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Ultrashort pulse compression method in bulk BBO crystal using electro-optically tunable cascaded second-order process: a theoretical analysis

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Abstract
We propose an electro-optically controllable cascaded second-order optical process that mimics as a third-order nonlinear process which is utilized for the compression of ultrashort pulses. Effective compression of optical pulses has been achieved by making efficient use of frequency doubling into an extraordinarily advantageous crystal like beta-barium-borate which is capable of generating shorter pulses within a few cycles. In accordance with simulation, it endeavors ≈ threefold compression in femtosecond pulse, i.e., 47 fs has been achieved by applying a voltage of ∓ 6.2 kV which delivers a phase mismatch $(\Delta k) = \pm 117.236\ \mathrm{m}^{-1}$ and effective cascaded refractive index (n_2^{cascade}) of $\pm 3.045 \times 10^{-20}\ \mathrm{m}^2/\mathrm{W}$. This competent compression leads to an increase in the value of peak intensity from 50 to 288 GW/cm^2. On account of the decent control in peak intensity, this promising methodology can be utilized for advanced scientific research, and also implemented easily in a large variety of applications in solid-state physics and medical field.

1 Introduction

Optical pulse compression has become a key area of research in the realm of optics which is extensively investigated for decades to generate ultrashort pulses [1–4]. Shorter pulses attracted much attention because of having higher peak power with no increase of laser pulse energy. Consequently, ultrashort pulse compression techniques have been widely employed in optical fibers as well as in nonlinear crystals for various fields as diverse as laser surgery, laser micromachining, spectroscopy, and two photon microscopy, etc. [5–9].

Previous studies were emphasized on pulse compression employing optical fiber where the energy was constrained to nanojoules. However, this is no longer the case as some groups of researchers already reported mJ level compression in hollow core fibers [10, 11]. Travers' group is also investigated on soliton dynamics in fibers for pulse self-compression in hollow core PCF at the μJ level [12], together with fiber geometrical scaling for energy up-scaling [13]. Moreover, the limitation of damaging the fiber due to pulse compression using higher order nonlinear effect has also been reported [14, 15]. On the other hand, beam distortion problem is encountered while using bulk materials having third-order nonlinearity (χ^3) as they become affected with continuum generation originating from the self-focusing [6]. Therefore, attention of many researchers has turned to the compression of the optical pulse using cascaded second-order (χ^2: χ^2) nonlinearity which can generate an equivalent χ^3 [16–20]. Whereas, quasi-phase matching is an important and well-established technique in the context of pulse broadening and pulse self-compression via cascaded χ^2:χ^2 interactions [21]. On the other side, cascaded second-order nonlinear process with angle and temperature tuning offers nonlinear phase shift significantly [22]. However, these techniques lead to some unacceptable cavity losses and require further additional setups [23]. To rectify the problem, an efficient methodology of electro-optically (EO) adjustable cascaded second-order nonlinear system has been introduced recently [24–26]. Predominantly, noncentrosymmetric mediums are highly popular for the generation of well-known phenomena named second-harmonic generation (SHG) where the fundamental (FF) is continuously converted into a second-harmonic (SH) while passing through an anisotropic medium having high second-order

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susceptibility [25]. Chen et al. [27] discovered a popular negative uniaxial crystal, beta-barium-borate (BBO, β-BaB_2O_4) which is very suitable for use in harmonic generation operations. Sheikh-Bahae et al. presented one paper covering all the measurements of nonlinear refraction of BBO crystal [28]. Due to adequate electro-optic coefficient, low thermo-optic coefficient, and feeble kerr self-focusing nonlinearity, BBO can be widely used for EO tunable cascaded χ^2:χ^2 process to develop a large equivalent χ^3 [29]. For femtosecond pulse compression, BBO has some advantageous properties like low dispersion and high damage threshold [30]. Additionally, the piezoelectric ringing effects are diminutive at repetition rates up to 6 kHz in BBO Pockel cell [31]. Recent theoretical developments have revealed that nonlinear phase shifts engendered by the cascaded second-order nonlinear process enables for ultra-short pulse compression [24, 32]. In particular, no study to date has been investigated for EO tunable pulse compression technique which can deliver shorter pulses as per requirement.

To illuminate this uncharted area, for the first time to our knowledge, we propose an electro-optically tunable ultrafast pulse compression technique performed in bulk material utilizing cascaded optical process. That is to say, a change in refractive indices (RIs) occurs because of the application of DC electric field to the *x*–*z* plane of BBO crystal [33, 34]. Accordingly, a phase mismatch is generated into the fundamentals while propagating over the crystal leading to the generation of nonlinear phase shift among the initial fundamental and reconverted fundamentals [24]. Because of higher electro-optic coefficient of BBO, a very minimal voltage is needed to generate required phase mismatch proceed to the nonlinear phase shift between FFs, transforming the non-phase-matched second-order nonlinear process into cascaded χ^2:χ^2 nonlinear process [25]. This phase shift further changes the effective nonlinear refractive index leading to the compression in pulse. The prime advantage of our proposed scheme is that during compression, we can control the peak intensity of optical pulse by tuning voltage as per our requirement.

The current article has been arranged as follows: in Sect. 2, the proposed scheme has been described in details and the theory is introduced. The simulation results are reported in Sect. 3. Finally, conclusions are epitomized in Sect. 4.

2 Theoretical approach

In this section, we propose and demonstrated an alternative means to furnish EO tunable optical pulse having high optical quality in bulk BBO crystal utilizing cascaded second-order nonlinear process which provides as illustrated in Fig. 1.

An external electric field has been applied along the *y*-axis of BBO. The fundamental pulse is presumed to be propagating through the direction in which type I (oo→e interactions) phase matching occurs [24]. The direction of type I critical phase matching is $\theta = 28.780761411°$ and $\phi = 90°$ for initial pulse having wavelength of 800 nm propagating on the *y*–*z* plane of single BBO crystal. The specimen dimension for BBO crystal is presumed as $30 \times 5 \times 4$ mm^3.

To understand the significance of optical pulse compression technique using electro-optical tuning, first, let us explain how electro-optic (EO) effect works in a transparent medium [24–26]. When external DC electric field has been applied along the y-axis of the nonlinear crystal, the RIs of that particular medium change as [35, 36]:

$$n_x' = n_o(1 + 0.5n_o^2 r_{22} E_y) \tag{1a}$$

$$n_y' = n_o(1 - 0.5n_o^2 r_{22} E_y) \tag{1b}$$

$$n_z' = n_e. \tag{1c}$$

Here, E_y is the electric field which is applied through the *y*-axis of the particular crystal which is responsible to get the revised refractive indices as n_x', n_y' and n_z'. When FF propagates through the *x*-direction of bulk BBO crystal, it is one component having a refractive index of n_y' polarized

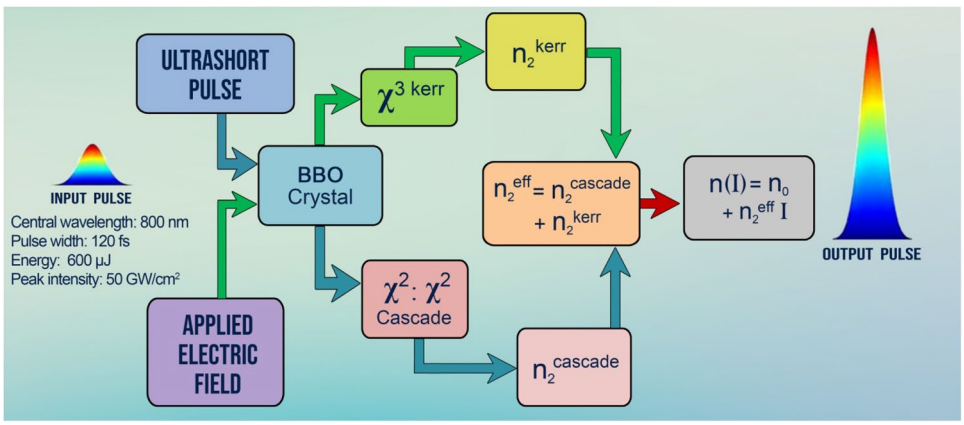

Fig. 1 Schematic depiction of proposed scheme

in the y-direction. On the other way, another component is polarized in the z-direction which has the refractive index value n_z'. r_{22} represents the electro-optic coefficient of the nonlinear crystal, whereas n_o and n_e are the ordinary and extraordinary refractive index, respectively[35]. Because of the updated refractive indices, a phase mismatch (k) has been introduced among the initial Fundamental and the fundamental achieved from back conversion of second harmonic. Phase mismatch (k) can be determined by the modified RIs of the crystal, as shown in Eq. 2 [36, 37]:

$$\Delta k = \frac{4\pi\left(n_{2\omega} - n_{\omega}\right)}{\lambda}. \tag{2}$$

Here, λ is the wavelength which is 800 nm, and $n_{2\omega}$ and n_{ω} are the modified RIs which are defined as:

$$n_{2\omega} = \sqrt{\frac{n_{o2}^2 \times n_{e2}^2}{n_{o2}^2 \sin^2\theta + n_{e2}^2 \cos^2\theta}} \tag{3}$$

$$n_{\omega} = n_{o1}(1 - 0.5 \times n_{o1}^2 \times r_{22} \times E_y). \tag{4}$$

The phase mismatch factor (kL) onward propagation length (L) is described as [24, 25]:

$$\Delta kL = L(k_{2\omega} - 2k_{\omega}), \tag{5}$$

where k_{ω} is the wave vector for fundamental as well as $k_{2\omega}$ is the wave vector for generated SH. Consequently, a nonlinear phase shift ($\Delta\phi^{NL}$) has been introduced by the cascaded second-order process that can be written as [19, 25, 38]:

$$\Delta\phi^{NL} \approx -\frac{\Gamma^2 L^2}{\Delta kL}, \tag{6}$$

where

$$\Gamma = \frac{\omega d_{eff}|E_0|}{c\sqrt{n_{2\omega} n_{\omega}}}. \tag{7}$$

Here, Γ denotes the coupling coefficient [19, 39]. Due to applied electric field, the modification in RIs is also proportional to the intensity of optical pulse while propagating through the crystal in cascaded χ^2:χ^2 process which is also equivalent to kerr effect [24]:

$$n(I) = n_o + n_2^{eff} I, \tag{8}$$

where n_2^{eff}, the effective nonlinear refractive index, represents as[6]:

$$n_2^{eff} = n_2^{cascade} + n_2^{Kerr}. \tag{9}$$

n_2^{eff} varies with nonlinear phase shift, $\Delta\phi^{NL}$ shown by the relation expressed as [22, 24, 40]:

$$n_2^{eff} = \lambda\Delta\phi^{NL}/(2\pi LI). \tag{10}$$

Here, I denote the intensity of light. $\Delta\phi^{NL}$ linearly varies along the intensity of optical pulse which is identical to optical kerr effect [4]. $n_2^{cascade}$ is the cascaded nonlinear RI which can be determined as:

$$n_2^{cascade} = -\frac{4\pi L d_{eff}^2}{c\varepsilon_0 \lambda \left(n_{\omega}\right)^2 n_{2\omega} \Delta kL}. \tag{11}$$

Basically optical pulse compression depends upon the change in effective nonlinear refractive index because of the electro-optic effect. Consequently, along with self-compression, some extra compression has been achieved due to the $n_2^{cascade}$.

Generally, after the proper electro-optic tuning the interaction between the fundamental electric field, E_1 and second-harmonic electric field, E_2 within the nonlinear crystal can be described by the following equations [4]:

$$\frac{\partial}{\partial z}E_1 = iE_1 \times E_2 \exp(i\Delta kz) + i2\pi(n_2^{eff} I_0) \times \frac{L_{NL}}{\lambda}\left(|E_1|^2 + |E_2|^2\right)E_1 \tag{12}$$

$$\left(\frac{\partial}{\partial z} + \frac{L_{NL}}{L_{GVM}}\frac{\partial}{\partial t}\right)E_2 = iE_1E_1 \exp(-i\Delta kz) + i4\pi(n_2^{eff} I_0) \times \frac{L_{NL}}{\lambda}\left(2|E_1|^2 + |E_2|^2\right)E_2. \tag{13}$$

Here, L_{NL} is the nonlinear interaction length and L_{GVM} is the length of group velocity mismatch. I_0 is the initial peak intensity described by Eq. 14, where E_0 is the initial peak fundamental field [18, 41]:

$$I_0 = \sqrt{\frac{\varepsilon}{\mu}}|E_0|^2/2. \tag{14}$$

Now, group velocity mismatch (GVM) plays a vital role in case of ultrashort pulses. In the presence of group GVM, a nonlinear frequency chirp has been generated due to cascaded χ^2:χ^2 process [42]. With the presence of large value of Δk, an effective $\Delta\phi^{NL}$ has been introduced before the separation of pulses due to GVM. Near the pulse peak, the frequency chirp is linear, because $\Delta\phi^{NL}$ affects the pulse intensity. To evaluate this point, we employed L_{GVM} [4, 41] as:

$$L_{GVM} = c\tau_0/(n_{1g} - n_{2g}), \tag{15}$$

where τ_0 is the pulse duration of initial fundamental, n_{1g} represents the group index of the FF frequency, and n_{2g} is basically the group index of SH frequency [4].

It is well known that the cascading of upconversion and downconversion processes leads to effective compression in optical pulse that propagates through a quadratic medium

under non-phase-matched conditions in favor of SHG. The sign convention of $\Delta\phi^{NL}$ depends upon the sign of the k [4]. For sufficient pulse compression negative phase shift is required in case of type I phase matching. Conceptually, our proposed scheme is quite similar to the methodology of traditional compressors: in first step the pulse acquired $\Delta\phi^{NL}$, and in a second step, then the pulse is compressed utilizing dispersive propagation [18]. However, in our case, we have utilized a single nonlinear crystal to serve both purposes. We have made use of BBO crystal of length (L) 30 mm in which we have tried to change the effective $\Delta\phi^{NL}$ between the launched and reconverted FFs.

In our case, coherence length (L_c) is higher than L_{GVM}, and thus, FF and SH pulses will separate from each other temporally before back conversion leading to deformation of temporal phase profile [18, 37, 39]. Therefore, we have considered $L_{GVM} \approx L_c$ to avoid temporal distortion phase profile. The L_{NL} is taken to be approximately 0.15 times of L_c to avoid the splitting of compressed Gaussian pulse and breaking of fundamental pulse onto two subpulses. For pulse compression, positive GVD is required which can be produced by a suitable transparent medium. As per previous research to get an optimum compression of ultra-short pulse, approx 1500 fs^2/mm required as GVD [4]. In our case, GVD value of BBO is negligible compared to the required value. Moreover, the output pulse duration after compression is not highly sensitive to the GVD. The coupled wave equations are solved numerically considering all important parameters neglecting group velocity dispersion (GVD). We investigated a well-established method known as symmetric split step beam propagation method to solve both the equations (Eqs. 12 and 13).

The anisotropic mediums which have high values of d_{eff} and L_{GVM} are the best candidate for this purpose [41]. Therefore, for the efficient compression of 120-fs pulse at 800 nm, we chose to utilize bulk BBO as our anisotropic medium which has $d_{eff} = 2$ pm/V and $L_{GVM} = 0.6$ mm with a crystal length of 30 mm (provided by Casix, Inc.) [4, 40, 42]. Sheikh Bahae and Ebrahim zadeh used kerr lens autocorrelation method to measure $n_2^{kerr} \approx 3.65 \pm 0.6 \times 10^{-20}$ m^2/W using a 76 MHz Ti:Sa oscillator giving 120 fs pulse at 800 nm [28, 43]. In our case, we implemented a measured experimental spectrum as input to generate the initial pulse for the simulation at 800 nm. The EO coefficient of BBO is taken as $r_{22} = 2.1$ pm/V [33]. Here, we also consider the absorption coefficient (α) for 800 nm [44].

In particular, the temperature dependence of refractive indices [45] for BBO crystal is given by:

$$n_{o,final} = n_o + \frac{dn_o}{dt}(T - T_0), \tag{16}$$

$$n_{e,final} = n_e + \frac{dn_e}{dt}(T - T_0), \tag{17}$$

where n_o and n_e are ordinary and extraordinary RIs at reference temperature, i.e., 20 °C. The value of temperature coefficient [35, 46] are given as:

$$\frac{dn_o}{dt} = -1.66 \times 10^{-6}/°C \quad \text{and} \quad \frac{dn_e}{dt} = -9.3 \times 10^{-6}/°C.$$

3 Results and discussion

In our calculations, we considered a measured experimental spectrum as input pulse having duration 120 fs pulse and pulse energy of 600 μJ at 800 nm to achieve effective compression [4]. The RIs along with the principal axes of the nonlinear crystal are calculated as $n_{o1} = 1.6614$, $n_{e1} = 1.5573$ for FF as subscript 1 defines the fundamental, and similarly, $n_{o2} = 1.6934$, $n_{e2} = 1.5687$ for SH as superscript 2 defines the second harmonic. In this proposed work, FF pulse is made to propagate toward x-axis of BBO crystal. Polarization of one of the component of FF occurs in y-direction with RI n_y, and the other polarization occurs in z-direction with RI n_z. It is assumed that FF having center wavelength of 800 nm is propagated at phase matching angle $\theta = 28.780761411°$ to the principle axis.

Modification in RIs comes as an effect of application of DC electric filed along the y-axis of the anisotropic crystal given by the equation, $V = E_y \times d$ [24, 37]. The electric filed (E_y) and voltage (V) are correlated by the crystal thickness (d). Figure 2 depicts that Δk can be adjusted easily by tuning the value of the voltage implemented to the crystal. It has been observed that for the application of zero voltage, no phase matching condition is introduced within the FFs propagating through the crystal. Therefore, tunable non-phase match condition can be developed by adjusting the voltage applied to the BBO crystal. By the application of ∓ 10 kV voltage, the maximum Δk is calculated as ± 189.09 m^{-1}.

As explained in Sect. 2, the two interacting electric fields E_1 and E_2 are taken as Gaussian pulses having Full Width Half maximum (FWHM) of FF as 120 fs, and peak intensity as 50 GW/cm^2. The intensity is taken, such that the focal length of configurable lens comes lesser than the diffraction length of the beam because of the phase being acquired by fundamental wave at crystal length (L). Each pulses are passed through the BBO having $L = 30$ mm and the L_{NL} of the interacting beam is made lesser than the length of the crystal, such that non linearity becomes prominent leading to variation in effective nonlinear refractive index. Considering only cascading phenomenon, by keeping $L_{NL} \ll L$, we have achieved ≈ threefold compression in pulse, i.e., 47 fs by applying voltage of ∓ 6.2 kV

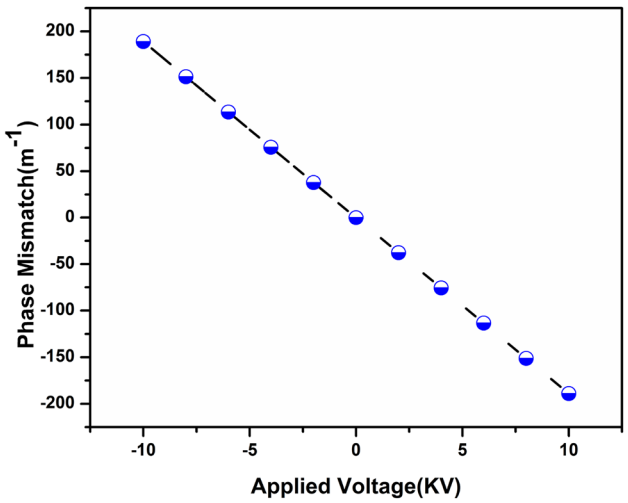

Fig. 2 Variation of phase mismatch with applied voltage

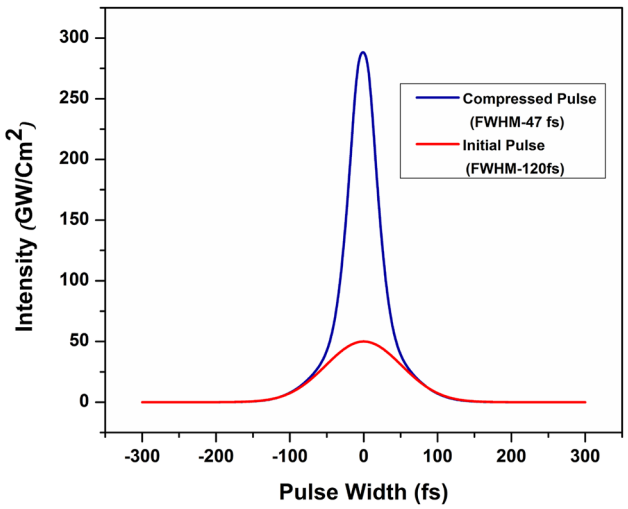

Fig. 3 Compression of 120 fs pulse to ≈ 47 fs

which produces a phase mismatch, $\Delta k = \pm 117.236\ \mathrm{m}^{-1}$, $\Delta\phi^{NL} = \pm 1.141\pi$ and $n_2^{cascade}$ of $\pm 3.045 \times 10^{-20}\ \mathrm{m}^2/\mathrm{W}$. Also the peak intensity of the compressed pulse has been achieved as 288 GW/cm^2, as shown in Fig. 3.

Upon incidence of the fundamental beam to the BBO crystal, the defocusing of the beam occurs due to the absence of proper phase shift. After continuous upconversion and downconversion of FFs, $\Delta\phi^{NL}$ appears in between the fundamental and reconverted fundamental wave leading to focusing of beam propagating along the direction of type I phase matching at that specific voltage. In this way the focusing and defocusing introduced within the crystal. From theoretical analysis, it can be coined out that by tuning the voltage being applied to the crystal, Δk can be changed which further leads to change in $\Delta\phi^{NL}$ and $n_2^{cascade}$ being function of Δk. The interdependence between Δk, $\Delta\phi^{NL}$, and $n_2^{cascade}$ within the crystal leads to zero $n_2^{cascade}$ in phase matching condition ($\Delta k = 0$, at zero applied voltage), and thus, by the variation in magnitude and polarity of applied voltage, we can get an apparent change in Δk and $n_2^{cascade}$. Whenever input pulse intensities reaches a particular threshold value (20–60 GW/cm^2) which feebly rely on the phase mismatch, triggers the compression in output pulse [4, 47]. Therefore, by applying 0 to ∓ 6.2 kV along y-direction of crystal, we have also observed the effective compression in pulse ranging from 120 to 47 fs, as shown in Fig. 4. Compression of pulse saturates beyond a certain limit of its peak intensity coming as interplay of cascading effect and no further compression is possible.

By electro-optic tuning of BBO crystal to achieve pulse compression under cascaded second-order non linear process, we have achieved electro-optically tunable pulse compression which comes as an effect of cascading of two second-order non linear process of SHG generation, in which we have seen tunable $n_2^{cascade}$ by the implementation of electric field into the BBO crystal. However, BBO is an anisotropic crystal it constitutes of χ^2 and χ^3 so, along with cascaded second-order non linearity, the effective kerr non linearity is also having prominent effect on compression of pulse. Considering 120 fs pulse at 800 nm, the effective kerr refractive index is $n_2^{kerr} \approx 3.65 \pm 0.6 \times 10^{-20}\ \mathrm{m}^2/\mathrm{W}$.

We have used the n_2^{kerr} along with $n_2^{cascade}$ and we have observed that, initially on the application of electric field, the kerr or third-order susceptibilities does not have prominent effect on compression of pulse and cascade effect is dominant until $\Delta k = 77.52\ \mathrm{m}^{-1}$ which produces $\Delta\phi^{NL} = \pm 1.6875\pi$ and n_2^{eff} of $\pm 4.5 \times 10^{-20}\ \mathrm{m}^2/\mathrm{W}$ by applying ∓ 4.1 kV. The maximum compression achieved as 57 fs considering both cascade and kerr properties. After that the total effective refractive index, i.e., $n_2^{cascade} + n_2^{kerr}$ becomes positive leading to decompression of pulse afterward, as shown in Fig. 5. On analyzing the pulse evolution, we have observed a dip in pulse peak intensity when the value of Δk increases beyond 77.52 m^{-1}, as shown in Fig. 6, and pulse further decompresses as the overall value of n_2^{eff}, i.e., $n_2^{cascade} + n_2^{kerr}$ goes on increasing with positive values.

After tuning the temperature in the range of 20–80 °C, we have encountered some change in refractive index, but that change in refractive indices is not sufficient enough to produce any probable change in compression of pulse, as shown in Fig. 7. In this section, all the simulation results to support entire theoretical analysis have been done using MATLAB software. To confirm our interpretation, we have performed numerical simulation utilizing symmetric split step beam propagation method. This method is the technique of choice considering the solution of nonlinear Schrödinger equation (NLSE) because of its simple implementation. It is basically an iterative process which is performed step-by-step for the

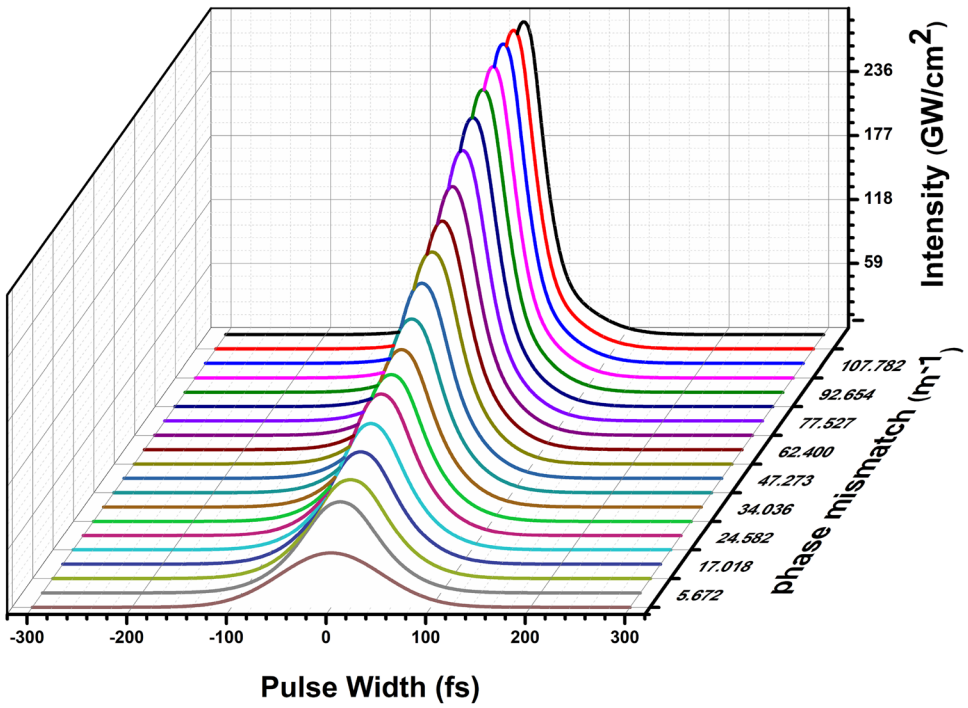

Fig. 4 Pulse evolution (compression) with effect of cascaded nonlinearity by variation of applied voltage at the end of BBO crystal

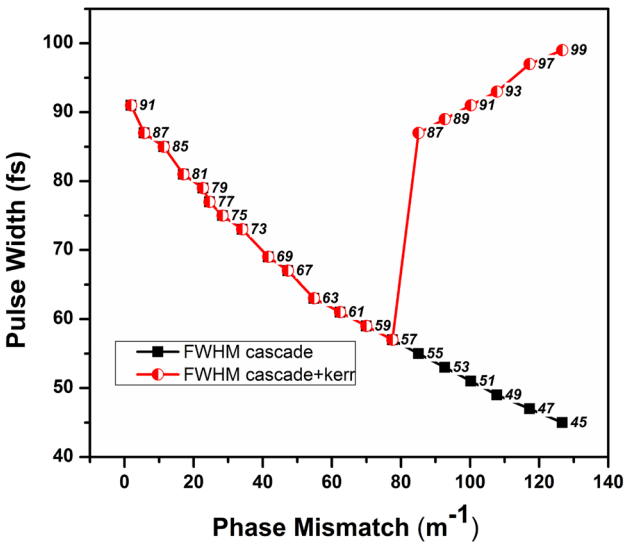

Fig. 5 Pulse width vs phase mismatch for n_2^{cascade} and $n_2^{\text{cascade}} + n_2^{\text{kerr}}$

entire length of the BBO crystal where the nonlinearity and dispersion acts simultaneously. Consequently, fourth-order Runge–Kutta algorithm has been utilized to find the solution of nonlinear propagation step in time domain as well as the dispersive propagation step has been solved in frequency domain.

The implementation of electro-optic tuning makes this approach flexible as we can get the compressed pulse as per our requirement depend on specific applications. Since the cascaded nonlinearity saturates, increasing the applied voltage does not increase the pulse compression ratio in an effective way. Due to the limitation of GVM, it is very challenging to achieve huge compression ratio both in theoretical or even experimental direction. To overcome this limitation, a medium with stronger quadratic nonlinearities can be utilized which is capable to increase the phase mismatch and thereby enter the stationary regime where the GVM effects are much weaker. As a benefit, cleaner compressed pulses could be generated and even it would be generated in a shorter nonlinear crystal. Currently, we are interrogating some other possible nonlinear crystals and phase matching conditions to achieve better pulse compression with high intensity. Pre-chirping can be also implemented in future for the betterment of this aforesaid approach.

4 Conclusion

In conclusion, we reported electro-optically tunable ultrashort pulse compression at 800 nm in a single BBO crystal on the basis of cascaded second-order nonlinear method both theoretically and analytically. Applying DC electric field to the bulk BBO crystal, a phase mismatch can be created to transform the second-order nonlinearity into cascaded nonlinearity. Thus, we obtained a value of Δk as $\pm 117.236\ \text{m}^{-1}$, by implementing a voltage of ∓ 6.2 kV on the x–z plane of bulk BBO crystal, where the sign convention of Δk depends on the polarity of the DC voltage. By varying the applied voltage, we successfully brought out variable ΔkL, i.e., the product of phase mismatch and corresponding interaction

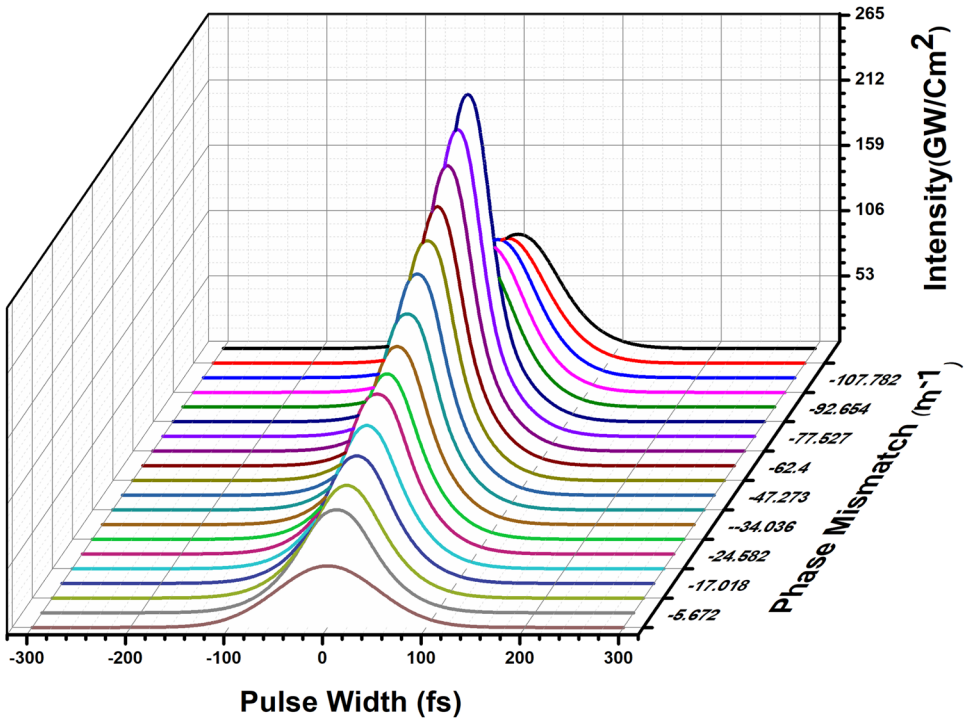

Fig. 6 Pulse evolution (compression) with collective effect of cascade and kerr non linearity by variation of applied voltage at the end of BBO crystal

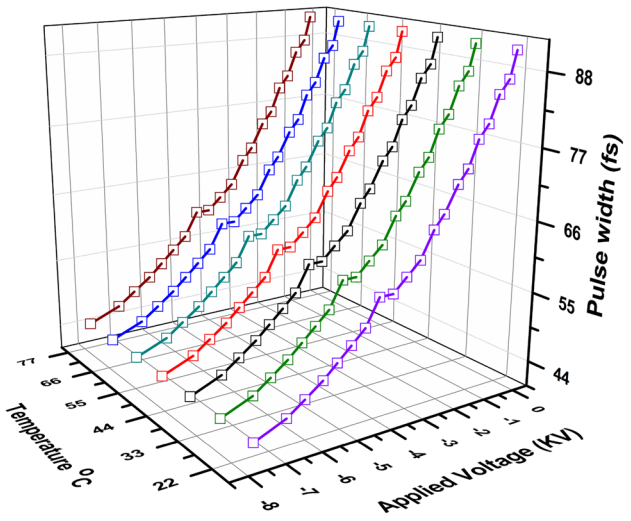

Fig. 7 Effect of temperature tuning on pulse compression

length within the BBO crystal, leading to the creation of phase shift between fundamental and reconverted fundamental wave which comes as an outcome of cascaded second-order process. This phase mismatch further leads to change in the n_2^{cascade} and, as an outcome, we have achieved tunable pulse compression for 120 fs going to 47 fs by adjusting the voltage from 0 to ∓ 6.2 kV.

In addition, we have also investigated the electro-optically tunable pulse compression coming out as an interplay of both cascaded and kerr nonlinearity, in which we have observed the same compression in pulse up to the applied voltage of ∓ 4.1 kV, i.e., 57 fs. On the other hand, tuning the voltage beyond -4.1 kV results in the decompression of pulse which indicates the dominance of kerr nonlinearity. Furthermore, we have also analyzed the effect of variation in temperature upon electro-optically tunable pulse compression and found that the change in temperature does not have any viable influence on effective compression.

This promising technique is quite easy to implement for large variety of uses and applications such as electrically driven compressors which can be used to produce sharp kicks of pulses helping in clear incision in eye surgery. It can be also utilized in the field of solid-state physics where compression-based laser-driven electron diffraction can be implemented to shape the images of molecules as they undergo bending and other vibrations.

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