic effect

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A theoretical model is proposed to numerically simulate the electro-optic effect in periodically poled lithium niobate (PPLN) on the slowdown of group velocity of ultrashort pulses. The simulation results show that, under the condition of wave-vector mismatching, the group velocity of ultrashort pulses can be controlled accurately by adjusting the DC electric field applied along the transverse direction (x-axis) of PPLN. Furthermore, the roles of other factors influencing the group velocity slowdown, including the intensity of input pulse, the wave-vector mismatching, and the operating temperature, are also analyzed and demonstrated.

Keywords: Transverse electric-optic effect; group-velocity control; PPLN; wave-vector mismatching.

1. Introduction

Slow light, which refers to the optical phenomenon marked by the substantially slowed down group velocity, is known to arise from light-matter interactions in the media, such as the atomic vapors,[1] semiconductors,[2] optical fibers[3] and various photonic crystal geometries. This optical phenomenon has attracted considerable attention due to its potential applications in optical buffers and optical signal processing.[4,5] Until now, the light-matter interactions used to obtain slow light can be generally divided into two categories. One draws support from the nonlinear effects to generate a rapid variation function of refractive index on the optical frequency within the "signal" light. The aforementioned nonlinear effects can be realized with the help of electromagnetically induced transparency (EIT),[6] coherent population oscillation (CPO),[7,8] and four wave mixing (FWM).[9] The other one modifies the spatial component (K-vector) of a propagating wave on the basis of the waveguide dispersion in a single negative metamaterial[10,11] or double negative metamaterials.[12] However, at least two laser resources and complicated operations are required in these schemes, and the complicated experimental system prevents its miniaturization and integration for the potential applications in future communication systems. Periodically poled lithium niobate (PPLN), which is of typical ferroelectric folded dielectric axes structure, has been extensively studied and considered as a versatile material for controlling the group velocity of light[13,14] and light polarization.[15] Recently, our previous work demonstrated that the group velocity of femtosecond pulses in MgO:PPLN can be tuned through cascaded quadratic nonlinearity generated from second harmonic generation (SHG) and difference frequency generation (DFG)[13] or Pockels effect.[14] The scheme proposed in Ref. 14 is straightforward to promise the possibility for the integration and miniaturization of key components which will be applied in the next generation optical communication systems.

Here we take a step further to demonstrate the slowdown of the group velocity of femtosecond pulses in PPLN with the application of transverse electro-optic effect. In this scheme, transverse DC voltage, intensity of input pulse, wave-vector mismatching, and operating temperature can serve as the influencing factors on the slowdown of the group velocity. By individually changing these factors, the slowdown of group velocity of pulses can be easily achieved and finely tuned. The new scheme, only consisted of a laser and a DC voltage source, greatly simplifies the experimental setup. Compared with other schemes, our scheme offers the advantages of low cost, simple operation and its potential integration on a microchip.

2. Theoretical Analysis

Assuming an extraordinary wave (EW) derived from a polarized beam splitter (PBS) is incident into a z-cut PPLN along y-direction (see Fig. 1). A pair of electrodes which is made of Ni is sputtered on the side surfaces of PPLN for conveniently applying a DC electric field along x-direction. The applied electric field drives the optical axes of the positive and negative domains in PPLN to rotate by angles of $+\theta$ and $-\theta$ with respect to the plane of polarization of input EW

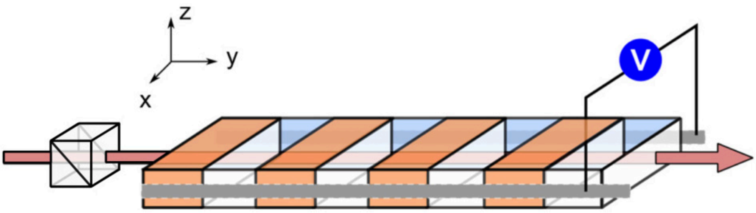


Fig. 1. Schematic for slowdown of group velocity of ultrashort pulse. The external voltage is conveniently applied on the electrodes sputtered on the side surfaces.

due to the transverse electro-optic effect.[16] Therefore, after passing through such a special structure whose each domain serves as a half wave plate, the plane of polarization of input pulse would change along the propagation in the PPLN. In our scheme, the poling period of PPLN is not chosen at the corresponding exact quasi-phase-matching (QPM) period of the input wavelength, so the wave-vector mismatching leads to "polarization coupling cascading" and makes the energy of input EW flow to the converted OW, but does not cause complete depletion. Then the energy flows back again. As a result, the input EW is decelerated by the group velocity difference between the EW and the OW.

To numerically model the scheme, the coupled wave equations under slowly varying envelope approximation can be generalized as follows:

$$\frac{\partial E_1}{\partial Z} + \frac{ik_1''}{2} \cdot \frac{\partial^2 E_1}{\partial t^2} = i\rho_1 E_2 \exp(i\Delta k_0 Z) + i\sigma_1[|E_1|^2 E_1 + 2|E_2|^2 E_1], \quad (2.1)$$

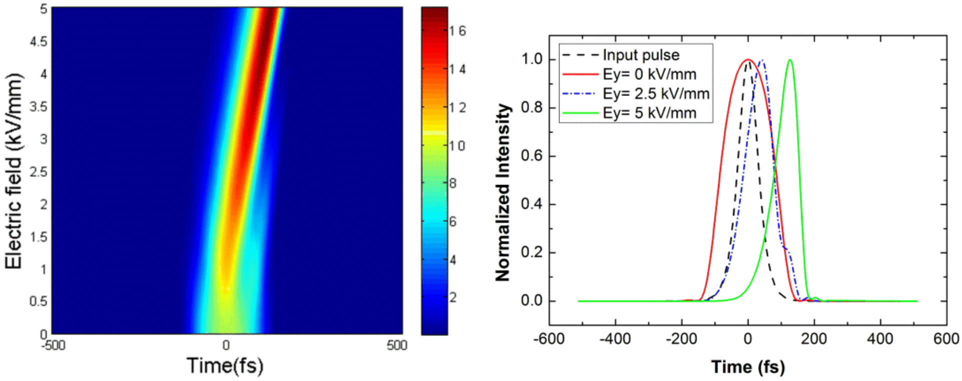
$$\frac{\partial E_2}{\partial Z} + \delta \cdot \frac{\partial E_2}{\partial t} + \frac{ik_2''}{2} \cdot \frac{\partial^2 E_2}{\partial t^2} = i(-\rho_2 E_1 \exp(-i\Delta k_0 Z)) + i\sigma_2[|E_2|^2 E_2 + 2|E_1|^2 E_2], \quad (2.2)$$

where $\rho_i(z) = \omega_i n_1^2 n_2^2 E_y \gamma_{51}/(c\sqrt{n_1 n_2})$ ($i = 1, 2$, which denotes the EW and the OW, respectively) and $\sigma_i = 3\omega_i \chi^{(3)}/(8cn_i)$. E_y denotes the applied DC electric field, $E_i(z,t)$ denotes the amplitude of the electric field of pulse, and n_1, n_2 denote the refractive indices of EW and OW, respectively. ω_i denotes the angular frequency. Time t is measured in a time frame of the input pulse. $\delta = k_1' - k_2'$ is the group velocity mismatching (GVM), where k_i' is the inverse group velocity, and $k_i'' = d^2k_i/d\omega^2$ is the group velocity dispersion (GVD), $\Delta k_0 = k_2 - k_1 = 2\pi(n_2 - n_1)/\lambda_0$ is the wave vector mismatching, where λ_0 is the central wavelength of the input pulse and k_i is the wave vector of the central frequency. The second terms on the right of Eqs. (2.1) and (2.2) indicate the cubic nonlinear process, including self phase modulation (SPM) and cross-phase modulation (XPM); they are critical in evaluating the duration of ultrashort pulses in even moderate intensity circumstances.

3. Simulation Results and Discussion

Assuming femtosecond pulses of 70 fs with its central wavelength located at 1550 nm are incident into a 20 mm-long PPLN, the initial operating temperature is set at 21°C. Making sure the wave-vector mismatching nonzero, the poling period is chosen at $\Lambda = 18.8\,\mu$m, which is close to the exact QPM period of $19.8\,\mu$m, and the corresponding wave vector phase mismatching $\Delta k = \Delta k_0 - \frac{2\pi}{\Lambda} = -0.0171$ ($1/\mu$m).

At first, we investigate the dependence of time delay of input pulse on the applied DC electric field [as shown in Fig. 2(a)]. A large amount of pulse delay can be achieved with the assistance of increasing the applied DC electric field. It means that the group velocity of pulse can be modulated and controlled accurately just by controlling the electric field. Figure 2(b) presents the output EW at different electric field intensities. The pulse broadens under the condition of no applying

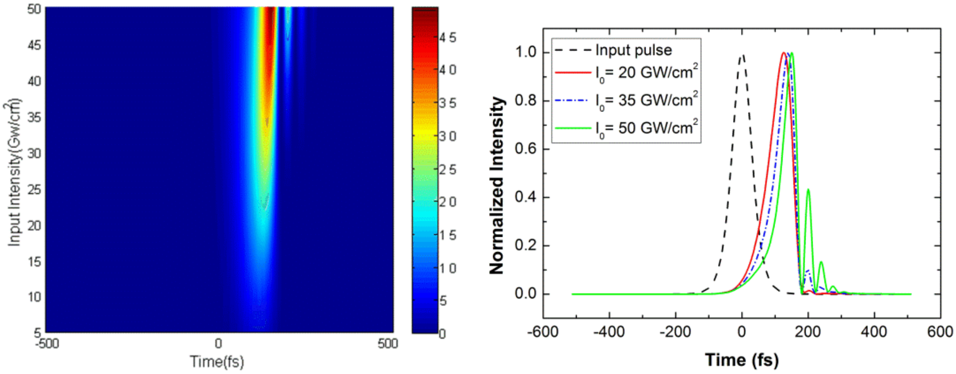


(a) (b)

Fig. 2. (a) The dependence of time delay of output pulse of EW on the applied electric field, where the intensity of input pulse $I_0 = 20\,\mathrm{GW/cm^2}$ and (b) the output EW at different applied electric fields. The black dash curve represents the input pulse. The red solid, blue dash dot, and the green solid represent the output pulse of EW at electric field of 0, 2.5 and $5\,\mathrm{kV/mm}$, respectively.

electric field because of group velocity dispersion. The time delay as large as 128 fs, which is 1.8 times the duration of input pulse, can be obtained at the applied electric field of $5\,\mathrm{kV/mm}$. However, the full width half maximum (FWHM) of output EW at $E_y = 5\,\mathrm{kV/mm}$ is narrower than that of $E_y = 2.5\,\mathrm{kV/mm}$ due to the large nonlinear phase shift induced by the phase inconsistence of nonconverted EW and the EW converted from OW.

Moreover, the relation between the time delay and the intensity of input pulse is also investigated in detail. From Fig. 3(a), setting the applied electric field fixed



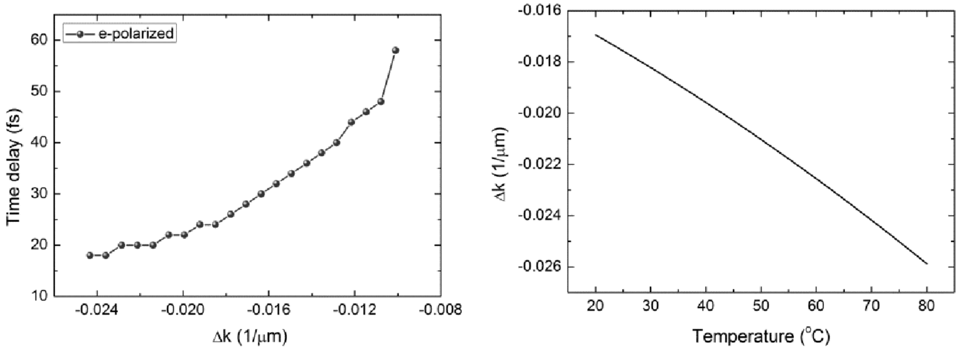
(a) (b)

Fig. 3. (a) The dependence of time delay of output pulse of EW on the intensity of input pulse, where the electric field $E_y = 5\,\mathrm{kV/mm}$ and (b) the output EW at different intensities of input pulse. The black dash curve is the input pulse. The red solid, blue dash dot and the green solid curves represent the output pulse of EW at input intensity of 20, 35 and $50\,\mathrm{GW/cm^2}$, respectively.

at 5 kV/mm, the time delay can be also modulated by controlling the intensity of input pulse. Therefore, we can conclude that the cubic nonlinearity induced by SPM and XPM contributes to the modulation of time delay of the pulse. Moreover, the time delay is varied in a smaller range than the one controlled by transverse electro-optic effect.

In Fig. 3(b), the time delays of 128, 136 and 144 fs are obtained by setting the intensity of input pulse at 20, 35 and 50 GW/cm^2, respectively. However, the intensity of input pulse could not go higher to achieve a larger time delay without distortion. The output EW at the input intensity of $I_0 = 50\,\mathrm{GW/cm}^2$ splits into three peaks due to the nonlinear phase shift induced by XPM and SPM. Therefore, the intensity of input pulse should not exceed 35 GW/cm^2.

When the wave-vector mismatching is not equal to zero, the reciprocal lattice vector provided by the periodic poling structure cannot fully compensate the phase difference between the EW and OW, and the energy of EW and OW converts into each other back and forth. The dependence of time delay on the wave-vector mismatching is demonstrated in Fig. 4(a). The curve of time delay grows moderately from 18 fs to 25 fs by changing Δk from $-0.022\,1/\mu$m to $-0.018\ 1/\mu$m, and then grows drastically after Δk beyond $-0.018\ 1/\mu$m, which indicates that the Δk determines the amount of energy exchange between the EW and the OW. A deeper energy exchange between EW and OW, when Δk approaches to zero, leads to larger time delay. Generally, Δk can be controlled by the operating temperature T and the poling period Λ. We further demonstrate that the relation between the temperature and the wave-vector mismatching Δk in Fig. 4(b). The wave-vector mismatching decreases with the increase of operating temperature and is inversely proportional to the operating temperature, which indicates less energy exchange between the EW and the OW in higher temperatures.



(a) (b)

Fig. 4. (a) Time delay of output pulse of EW as a function of wave-vector phase mismatching Δk and (b) the dependence of the wave-vector phase mismatching Δk on the operating temperature.

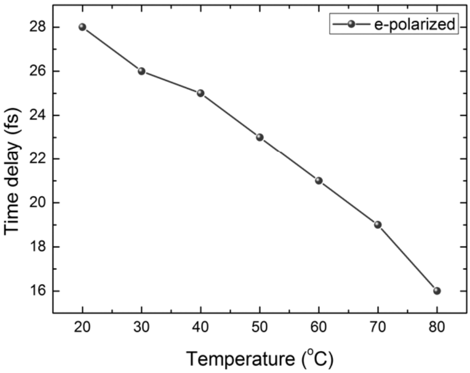


Fig. 5. The dependence of the time delay of output pulse of EW on the operating temperature, where the input intensity $I_0 = 20\,\mathrm{GW/cm^2}$ and electric field $E_y = 5\,\mathrm{kV/mm}$.

The relation between the time delay and the operating temperature is shown in Fig. 5. The pulse delay declines with the increase of operating temperature, which forces the Δk to decrease and depart away from zero. So less energy between EW and OW exchanges in higher temperatures and the influence on group velocity of pulse becomes weaker. Therefore, besides the ways for controlling the strength of applied electric field and the intensity of input pulse, the modulation of operating temperature is an another feasible and simple approach to control the time delay of pulse.

4. Conclusion

In conclusion, we present a full numerical simulation on the group velocity control of ultrashort pulses through quadratic and cubic nonlinear process based on individually controlling the applied electric field and the intensity of input pulse. The investigation reveals that the time delay induced by transverse electro-optic effect is larger than that induced by the intensity of input pulse. Moreover, the dependence of the time delay on the wave-vector mismatching Δk is also investigated in detail. As the Δk approaches to zero, a larger time delay can be achieved. Among the methods for changing Δk, the modulation of temperature is a simple and feasible approach to realize. It is also demonstrated that changing the operating temperature is an efficient way for slowing down the group velocity of ultrashort pulses.

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