Dependences of the group velocity for femtosecond pulses in MgO-doped PPLN crystal

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Abstract: Theoretical investigation on the group velocity control of ultrafast pulses through quadratic cascading nonlinear interaction is presented. The dependences of the fractional time delay as well as the quality factor of the delayed femtosecond pulse on the peak intensity, group velocity mismatch, wave-vector mismatch and the pulse duration are examined. The results may help to understand to what extent some optical operation parameters could have played a role in controlling the ultrashort pulses. We also predict the maximum achievable pulse delay or advancement efficiency without large distortions. A compact solid medium integrating multiple functions including slowing light, wavelength conversion or broadcasting on a single chip, may bring significant practicality and high integration applications at optical communication band.

OCIS codes: (190.0190) Nonlinear optics; (190.2620) Frequency conversion; (190.7110) Ultrafast nonlinear optics; (320.2250) Femtosecond phenomena.

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1. Introduction

Many interests have been focused on manipulating the group velocity of light pulses [1–4]. Its main goals include the understanding of physical laws for light pulse propagation as well as many promising applications such as controllable optical delay lines, all-optical memories, and data resynchronization devices for all optical communication [5]. Recent research has mainly focused on minimizing pulse distortion, producing a controllable pulse velocity and delaying a pulse by more than the width of the pulse. With the rapid growth of the transmitting data amount, techniques for controllably delaying ultrafast pulses are urgently demanded in future high speed and large capacity optical networks [5]. Slow light techniques that can offer large fractional delay and distortion-free propagation are especially attractive.

In Ref [6], Gauthier proposed pulse distortion can be avoided by operating in the nonlinear optical regime. By employing this method [7], Mok et al, obtained a slow-light delay time that is about two and a half pulse widths by using gap solitons. Noticing that most of the optical packets utilized in next-generation high speed information networks will become shorter and shorter in time domain in order to meet the practical requirement of a high data rate, high throughput performance in optical-telecommunication systems. Most pulse durations reported in previous study are of the order of millisecond to picosecond region. Group velocity control of femtosecond pulses was also demonstrated through $\chi^{(2)}$ cascading interactions in quasi-phase-match (QPM) gratings [8].

In this paper, the group velocity control performance based on $\chi^{(2)}$ cascading interactions was investigated in detail. Variation of the fractional delay as well as the delayed pulse quality in QPM gratings with different optical parameters was analyzed. An evaluation factor was also proposed to assess the performance of the delay controlling scheme at the end of our analysis. By this mean, the optimum conditions for best delay performance were found under different situations. In addition, it should be mentioned that in our previous research [9,10], all optical wavelength broadcasting and wavelength conversion can also be realized in such QPM gratings. By properly designing the poling period, we cannot only get different harmonic waves [11,12], convert the signal to desired wavelength but also slow down the signal pulse in C-band. Then we gain the ability to harness the photons in just one chip. This may pave the way for the realization of the photonic integrated chip which can create the optical equivalent of the silicon electronic chip for light-based signal-processing tasks in future all-optical networks.

2. Theoretical model

In our work, we consider that a femtosecond pulse with 50 fs duration is incident onto a z-cut 5 mol% MgO: PPLN crystal along y direction (see inset of Fig. 1). The signal pulse which is called the FF pulse (central wavelength at ω_{FF}) generates the second harmonic (SH) wave first, then the SH wave will be converted back to the FF due to wave-vector mismatching. When the energy is converted to the SH field, it propagates with the group velocity of the SH field. As a result, the signal experiences deceleration or acceleration since it is dragged by the slower or faster SH pulse depending on the sign of the slight group-velocity mismatch (GVM)

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and energy exchange between the signal and the SH. We choose *5mol%* MgO:PPLN crystal to be the representative medium due to its unique material dispersion [9,10,13]: in type-I geometry (e:o + o), the group velocity matching for second harmonic generation (SHG) occurs at the fundamental wavelength of 1560 nm combined with broadband QPM [10].

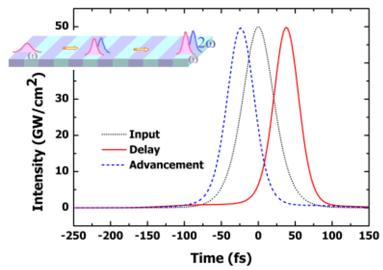

Fig. 1. The waveform of the input (black dot line) and the output (red solid line for delay and blue dash line for advancement) pulse. Inset: schematic diagram of the group velocity control scheme through quadratic cascading interaction.

In order to get an estimated image for our simulation, we here first perform an approximate analysis in the absence of dispersion. We first consider a type I QPM geometry in this quadratic cascading interaction and the nonlinear coefficient d_{31} is used. The coupled wave equations governing the propagation of the FF and SH waves under the slowly varying envelope approximation can be generalized as [14]:

$$\begin{aligned}\frac{\partial E_1}{\partial z}+\frac{ik_1^{''}}{2}\frac{\partial^2 E_1}{\partial t^2}&=i\rho_1 E_1^* E_2 exp\left(i\Delta k_0 z\right)+i\sigma_1\left[\left|E_1\right|^2 E_1+2\left|E_2\right|^2 E_1\right]\\ \frac{\partial E_2}{\partial z}+\delta\frac{\partial E_2}{\partial t}+\frac{ik_2^{''}}{2}\frac{\partial^2 E_2}{\partial t^2}&=i\rho_2 E_1 E_1 exp\left(-i\Delta k_0 z\right)+i\sigma_2\left[\left|E_2\right|^2 E_2+2\left|E_1\right|^2 E_2\right].\end{aligned} \tag{1}$$

where $\rho_i(z) = \pm\,\omega_i d_{31}/cn_i$ (the positive and negative sign depend on the distribution of second-order nonlinearity along the QPM grating, and $i = 1,2$) and $\sigma_i = 3\omega_i\chi^{(3)}/8cn_i$. The $\chi^{(3)}$ terms are the cubic nonlinear terms include self phase modulation (SPM) and cross phase modulation (XPM). Since the input intensity is quite high, they cannot be neglected in our simulation. And they may counteract the cascading quadratic nonlinearity and reduce the net nonlinearity which will contribute to the construction of slow light soliton. $E_i(z,t)$ denotes the amplitude of the electric field, n_i denotes the refractive index and ω_i denotes the angular frequency. The subscripts 1 and 2 correspond to FF and SH pulses, respectively. Time t is measured in a time frame moving with the linear group velocity of the FF pulse. $k_i^{'}$ is the inverse group velocity, and $k_i^{''} = d^2k_i/d\omega^2$ is the group velocity dispersion (GVD); $\delta = k^{'}_{SH}-k^{'}_{FF}$ is the GVM, $\Delta k_0 = k_2-2k_1$ is derived from Sellmeier's equation for MgO:LN [15].In our simulation, only the FF light is incident onto the quadratic medium, in the limit of large wave-vector mismatch, an equation of motion for the FF field can be derived from Eq. (1) as following [16,17]:

$$i\frac{\partial E_1}{\partial z}+2i\delta\frac{\rho_1\rho_2}{\Delta k^2}\left|E_1\right|^2\frac{\partial E_1}{\partial t}-\frac{k_2^{''}}{2}\frac{\partial^2 E_1}{\partial t^2}+\frac{\rho_1\rho_2}{\Delta k}\left|E_1\right|^2 E_1=0, \tag{2}$$

where $\Delta k = k_2-2k_1-2\pi/\Lambda$, and Λ is the poling period. In the case of negligible GVD, The general solution $E_1(z,t) = I_1(z,t)^{1/2}exp(i\phi(z,t))$ of Eq. (2) can be written as [18]

$$I_1 = f(t+z\gamma I_1), \tag{3}$$

where $I_1(z,t) = |E_1(z,t)|^2$ is the square of the amplitude and $\phi(z,t)$ is the phase

$$\phi = z\kappa I_1 + g(t+z\gamma I_1). \tag{4}$$

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In the Eq. (3) and (4), $f(t) = I(t,0)$ is the initial pulse shape, and $g(t)$ is the initial pulse distribution, $\gamma = -2\delta\rho_1\rho_2/\Delta k^2$, and $\kappa = \rho_1\rho_2/\Delta k$.

As shown in Eq. (3), the dragging by the slower SH wave in case of $\gamma<0$, is proportional to the parameter δ because of increased dragging with larger GVM; And it is also inversely proportional to Δk^2, due to the lower amount of SH wave generated from the FF wave and less efficient dragging for increasing wave-vector mismatch. We also noted that the delay of FF pulse increases by increasing the FF pulse intensity, which has detailed discussion in Ref [16]. by the authors.

3. Results and discussion

The input FF is a transform-limited *50 fs* pulse (peak intensity: $50\ GW/cm^2$) at the wavelength of *1530 nm* and the temperature is set to be *20°C*. Numerical simulation is carried out to solve Eq. (1) with a symmetric split-step beam-propagation method (BPM) and the waveforms of the input and output pulses are shown in Fig. 1. Firstly, we investigate the fractional time delay of the output FF pulse as a function of the FF input peak intensity (as is seen in Fig. 2). Besides, we also evaluate the quality of the output pulses. The pulse shape of quadratic soliton is very close to the hyperbolic-secant or Gaussian functions. In simple terms, a sech^2 (t) function is used to fit the central part of the FF and SH pulses at each position. In this paper, the term “Quality Factor” is defined as the fractional amount of energy carried by the central spike of the FF and SH pulses, normalized by the launched energy. It should be noted that, in most of our simulations, when the quality factor drops below 0.75, the pulse will degrade and split into a multi-peaked structure, being no longer tolerable for maintaining pulse integrity. From the inset in Fig. 2, we can see the pulse broadening with no time delay at low intensity case (below $0.1\ GW/cm^2$). Group delay control by varying input FF peak intensity can be realized at higher intensity due to the strong nonlinear interaction and dragging between the FF and SH pulses. The rate of time delay increment decreases with the increasing input peak intensity. This is consistent with the theoretical prediction because the quadratic cascading nonlinearity saturates with the increasing input intensity. But we can also find that with the input pulse peak intensity increased, the quality factor decreases, which is due to the strong interaction between the FF and SH pulses that results in a broad pedestal accompanied by the main spike [19].

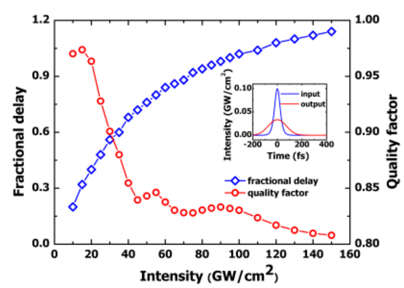

Fig. 2. The fractional time delay (blue diamond line) and the quality factor (red circle line) dependences of input pulse peak intensity. The wavelength of the input FF is *1530* nm at the wave-vector mismatch $\Delta kl = 30\pi$. The inset shows the input (blue line) and output (red line) pulse at low input intensity (0.1 GW/cm^2).

GVM represents the group velocity difference between the FF and the SH pulses. In the presence of GVM, the FF and the SH waves will mutually trap and drag each other and propagate with a velocity between the non-interacting FF and SH group velocities. We can find in Fig. 3(a) that the fractional time delay increases nearly linearly with the GVM when it is not too large. It will come to a peak value and then shift to decrease with greater GVM, because the group velocity difference between the FF and SH pulses becomes larger, which counteract the overlap of these two pulses and will weaken the dragging effect. The waveform of the delayed output pulse distorts due to the large walk-off. The quality factor first maintains

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around a relatively high value and drops to decrease, which is consistent with the tendency of the variation of the fractional time delay. We also found out that, when other circumstances stay the same, smaller wave-vector mismatch (Δk) is always accompanied by lower quality factor and larger fractional time delay.

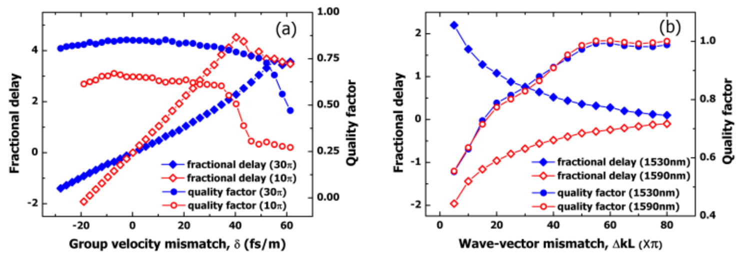

Fig. 3. (a) The fractional time delay (diamond) and the quality factor (circle) as a function of the group velocity mismatch. The blue line shows the case of wave-vector mismatch $\Delta kl = 10\pi$ while the red line represents $\Delta kl = 30\pi$. (b) The fractional time delay (diamond) and the quality factor (circle) as a function of the wave-vector mismatch. The wavelength of the input FF is *1530* nm (*GVM = 15.5 fs/m*) for blue line and *1590* nm (*GVM = –14.3 fs/m*) for red line.

From above, we can find that with the larger wave-vector mismatch, the group velocity of the FF pulse changes less than that with the smaller mismatch. Then we investigate how the wave-vector mismatch influences over the time delay. From Fig. 3(b) we can find that under the same group velocity mismatch, the time delay slowly decreases towards zero with the wave-vector mismatch increased. The time delay is reduced due to the lower converted amount of the SH waves which contributes to the dragging. The red empty diamond line shows the pulse acceleration case. The smaller wave-vector mismatching can lead to larger fractional time delay but with a lower quality factor. The reason is similar with the explanation given in Fig. 2.

Another factor which may give an important impact on the delaying performance is the input duration of the injected pulses. As can be seen in Fig. 4, the fractional time delay come to a peak value around *30 fs* where the quality factor is also close to maximum. For it's the minimum pulse duration that can tolerate the given GVM without the complete walk-off between the FF and SH wave. So in practical case, we can carefully choose the input pulse duration to get a high fractional delay with good pulse quality simultaneously.

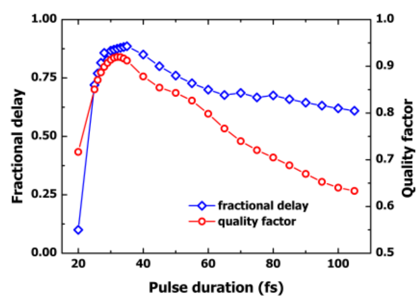

Fig. 4. The fractional time delay (blue diamond line) and the quality factor (red circle line) as a function of the input pulse duration. The wavelength and the input peak intensity is $50GW/cm^2$.

Besides these independent analyses above, there's always a trade-off between the fractional time delay and the quality factor under different situations. It is impossible to obtain infinite time delay without the degradation of the quality factor. So here considering a comprehensive and practical evaluation on the performance of controlling fs laser pulses, we defined an evaluation factor named 'delay-quality production' (DQP). The definition equation can be expressed as follows, where τ denotes the fractional time delay and *Q* is the quality factor.

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$$DQP = \tau \times Q. \quad (5)$$

One can evaluate the delaying performance by DQP. In the practical point of view, since the poling period of the MgO:PPLN crystal is fixed after it is fabricated, we can't modulate the group velocity mismatch and the wave-vector mismatch independently. It's more efficient to tune the peak intensity and the duration of the input pulse to obtain the maximum DQP. Figure 5 gives an example to optimize the delaying performance by selecting the specific peak intensity and duration of the input pulse. We can see that the optimum input pulse duration can always be found with different input peak intensity. This can help us to find the optimum conditions for this group velocity control scheme by looking for the largest achievable DQP.

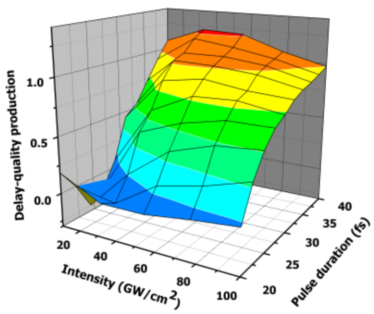

Fig. 5. DQP as the function of the input pulse duration and the input pulse peak intensity.

Based on the study on the fundamental factors which contribute to the group velocity control approaches, one can expand the study by introducing some additional modulation means such as electrical [20], thermal (both to modify the optical properties of the medium) or optical (to modify either the optical properties of the medium or the input light) modulation to achieve expected result. In addition, one can get higher quality factor with smaller fractional delay than that can be obtained in periodic grating with the same achievable maximum DQP by employing continuously linearly chirped QPM grating instead. As a matter of fact, linearly and non-linearly chirped configurations have been explored theoretically and experimentally in previous researches, with results showing high quality factor with high fractional delay [21,22]. Chirped gratings may not only be helpful in pulse quality orientated delaying schemes but also introduce improvements and new interesting features for photonic integrated chip.

4. Conclusion

In summary, we presented a full theoretical analysis to evaluate origins of group velocity control of ultrafast pulses through quadratic nonlinear cascading process. Our analyses show that the impact of the fractional time delay depends on the input intensity, group velocity mismatch, wave-vector mismatch and the input pulse duration. In particular we have found that, for a given QPM grating, one can choose the proper peak intensity and pulse duration of the input pulse to obtain the optimum fractional time delay with good pulse quality. According to our simulation results, large time delay with little distortion can be obtained to realize ultrafast optical signal process. Since this slowing down scheme is accompanied with wavelength conversion process, this approach can simultaneously realize these two functions on a single chip which is eagerly demanded for all optical communication systems.

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