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High-energy pulse compressor using self-defocusing spectral broadening in anomalously dispersive media

Bache, Morten

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(71) Applicant: **DANMARKS TEKNISKE UNIVERSITET** [DK/DK]; Anker Engelunds Vej 101 A, DK-2800 Kgs. Lyngby (DK).

(72) Inventor: **BACHE, Morten**; Fuglegårdsvej 13, DK-2820 Gentofte (DK).

(74) Agent: **ZACCO DENMARK A/S**; Arne Jacobsens Allé 15, DK-2300 Copenhagen S (DK).

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(54) **Title**: HIGH-ENERGY PULSE COMPRESSOR USING SELF-DEFOCUSING SPECTRAL BROADENING IN ANOMALOUSLY DISPERSIVE MEDIA

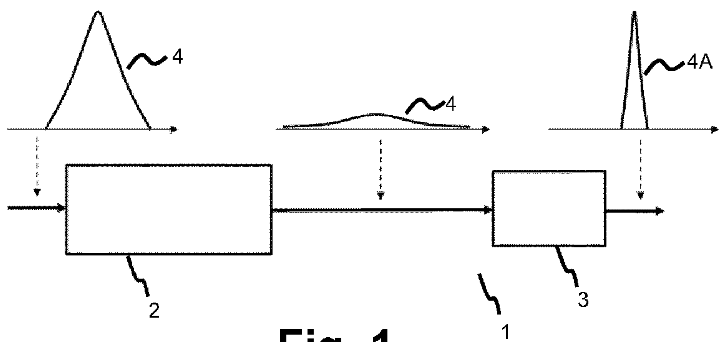

Fig. 1

(57) **Abstract**: A method and a pulse compressor (1) for compressing an optical pulse, wherein the pulse compressor comprising a bulk quadratic nonlinear medium (2) adapted for generating a negative nonlinear phase variation on the optical pulse and having a negative group-velocity dispersion, and a dispersive unit (3) with a net positive dispersion. Furthermore, the net positive dispersion in the dispersive unit at least partially compensates for the negative nonlinear phase variation and the negative group-velocity dispersion produced by the bulk quadratic nonlinear medium when the optical pulse passes through the bulk quadratic nonlinear medium and subsequently through the dispersive unit thereby generating a temporally compressed optical pulse. For 1 micron lasers second-harmonic generation at high intensities yields spectral broadening due to self-defocusing by the Kerr-nonlinearity which can subsequently be compressed by providing normal dispersion. As KDP crystals can be glued together, large apertures of the pulse compressor are possible making this method suitable for pulse compression in Joule-class lasers.

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HIGH-ENERGY PULSE COMPRESSOR USING SELF-DEFOCUSING SPECTRAL BROADENING IN ANOMALOUSLY DISPERSIVE MEDIA

BACKGROUND

Amplification of femtosecond pulses is inevitably bandwidth limited and therefore subsequent pulse compression is desired. Recent advances in Yb-based laser amplifiers promise diode-pumped terawatt peak powers (joule-class energies), but the pulse durations are on the 200 fs scale.

A standard pulse compression techniques employed today, introduces spectral broadening through nonlinear effects in a gas (preferably noble) contained in a hollow fiber or capillary and temporal compression is achieved after the fiber by use of dispersive elements that compensate for an accumulated chirp. This technique is capable of handling pulse energies on the milliJoule scale, and is limited by onset of filamentation and by practical size requirements, such as the fiber length and the radius. Commonly, the energy introduced into a hollow fiber is between 1 mJ to 5 mJ, and the length of a hollow fiber is between 30 cm to 100 cm.

Alternatively, more energetic pulses can be compressed if the guiding property of the fiber is replaced by self-guidance in the gas by producing a filament. This technique is capable of compressing pulses having several mJ of energy, up to 10 mJ, but suffers from self-focusing effects and ionization of the gas.

It is known that self-focusing effects can be avoided by applying a negative nonlinearity (or negative nonlinear phase variation) to an optical pulse through a hollow fiber or a crystal (i.e. bulk material). Thus, the negative nonlinearity is applied in most cases either by a Kerr nonlinearity close to a resonance or by cascaded quadratic nonlinear effects, such as second-harmonic generation.

It is disadvantageous using an optical fiber in a pulse compressor due to the physical size of the optical fiber as well as the needed gas pressure chamber around it, and thereby, the lack of the compactness of the pulse compressor is not suitable to be implemented into a laser device.

It is further disadvantageous using a hollow optical fiber or a capillary in a pulse since the amount of energy injected into these is limited to few millijoules due to filamentation, length and radius of the optical fiber or capillary.

It is also disadvantageous applying negative nonlinearity to an optical pulse in a crystal, a piece of dielectric material such as a glass, or a hollow fiber based on a Kerr nonlinearity close to a resonance, since a high energy loss due to radiation loss and multi photon loss is introduced to the optical pulse.

It is furthermore disadvantageous to use a negative nonlinear phase variation in a crystal having a positive group-velocity dispersion because the accumulated chirp across the pulse is only linear in a very limited range, and this leads to a compressed pulse with a reduced amount of energy in the compressed spike and with significant leading and trailing pulse components.

SUMMARY

It is an object of the present invention to provide a pulse compressor, wherein the amount of injected energy into the pulse compressor is increased into the joule class, and thereby, making the pulse compressor able to exploit fully the joule-class energy of the laser when compressing the pulse.

Furthermore, it is an object of the present invention to provide the pulse compressor with a compact design wherein the dispersive media is a bulk quadratic nonlinear medium or a crystal.

Additionally, it is an object of the present invention to provide the pulse compressor with a dispersive media without involving any kind of gas species and/or an optical fiber.

Discloses herein is a pulse compressor for compressing an optical pulse. The pulse compressor comprises a bulk quadratic nonlinear medium adapted for generating a negative nonlinear phase variation on the optical pulse and having a negative group-velocity dispersion, and a dispersive unit with a net positive dispersion, wherein the net positive dispersion in the dispersive unit at least partially compensates for the negative nonlinear phase variation and the negative group-velocity dispersion produced by the bulk quadratic nonlinear medium when the optical pulse passes through the bulk quadratic nonlinear medium and subsequently through the dispersive unit thereby generating a temporally compressed optical pulse.

Alternatively, disclosed herein is a pulse compressor for compressing an optical pulse. The pulse compressor comprises a bulk quadratic nonlinear medium adapted for generating a negative nonlinear phase variation and a negative group-velocity dispersion on the optical pulse, and a dispersive unit with a net positive dispersion, wherein the net positive dispersion in the dispersive unit at least partially compensates for the negative nonlinear phase variation and the negative group-velocity dispersion produced by the bulk quadratic nonlinear medium when the optical pulse passes through the bulk quadratic nonlinear medium and subsequently through the dispersive unit thereby generating a temporally compressed optical pulse.

It is an advantage that the bulk quadratic nonlinear medium having a negative nonlinear phase variation on the optical pulse and negative group-velocity dispersion, because the linear chirp that is accumulated across the pulse during the spectral broadening phase through the combined action of the nonlinearity and the group-velocity dispersion, will extend over a significantly larger part of the initial pulse compared to the case where the group-velocity dispersion is positive, enabling a superior compressed pulse quality when compensated for by the dispersive element.

It is a further advantage that the bulk quadratic nonlinear medium has a negative nonlinearity or a negative nonlinear phase variation, since self-focusing effects are excluded from happening in the spectral broadening stage.

In one or more embodiments, the negative nonlinear phase variation is introduced by the cascading effect that can be realized by a phase-mismatched frequency-conversion process. By using the bulk quadratic nonlinear medium tuned close to phase matching, the negative nonlinear phase shift is imposed on the optical pulse which is similar to a negative self-defocusing Kerr nonlinearity. A requirement for the nonlinear phase shift to be negative is that the phase-mismatched harmonic has a phase velocity that is slower than the optical pulse. By tuning the phase mismatch parameter close enough to a phase matching point, the negative nonlinear phase shift is increased and it may then happen that it can overcome competing positive cubic nonlinearities stemming from the material electronic Kerr nonlinearity. This yields a net negative nonlinearity that induces spectral broadening of the optical pulse with a negative quadratic phase, which in time domain gives a pulse with a linear negative chirp. This occurs through an effect akin to self-phase modulation. Since both group-velocity dispersion and the net nonlinearity have the same sign (negative), this is the so-called wave-breaking regime, where spectrally significant broadening occurs and temporally the initial Gaussian-shaped pulse develops into a flat top pulse with very steep shock fronts.

Alternatively, the bulk quadratic nonlinear medium may be adapted for generating a net negative nonlinearity on an optical pulse and having negative group-velocity dispersion (GVD).

In one or more embodiments, the optical pulse operating at a pump wavelength may be injected into the bulk quadratic nonlinear medium, wherein the bulk quadratic nonlinear medium may apply anomalous group velocity dispersion to the optical pulse when the pump wavelength is within a wavelength range configured to the bulk quadratic nonlinear medium.

A second order dispersion coefficient of the bulk quadratic nonlinear medium may be negative when the optical pulse is operating in the anomalous group velocity dispersion regime of the bulk quadratic nonlinear medium, i.e. the GVD and the negative nonlinearity both contribute to a negative chirp across the optical pulse, equivalent to a quadratic spectral phase with a negative sign. Because both the GVD and the nonlinearity are negative this chirp across the optical pulse becomes very linear, and therefore, easy to compensate for in a later stage with standard dispersive elements in a dispersive unit. Thereby, a further technical effect of having a linear chirp across the spectrum of the optical pulse is an improved compression of the optical pulse wherein the compression factor and the pulse quality improves significantly.

Furthermore, the negative self-defocusing is applied to the optical pulse in the bulk quadratic nonlinear medium when the cascading nonlinearity is negative. The negative self-defocusing prevents the optical pulse experiencing whole-beam or small scale self-focusing effects that otherwise would plague the spectral broadening of the optical pulse in the bulk quadratic nonlinear medium. This implies that the energy of the optical pulse is only limited by the aperture size of the bulk quadratic nonlinear medium.

The dispersive unit may receive the optical pulse from the bulk quadratic nonlinear medium applying a net positive dispersion to the bulk quadratic nonlinear medium for compensating the applied negative nonlinear phase variation and negative group-velocity dispersion, and thereby, the optical pulse is compressed or at least partially temporally compressed. The dispersive unit may comprise at least a pair of diffraction gratings with an inverting telescope between them, at least a pair of prisms, at least one or more dispersive mirrors, at least a pair of double-pass diffraction gratings with an inverting telescope between them and/or at least a pair of double-pass prisms.

In one or more embodiments, the pump wavelength of the optical pulse may be between 0.7 µm to 1.4 µm, 1.1 µm to 2.5 µm, 1.7 µm to 3.5 µm, 1.5 µm to 3 µm, 3 µm to 5.5 µm, 3 µm to 7 µm, 4 µm to 9 µm, 5 µm to 10 µm, or 6 µm to 12 µm.
In one or more embodiments, the wavelength range wherein the bulk quadratic nonlinear medium may apply anomalous group velocity dispersion to the optical pulse may be between 0.7 µm to 1.4 µm, 1.1 µm to 2.5 µm, 1.7 µm to 3.5 µm, 1.5 µm to 3 µm, 3 µm to 5.5 µm, 3 µm to 7 µm, 4 µm to 9 µm, 5 µm to 10 µm, or 6 µm to 12 µm.

The compression factor (f_c) of the compressed optical pulse may be defined as being the ratio of an input Full-Width-Half-Maximum ($FWHM_{input}$) of the optical pulse going into the bulk quadratic nonlinear medium over an output FWHM ($FWHM_{output}$) of the optical pulse going out from the bulk quadratic nonlinear medium , i.e. $f_c = FWHM_{input} / FWHM_{output}$.

The pulse quality (Q_c) of the compressed optical pulse, i.e. the optical pulse going out from the dispersive unit, is defined as the ratio of the fractional amount of energy carried by the central spike of the compressed optical pulse (i.e. Gaussian fitted energy of the optical pulse central spike) over the optical pulse going into the bulk quadratic nonlinear medium.

In one or more embodiments, the spectral broadening of the optical pulse is achieved in a bulk material with quadratic nonlinearities, operating in the anomalous dispersion regime and exploiting a nonzero positive phase mismatch of a frequency conversion process resulting in an overall self-defocusing (negative) Kerr like nonlinearity. When followed by a set of dispersive elements with a set of dispersive elements with net positive dispersion that compensate for the negative chirp accumulated in the bulk medium, the optical pulse is at least partially temporally compressed.

In one or more embodiments, the negative nonlinear phase variation is generated by cascaded second harmonic generation.

In one or more embodiments, the pulse compressor is configured with the negative nonlinear phase variation generated by cascaded second-harmonic generation, cascaded sum frequency generation, cascaded difference frequency generation or cascaded optical rectification.

It is advantageous generating the negative nonlinear phase variation by cascaded second-harmonic generation, cascaded sum frequency generation, cascaded difference frequency generation or cascaded optical rectification compared to the self-defocusing Kerr nonlinearity found close to resonance, since the energy loss in the bulk quadratic nonlinear medium is reduced significantly due to minimal radiation loss and minimal multi-photon absorption, which occurs if the negative nonlinear phase variation is generated mainly by Kerr nonlinearity.

In one or more embodiments, the pulse compressor further comprising a dispersive control element provided before the bulk quadratic nonlinear medium, the dispersive control element being adapted for controlling temporal chirp of the optical pulse before and/or upon entering the bulk quadratic nonlinear medium.

In one or more embodiments, the pulse compressor configured with the dispersive control element is a tilting element for tilting a front of the optical pulse before and/or upon entering the bulk quadratic nonlinear medium. The dispersive control element may be a tilting element for tilting the beam line before and/or upon entering the bulk quadratic nonlinear medium.

It is an advantage of tilting the optical pulse front before entering the bulk quadratic nonlinear medium, since the tilting in the bulk quadratic nonlinear medium reduces the zero group-velocity dispersion wavelength of the bulk quadratic nonlinear medium significantly, and thereby, the pump wavelength of the optical pulse can be reduced so to perform pulse compression.

For example, by tilting the optical pulse front before entering an ADP crystal the zero group-velocity dispersion wavelength of 0.984 μm could be reduced to below 0.8 μm. Thereby, using an ADP crystal the tilting of the optical pulse may reduce the zero group-velocity dispersion wavelength so that a Ti:Sapphire pulsed laser combined with an ADP crystal may be used for performing pulse compression.
In one or more embodiments, the pulse-front tilting of the optical pulse is denoted by a tilt angle, wherein the tilt angle is measured with respect to a beam line parallel to an input surface of the bulk quadratic nonlinear medium. The pulse tilt angle may be between 0.5° to 10°, 1° to 5°, 2° to 20°, 10° to 25°, or 10° to 45°.

In one or more embodiments, the dispersive control element may be a grating compressor, where the dispersive control element combined with the bulk quadratic nonlinear medium results in a further enhanced compression of the optical pulse, i.e. the compression factor (f_c) is further increased.

The pulse compressor may further comprise a beam collimator configured to collimate the optical pulse entering the bulk quadratic nonlinear medium or the dispersive control element.

In one or more embodiments, the beam collimator collimates the optical pulse entering the bulk quadratic nonlinear medium, and thereby, diffractive effects or beam-focusing contributions to the second-harmonic generation process may be avoided or reduced.

In one or more embodiments, the bulk quadratic nonlinear medium is configured to have a cascading nonlinear refractive index and a Kerr nonlinear refractive index, and wherein the cascading refractive index is negative and its absolute value larger than the Kerr nonlinear refractive index.

To achieve self-defocusing effect on the optical pulse, the pump wavelength of the optical pulse may be within a wavelength range configured to the bulk quadratic nonlinear medium, wherein the absolute value of the cascading nonlinear refractive index of the respective bulk quadratic nonlinear medium may be larger than the Kerr nonlinear refractive index of the respective bulk quadratic nonlinear medium.

In one or more embodiments, the bulk quadratic nonlinear medium is configured to operate in a wavelength range between 0.7 μm to 1.4 μm, 1.1 μm to 2.5 μm, 1.7 μm to 3.5 μm, 1.5 μm to 3 μm, 3 μm to 5.5 μm, 3 μm to 7 μm, 4 μm to 9 μm, 5 μm to 10 μm, or 6 μm to 12 μm.

In one or more embodiments, the bulk quadratic nonlinear medium comprises a wide-gap dielectric or bulk quadratic nonlinear media, such as BBO (beta-BaB_2O_4), $LiNbO_3$, KDP (KH_2PO_4), DKDP (KD_2PO_4), ADA ($NH_4H_2AsO_4$), KDA ($NH_4H_2AsO_4$), DKDA ($ND_4D_2AsO_4$), ADP ($NH_4H_2PO_4$), DADP ($ND_4D_2PO_4$), RDP (RbH_2PO_4), KTP ($KTiOPO_4$), KTA ($KTiOAsO_4$), $LiTaO_3$, $BaGa_4S_7$, $LiInS_2$, $LiGaS_2$, $LiGaSe_2$, or any other kind of bulk quadratic nonlinear media exhibiting a quadratic $\chi^{(2)}$ optical nonlinearity

In one or more embodiments, the bulk quadratic nonlinear medium comprises a semiconductor material, such as GaSe, ZnSe, AlGaAs, $CdSiP_2$, $ZnGeP_2$, $CdGa_2S_4$, ZnTe, $LiGaTe_2$, $CdGeP_2$, or any other kind of a semiconductor material exhibiting a quadratic $\chi^{(2)}$ optical nonlinearity.

In one or more embodiments, the bulk quadratic nonlinear medium is characterized by having a propagation axis with a first length of above 1mm, above 5 mm, above 10 mm, above 25 mm, and above 50 mm, wherein the first length extending in parallel to the direction of propagation of the optical pulse.

In one or more embodiments, the bulk quadratic nonlinear medium is characterized by having a first width of above 1 mm, above 5 mm, above 10 mm, above 25 mm, and above 50 mm, and wherein the first width being perpendicular to the first length; and/or the bulk quadratic nonlinear medium is characterized by having a second width of above 1mm, above 5 mm, above 10 mm, above 25 mm, and above 50 mm, and wherein the second width being perpendicular to the first length and perpendicular to the first width.

It is advantageous using a bulk quadratic nonlinear medium since the pulse compressor may be more compact than a pulse compressor based on a gas-filled hollow optical fiber or filamentation in a hollow capillary.

In one or more embodiments, the optical pulse is generated by a laser source configured with a pulse shaper and/or by a laser source being a Ti:sapphire laser, an InGaAs laser, an AlGaIn laser, an AsSb laser, a Xe-He laser, a CO_2 laser, a GaAlAs laser, a dye laser, a Cr:ZnS laser, a Cr:ZnSe laser, a Cr:forsterite laser, an Er-doped laser, a Tm-doped laser, a Ho-doped laser, an Yb-doped laser or any kind of laser parametric amplifiers.

In one or more embodiments, the dispersive unit includes at least one or more of the following combinations: a pair of diffractions gratings, a pair of prisms, one or more dispersive mirrors, a pair of double-pass diffraction gratings, and/or a pair of double-pass prisms.

Disclosed herein is also a laser system configured with a pulse compressor according to the above.

Disclosed herein is also a pulse compressing method comprising the following steps:

- guiding an optical pulse from a laser source through a bulk quadratic nonlinear medium with negative nonlinear phase variation and negative group-velocity dispersion thereby obtaining a self-defocusing pulse that is spectrally broadened due to the self-defocusing nonlinearity, and
- guiding the self-defocusing pulse through a dispersive unit with a net positive dispersion for compensating negative nonlinear phase variation and negative group-velocity dispersion generated in the bulk quadratic nonlinear medium, and thereby, obtaining a temporally compressed pulse.

The advantages obtained by this method are as outline for the pulse compressor above.

In one or more embodiments, the negative nonlinear phase variation is generated by cascaded second harmonic generation.

In one or more embodiments, guiding the optical pulse into the bulk quadratic nonlinear medium is obtained by using a dispersive control element.

In one or more embodiments, guiding the optical pulse into a dispersive control element or the bulk quadratic nonlinear medium is obtained by using a beam collimator.

In one or more embodiments, a pump wavelength of the optical pulse may be optimized so that a self-steepening effect on the temporally compressed pulse is minimized or eliminated.

In one or more embodiments, a pump wavelength of the optical pulse may be optimized so that a self-steepening effect on the temporally compressed pulse is minimized or eliminated.

In one or more embodiments, the pulse compressor method further comprises generating an optical pulse, wherein the optical pulse is generated by a laser source configured with a pulse shaper and/or by a laser source being a Ti:sapphire laser, an InGaAs laser, an AlGaIn laser, an AsSb laser, a Xe-He laser, a CO_2 laser, a

GaAlAs laser, a dye laser, a Cr:ZnS laser, a Cr:ZnSe laser, a Cr:forsterite laser, an Er-doped laser, a Tm-doped laser, a Ho-doped laser, an Yb-doped laser or any kind of laser parametric amplifiers.

In one or more embodiments, the bulk quadratic nonlinear medium operates in an anomalous group velocity dispersion regime, where the negative group velocity dispersion and the negative nonlinear phase variation contribute to a linear and negative chirp across the optical pulse.

The linear chirp across the optical pulse enables a superior compressed pulse quality when compensated for by a dispersive element.

BRIEF DESCRIPTION OF THE FIGURES

A more detailed description follows below with reference to the drawing, in which:

Fig. 1 shows a pulse compressor comprising a bulk quadratic nonlinear medium and a dispersive unit,

Fig. 2A shows a pulse compressor comprising a bulk quadratic nonlinear medium, a dispersive unit and a dispersive control element,

Fig. 2B shows a pulse compressor wherein a dispersive control element is a tilting element for tilting the optical pulse entering a bulk quadratic nonlinear medium,

Fig. 3A shows a pulse compressor comprising a bulk quadratic nonlinear medium, a dispersive unit and a dispersive control element, and a laser source,

Fig. 3B shows a pulse compressor comprising a bulk quadratic nonlinear medium, a dispersive unit and a dispersive control element, a laser source, and a beam collimator,

Fig. 4 shows a Figure-of-Merit as a function of pump wavelength for different bulk quadratic nonlinear media cut for non-critical phase-mismatched second-harmonic generation.

Figs. 5A-C show different ways of stacking multiple bulk quadratic nonlinear media,

Fig. 6A shows a simulated result of compression factor and pulse quality as a function of first length of a KDP crystal pumped with 200 fs at 1030 nm pulses,

Fig. 6B shows simulated results of compression factor and pulse quality as a function of first length of a RDP crystal pumped with 200 fs at 1057 nm pulses.

Fig. 7 shows a pulse compressing method,

Fig. 8A shows an overview over KDP and its isomorphs, where the zero-group velocity mismatch wavelength (λ_{ZGVM}) is calculated as the wavelength where both phase matching and zero-group velocity mismatch is achieved.

Fig. 8B shows a table disclosing an overview over KDP and KDPs isomorphs with respective parameters,

Fig. 9A shows a compression figure-of-merit as a function of position z for three bulk quadratic nonlinear media,

Fig. 9B shows a normalized intensity profile as a function of wavelength for compressed optical pulses,

Fig. 9C shows the spectral phase profile before and after applying optimal group-delay dispersion compensation,

Fig. 10 A and 10B show a normalized intensity profile as a function of wavelength and time, respectively, for a compressed optical pulse with minimized self-steepening,

Fig. 11 shows the compression FOM as a function of first length for a congruent lithium niobate bulk quadratic nonlinear medium,

Fig. 12 shows a pulse compressing method comprising a pump wavelength optimization step for minimizing self-steepening,

Fig. 13 shows a multi-stage pulse compressor.

DETAILED DESCRIPTION

Fig. 1 shows a pulse compressor 1 for compressing an optical pulse 4. The pulse compressor 1 comprising a bulk quadratic nonlinear medium 2 adapted for generating a negative nonlinear phase variation on the optical pulse 4 and having negative group-velocity dispersion, and a dispersive unit 3 with a net positive dispersion. The net positive dispersion in the dispersive unit 3 at least partially compensates for the negative nonlinear phase variation and the negative group-velocity dispersion produced by the bulk quadratic nonlinear medium 2 when the optical pulse 4 passes through the bulk quadratic nonlinear medium 2 and subsequently through the dispersive unit 3 thereby generating a temporally compressed optical pulse 4A.

A non-critical phase matching crystal may be denoted as a bulk quadratic nonlinear medium 2 which its phase mismatching parameter is independent of the beam angle. The non-critical phase matching crystal may be, such as a KTP, a KTA, a $LiTaO_3$, a $LiNbO_3$, a $BaGa_4S_7$, a $LiInS_2$, a $LiGaS_2$, a GaSe, a ZnSe, an AlGaAs, a $ZnGeP_2$, a $LiGaSe_2$, a $CdGa_2S_4$, a ZnTe, a $LiGaTe_2$, a $CdSiP_2$ or a $CdGeP_2$ crystal. The advantage of having a non-critical phase matching crystal is that the generated second-harmonic has no spatial walk-off angle, the quadratic nonlinearities are large, and that compression of the pulse provided by the pulse compressor 1 may be unaffected of a misaligned beam angle.

Alternatively, a first polarization of the entering optical pulse may be orthogonal to a second polarization of the bulk quadratic nonlinear medium, wherein the bulk quadratic nonlinear medium 2 is a birefringent phase matching crystal, such as KDP or its isomorphs.

Alternatively, the tuning of the phase mismatch factor Δk may be used to tune the width or the FWHM of the compressed optical pulse 4A.

In the bulk quadratic nonlinear medium 2, the negative nonlinear phase variation may be generated by cascaded second-harmonic generation, cascaded sum frequency generation, cascaded difference frequency generation or cascaded optical rectification.

The bulk quadratic nonlinear medium 2 may be a wide-gap dielectric or crystals, such as BBO (beta-BaB_2O_4), $LiNbO_3$, KDP (KH_2PO_4), DKDP (KD_2PO_4), ADA ($NH_4H_2AsO_4$), KDA ($NH_4H_2AsO_4$), DKDA ($ND_4D_2AsO_4$), ADP ($NH_4H_2PO_4$), DADP ($ND_4D_2PO_4$), RDP (RbH_2PO_4), KTP ($KTiOPO_4$), KTA ($KTiOAsO_4$), $LiTaO_3$, $BaGa_4S_7$, $LiInS_2$, $LiGaS_2$, $LiGaSe_2$ or any other kind of crystals exhibiting a quadratic $\chi^{(2)}$ optical nonlinearity. Furthermore, the bulk quadratic nonlinear medium 2 may be a semiconductor material, such as GaSe, ZnSe, AlGaAs, $CdSiP_2$, $ZnGeP_2$, $CdGa_2S_4$, ZnTe, $LiGaTe_2$, $CdGeP_2$, or any other kind of a semiconductor material exhibiting an optical nonlinearity or a quadratic $\chi^{(2)}$ optical nonlinearity.

Additionally, the bulk quadratic nonlinear medium 2 may be configured to operate in a wavelength range between 0.7 μm to 1.4 μm, 1.1 μm to 2.5 μm, 1.7 μm to 3.5 μm, 1.5 μm to 3 μm, 3 μm to 5.5 μm, 3 μm to 7 μm, 4 μm to 9 μm, 5 μm to 10 μm, or 6 μm to 12 μm.

Furthermore, the dispersive unit 3 includes at least one or more of the following combinations, a pair of diffractions gratings, a pair of prisms, one or more dispersive mirrors, a pair of double-pass diffraction gratings and/or a pair of double-pass prisms.

Fig. 2 shows the pulse compressor 1 which further comprises a dispersive control element 5 provided before the bulk quadratic nonlinear medium 2. In fig. 2A the dispersive control element 5 is being adapted for controlling temporal chirp of the optical pulse 4 before and/or upon entering the bulk quadratic nonlinear medium 2.

In this particular example the optical pulse 4 is being controlled before entering the bulk quadratic nonlinear medium 2.

In fig. 2B the dispersive control element 5 is a tilting element for tilting 6 the optical pulse front 4 before and/or upon entering the bulk quadratic nonlinear medium 2. In this particular example, the tilting of the optical pulse front 4 is before entering the bulk quadratic nonlinear medium 2. The tilting of the optical pulse front 4 may be represented by a pulse front tilt angle (Θ_i), wherein the angle (Θ_i) is determined with respect to a beam line 10 perpendicular to an input surface 11 of the bulk quadratic nonlinear medium 2. The pulse front tilt angle (Θ_i) may be between 0.5° to 10°, 1° to 5°, 2° to 20°, 10° to 25°, or 10° to 45°.

In one or more embodiments, the change in the pulse front tilt (Θ_i) would change the zero group-velocity dispersion wavelength (λ_{ZD}), i.e. increasing the tilt angle (Θ_i) would decrease the zero order dispersion wavelength (λ_{ZD}). Furthermore, it is possible to optimize the zero group-velocity mismatch wavelength (λ_{ZGVM}) to the pump wavelength (λ_p) of the optical pulse 4, and thereby, obtaining an optimized pulse compression wherein the wavelength difference between the zero group-velocity mismatch wavelength (λ_{ZGVM}) of the bulk quadratic nonlinear medium 2 and the pump wavelength (λ_p) of the optical pulse 4 is reduced.

Additionally, by being able to tune the zero group-velocity dispersion wavelength (λ_{ZD}), the bulk quadratic nonlinear medium 2 or the pulse compressor 1 may be more flexible in its use with different laser sources 7.

In one or more embodiments, the change in crystal rotation angle (Θ_A), would change the phase mismatch parameter for second harmonic generation (SHG) Δk, and thereby, it is an advantage of being able to change the crystal rotation angle since the phase mismatch parameter for second harmonic generation (SHG) Δk may be optimized so to eliminate or reduce the self-defocusing effect on the optical pulse in the bulk quadratic nonlinear medium.

Fig. 3A shows a pulse compressor 1 having a laser source 7, wherein the optical pulse 4 may be generated by the laser source 7 configured with a pulse shaper and/or by the laser source 7 being a Ti:sapphire laser, an InGaAs laser, an AlGaIn laser, an AsSb laser, a Xe-He laser, a CO_2 laser, a GaAlAs laser, a dye laser, a Cr:ZnS laser, a Cr:ZnSe laser, a Cr:forsterite laser, an Er-doped laser, a Tm-doped laser, a Ho-doped laser, or an Yb-doped laser.

Fig. 3B shows a pulse compressor 1 having a laser source 7 and a beam collimator 8, wherein the beam collimator 8 may be configured to collimate the optical pulse 4 entering the bulk quadratic nonlinear medium 2 or the dispersive control element 5. In this particular example, the optical pulse 4 is collimated into the dispersive control element 5.

Fig. 4 shows a figure-of-merit (FOM) defining the ratio between a cascading nonlinear refractive index and a Kerr nonlinear refractive index, wherein the FOM is calculated for different bulk quadratic nonlinear media 2X as a function of pump wavelengths (λ_p). The starting point (low-wavelength) of a particular curve is the onset of anomalous dispersion, i.e. the zero group-velocity dispersion wavelength (λ_{ZD}). The ending point (high-wavelength) of a particular curve is the IR absorption edge. Furthermore, the figure shows for different pump wavelengths (λ_p) where the cascading nonlinear refractive index is larger than the Kerr nonlinear refractive index of different bulk quadratic nonlinear media 2X, i.e. the self-defocusing limit of a bulk quadratic nonlinear medium 2.

It is an advantage of using bulk quadratic nonlinear media for pulse compression since applying quasi phase matching (QPM) would not be necessary when FOM is above 1 at a specific pump wavelength. Alternatively, when FOM is below 1 it is possible to increase the FOM to above 1 at a specific pump wavelength for a specific bulk quadratic nonlinear media by applying QPM.

Fig. 5A-C show a bulk quadratic nonlinear medium 2 characterized by having a first length (1. Length), a first width (1. Width) and a second width (2. Width). Furthermore, figure 5A-C show several examples on different ways of stacking or combining multiple bulk quadratic nonlinear media 2X into one bulk quadratic nonlinear medium 2.

Fig. 5A shows a single bulk quadratic nonlinear medium 2 characterized by the first width, (B) shows a bulk quadratic nonlinear medium 2 comprising a first bulk quadratic nonlinear medium 2A stacked with a second bulk quadratic nonlinear medium 2B resulting in an increased first width, and (C) shows a bulk quadratic nonlinear medium 2 comprising multiple bulk quadratic nonlinear media 2X wherein the first width may be further increased.

Fig. 5B shows a bulk quadratic nonlinear medium 2 characterized by the first width and the second width, (B) shows a bulk quadratic nonlinear medium 2 comprising a first bulk quadratic nonlinear medium 2A, a second bulk quadratic nonlinear medium 2B, a third bulk quadratic nonlinear medium 2C and a fourth bulk quadratic nonlinear medium 2D stacked together and wherein the stacking resulting in an increased first width and in an increased second width, and (C) shows multiple bulk quadratic nonlinear media 2X stacked together and wherein the first width and the second width may be further increased.

Fig. 5C shows a bulk quadratic nonlinear medium 2 characterized by the first length extending in parallel to the direction of the propagation axis 9, and (B) shows a bulk quadratic nonlinear medium 2 comprising a first bulk quadratic nonlinear medium 2A, a second bulk quadratic nonlinear medium 2B and/or another bulk quadratic nonlinear medium 2X applied together so that the first length increases.

In another example, the multiple bulk quadratic nonlinear media 2X may be applied together with a distance and no distance between the multiple bulk quadratic nonlinear media 2X.

By having the possibility of stacking multiple similar bulk quadratic nonlinear media 2X would imply that the energy of the optical pulse 4 is not limited by the aperture size of the bulk quadratic nonlinear medium comprising multiple bulk quadratic nonlinear media 2X stacked together. Furthermore, by increasing the first length of the bulk quadratic nonlinear medium 2 the compression of the optical pulse 4 would be improved, and thereby, the compression factor (fc) would increase.

The bulk quadratic nonlinear media 2X may be stacked together in such a way that the first width, the second width and/or the first length changes. The multiple bulk quadratic nonlinear media 2X are either glued together with an index-matching-glue or fixed together by a frame wherein an index-matching-oil is applied between each bulk quadratic nonlinear medium 2.

Figs. 6A and 6B show a simulated result of the compression factor (f_c) and the pulse quality (Q_c) of a compressed optical pulse 4A as a function of a first length (z) for two different nonlinear media 2.

Fig. 6A shows the simulated result wherein the bulk quadratic nonlinear medium 2 is a KDP crystal and wherein the width of the optical pulse entering the bulk quadratic nonlinear medium is 200 fs at 1030 nm. The intensity going into the bulk quadratic nonlinear medium is 60GW/cm^2.

The compression factor (f_c) is increasing and the pulse quality is decreasing when increasing the first length, i.e. increasing the propagation length of the optical pulse 4 within the KDP crystal providing an improved compression factor at the expense of a decreased pulse quality. For example, the first length is equal to 50 mm and the compressed optical pulse 4A would be compressed with a compression factor of 2.5 and the pulse quality is 84 %, i.e. 84 % of the energy going into the bulk quadratic nonlinear medium 2 is located in the central spike of the compressed optical pulse 4A which has a compressed width of 80 fs (200/2.5 = 80 fs).

Fig. 6B shows similar simulated results wherein the bulk quadratic nonlinear medium 2 is a RDP crystal and wherein the width of the optical pulse entering the bulk quadratic nonlinear medium is 200 fs at 1057 nm. The intensity going into the bulk quadratic nonlinear medium is 100GW/cm^2.

Fig. 7 shows a pulse compressing method 20, wherein the method 20 starts by guiding an optical pulse 4 through a bulk quadratic nonlinear medium 2 with negative nonlinear phase variation and negative group-velocity dispersion 20A, and thereby, the bulk quadratic nonlinear medium is configured to give a self-defocusing nonlinearity and which has anomalous dispersion. At the output of the bulk quadratic nonlinear medium 2 a spectral broadening of the optical pulse 4 is obtained through self-defocusing 20B. Furthermore, the self-defocusing pulse 4 is guided through a dispersive unit 3 with a net positive dispersion for compensating negative nonlinear phase variation and negative group-velocity dispersion generated in the bulk quadratic nonlinear medium (2, 20C). A temporally compressed pulse 4A is obtained at an output of the pulse compressor 1.

In an exemplary method, the method 20 may start by generating 20A an optical pulse 4 by a laser source 7 configured with a pulse shaper and/or by a laser source 7 being a Ti:sapphire laser, an InGaAs laser, an AlGaIn laser, an AsSb laser, a Xe-He laser, a CO_2 laser, a GaAlAs laser, a dye laser, a Cr:ZnS laser, a Cr:ZnSe laser, a Cr:forsterite laser, an Er-doped laser, a Tm-doped laser, a Ho-doped laser, or an Yb-doped laser.

In another exemplary method the guiding of the optical pulse 4 into the bulk quadratic nonlinear medium 2 is obtained by using a dispersive control element 5. In a further exemplary method the guiding of the optical pulse 4 into a dispersive control element 5 or the bulk quadratic nonlinear medium 2 is obtained by using a beam collimator 8.

Figs. 8A-B show an overview over KDP and its isomorphs. Zero-group velocity mismatch wavelength (λ_{ZGVM}) is calculated as the wavelength where both phase matching and zero-group velocity mismatch is achieved. The supported FWHM temporal duration (T_{FWHM}) is calculated based on a Gaussian spectrum centred at λ_{ZGVM}, and broadened so its -10 dB blue edge is located at zero-dispersion wavelength (λ_{ZD}).

Fig. 8A shows the Gaussian spectrum centred at λ_{ZGVM} and through the self-defocusing nonlinearity will have experienced spectral broadening to a bandwidth ($\Delta\lambda$), where $\Delta\lambda$ defines the bandwidth wherein the spectral broadening to the blue side (low wavelength) does not surpass the -10 dB level at the zero-dispersion wavelength (λ_{ZD}) of the bulk quadratic nonlinear medium 2, and where the spectral broadening to the red side (high wavelength) is assumed to be symmetric and equal to that of the blue side.

Fig.8B shows the calculated λ_{ZGVM}, λ_{ZD}, $\Delta\lambda$, as well as experimental data for the UV edge and IR edge of the transmission spectrum for different KDPs and its isomorphs.

KDP is one of the very rare crystals with a zero dispersion wavelength (λ_{ZD}). around 1.0 µm, and is therefore suitable for compression of Yb-based lasers and Cr:Forsterite lasers.

The bulk quadratic nonlinear medium 2 may provide a self-steepening effect on the optical pulse 4 which would result in an optical pulse 4 which is asymmetric around the peak of the optical pulse 4. Self-steepening occurs because the intense central part of the optical pulse 4 travels either slower or faster than the low –intensity part. Therefore, the one side of the optical pulse 4 in time domain escapes from the peak while the other part catches up with the peak, and therefore the compressed optical pulse 4A becomes asymmetrical around the peak of the optical pulse resulting in a reduced quality factor (Q_c) and compression factor (f_c).

The pump wavelength λ_p of the optical pulse 4 entering the bulk quadratic nonlinear medium 2 can be optimized so that the effect of the self-steepening is minimized. By minimizing the self-steepening effect on the optical pulse passing through the pulse compressor, would result in a compressed optical pulse 4A with a further improved quality factor (Q_c) and a further improved compression factor (f_c).
Based on the nonlinear Schrödinger equation the intensity and phase self-steepening nonlinear coefficients are expressed in following ways;

$$n_{2,ss}(I) = \frac{1}{\omega_1}\left(2n_{2,casc}\left[2 + \frac{\omega_1 d_{12}}{\Delta k}\right] + 3n_{2,Kerr}\right) \quad \text{(Eq 1)},$$

$$n_{2,ss}(\varphi) = \frac{1}{\omega_1}\left(2n_{2,casc}\left[1 + \frac{\omega_1 d_{12}}{\Delta k}\right] + n_{2,Kerr}\right) \quad \text{(Eq 2)},$$

wherein equation 1 refers to the intensity self-steepening nonlinear coefficient and equation 2 refers to the phase self-steepening nonlinear coefficient. Control over these parameters is offered both through $n_{2,casc} \sim -d_{eff}^2/\Delta k$, and through the ratio$d_{12}/\Delta k$, where d_{12} is the Group-Velocity-Mismatch parameter.

The phase mismatch parameter for second harmonic generation (SHG) is $\Delta k = k_2 - 2k_1$, i.e. the difference between the harmonic wavevector and twice the pump wavevector. Thus, for cascaded SHG the requirement for a negative cascading nonlinearity is that the SH phase velocity is smaller than the pump phase velocity.

The equation (Eq. 1) for the intensity self-steepening nonlinear coefficient ($n_{2,ss}(I)$) and the equation (Eq. 2) for the phase self-steepening nonlinear coefficient ($n_{2,ss}(\varphi)$) show that the cascading allows controlling self-steepening nonlinear coefficients through the cascading nonlinear coefficient $n_{2,casc}$. Generally, the intensity equation (Eq 1) does not depend on the phase, and it can therefore be solved directly. The solution gives the self-steepening effect in time domain described above. Therefore, by minimizing or even nulling the intensity self-steepening $n_{2,ss}(I)$ will lead to minimal or zero self-steepening of the optical pulse 4.

The phase equation (Eq 2) describes how the phase is influenced by self-steepening, and how self-steepening causes an asymmetric evolution of the spectral broadening by self-phase modulation. Therefore minimizing or even cancelling $n_{2,ss}(\varphi)$ will lead to minimal (or zero) asymmetry in the broadened spectrum of the optical pulse 4 passing through the bulk quadratic nonlinear medium 2. For our purposes the effect caused by the intensity self-steepening nonlinear coefficient is the most important one to control.

In the case where the phase mismatching coefficient is positive ($\Delta k>0$), cascaded self-defocusing results, and we may consider two cases as to achieve an overall self-defocusing nonlinear effect ($|n_{2,casc}| > n_{2,Kerr}$): first case, when $d_{12}<0$ self-steepening cannot be cancelled completely, but only minimized; and second case, when $d_{12}>0$ self-steepening can be cancelled, i.e. $n_{2,ss}(I)$ = 0, for a certain phase-mismatch value (Δk). Having $d_{12}>0$ requires that the pump wavelength λ_p is above zero-group velocity mismatch wavelength, i.e. $\lambda_p>\lambda_{ZGVM.}$

The pulse compressor 1 may receive an optical pulse 4 being pumped at a pump wavelength λ_p wherein the self-steepening in the bulk quadratic nonlinear medium 2 is minimized or eliminated and providing self-defocusing effect on the optical pulse 4 going out from the bulk quadratic nonlinear medium 2. Furthermore, the net positive dispersion in the dispersive unit 3 at least partially compensates for the negative nonlinear phase variation and the negative group-velocity dispersion produced by the bulk quadratic nonlinear medium 2 when the optical pulse 4 passes through the bulk quadratic nonlinear medium 2 and subsequently through the dispersive unit 3 thereby generating a temporally compressed optical pulse 4A with minimized or eliminated self-steepening.

Figs. 9A-C compare three compressed optical pulses 4A, wherein each pulse has propagated 80 mm through a KDP, a RDP, and an ADP crystal, respectively. For all three crystals the cascaded nonlinearity is kept identical, and since their respective d_{eff}, i.e. effective quadratic nonlinearity, are different, the phase mismatch for each crystal has been chosen to be Δk=1.30 mm^{-1}, Δk=1.50 mm^{-1}, and Δk=1.90 mm^{-1}, respectively, for KDP, RDP and ADP. The input intensity of the optical pulse 4 is fixed at I_0 = 40 GW/cm^2 and the pump wavelength is 1057 nm. In this particular example the pump wavelength is denoted by λ_1.

Fig. 9A shows a compression figure-of-merit (FOM) as a function of first length (1. length, z) of a respective bulk quadratic nonlinear medium. The compression FOM may be used as a gauge for the compression performance of the bulk quadratic nonlinear medium. The compression FOM, FOMc is read as followed:

$$FOM_C = sgn(GDD)\frac{I_{c,peak}\bar{R}^2_{fit}}{\eta_c},$$

wherein $I_{c,peak}$ is the peak intensity of the compressed optical pulse 4A, $\bar{R}^2_{fit}$ is a measure of how much the compressed optical pulse is adapted to a Gaussian shape, η_c is found as the ratio between the temporal duration of the compressed optical pulse after GDD compensation 4A and the duration of an ideal compressed optical pulse, i.e. wherein a spectral phase across the optical pulse is assumed completely linear or flat. $I_{c,peak}$ is an excellent measure of the combined effect of the compression factor and pulse quality.

Position z may represent a propagation length within a bulk quadratic nonlinear medium.

The simulations are assuming plane-waves (no diffraction) and model SHG through coupled-wave envelope equations. Full (exact) dispersion is taken into account, as well as self-steepening and Kerr self- and cross-phase modulation. When compressing the pulses temporally only a quadratic spectral phase compensation is implemented, i.e. only a suitably chosen amount of group-delay dispersion (GDD) is applied to the spectral phase. No third- or higher-order phase components are compensated. The optimal GDD can be chosen in a number of ways, but the best way numerically is to find the GDD that maximizes the compressed pulse intensity; this gives within a small margin the same result as when optimizing GDD to give the shortest pulse (which is the goal, but such an optimization algorithm is much more computational intensive and prone to spurious results). With a propagation length (z) of 8 mm to 28 mm the compression performance is higher for the ADP crystal, and above 28 mm the RDP crystal has the highest compression performance.

Furthermore, the intensity profile as a function of time is seen for each crystal in 12A, 12B and 12C for RDP, KDP and ADP, respectively. At the propagation length of 80 mm, it is seen that the intensity profile for each crystal (12A, 12B, 12C) illustrate a more symmetrical optical pulse for the RDP crystal (applied GDD=+880 fs^2). For the ADP (applied GDD=+1840 fs^2) it is seen that the optical pulse is very strong asymmetric due to increased self-steepening effects.

The compression FOM, i.e. FOM_C, may at least be above 1.3, above 1.5 or above 1.7.

Fig 9B shows a normalized intensity profile as a function of wavelength for each compressed optical pulse. The compressed optical pulse 4A''' of the ADP crystal is strongly asymmetric around the pump wavelength which is due to a strong self-steepening effect induced to the compressed optical pulse 4A. The self-steepening effect is obtained since the zero-group velocity mismatch wavelength of the ADP crystal is located far away from the pump wavelength. Furthermore, the self-steepening effect becomes lower, i.e. less severe, for the compressed optical pulse

4A'' of the KDP crystal and even lower for the compressed optical pulse 4A' of the RDP crystal, since the zero-group velocity mismatch wavelength of the KDP crystal and the RDP crystal is located closer to the pump wavelength. The pump wavelength is represented by the centre wavelength of the optical pulse injected into the respective crystals.

Fig. 9C shows the spectral phase profile, before and after applying a net dispersion (i.e. before and after applying a group-delay-dispersion (GDD) compensation), as a function of wavelength for each optical pulse. It is seen that the spectral phase across the compressed optical pulse for the RDP crystal has less variation, and thereby, this explains why the normalized intensity profile for the compressed optical pulse 4A' of the RDP crystal is more symmetric around the pump wavelength than for the KDP crystal.

Thus, an increased flatness (i.e. linearity) of the spectral phase across the optical pulse increases the compression performance and the pulse quality Q_c.

Figs. 10A-B show the normalized intensity profile for the optical pulse being injected into the ADP crystal and for the compressed optical pulse. The pump wavelength or the phase mismatch parameter Δk is optimized so that the self-steepening effect to the compressed optical pulse is reduced or eliminated. The pump wavelength may be denoted as an optimized pump wavelength. The optimized pump wavelength for any bulk quadratic nonlinear medium is where the intensity self-steepening nonlinear coefficient is zero or reduced to a minimum. In this particular example, the pump wavelength λ_p is 1012 nm with 100 fs pulse duration. At the pump wavelength the intensity self-steepening nonlinear coefficient is zero at $\Delta k=2.0\ mm^{-1}$ and $\Delta k=2.8\ mm^{-1}$. The chosen phase mismatch coefficient Δk is the lowest as to reduce cross phase modulation (XPM). The input intensity of the optical pulse 4 is fixed at I_0 = 125 GW/cm^2. The propagation length of the optical pulse is 70 mm.

Fig 10A shows the normalized intensity profile as a function of time for the optical pulse 4 being injected into the ADP crystal 2, the optical pulse going out from the crystal 2 i.e. a self-defocused optical pulse, and the compressed optical pulse 4A. Additionally, the spectral phase profile after and before providing the GDD compensation to the optical pulse 4 as a function of time is seen in fig. 10A. It is clearly seen that when the injected pump wavelength is optimized the compressed optical pulse is perfectly symmetrical around the main pulse. Furthermore, it is seen that the phase profile across the optical pulse is very linear.

Fig 10B shows the normalized intensity profile as a function of wavelength for the optical pulse 4 being injected into the ADP crystal and the optical pulse going out of the crystal i.e. a self-defocused optical pulse, and the compressed optical pulse 4A. Additionally, the spectral phase profile after providing the GDD compensation to the optical pulse 4 as a function of time. It is clearly seen that the compressed optical pulse 4A around the pump wavelength is perfectly symmetrical.

Thus, by optimizing the pump wavelength for reducing or eliminating self-steepening effect on the optical pulse propagating through a bulk quadratic nonlinear medium would provide an optimized and an improved compression of the optical pulse and an improved pulse quality.

The pump wavelength λ_p may be optimized when one or more of the following criteria may be fulfilled;

- SHG phase mismatch is above zero, i.e. $\Delta k>0$,
- if group-velocity-mismatch parameter is above zero, i.e. $d_{12}>0$, the pump wavelength may be above zero-group velocity mismatch wavelength configured to the bulk quadratic nonlinear medium, $\lambda p>\lambda_{ZGVM}$,
- the cascading nonlinear refractive index is larger than the Kerr nonlinear refractive index, i.e. $n_{2,casc}>n_{2,Kerr}$, wherein both the cascading nonlinear refractive index and the Kerr nonlinear refractive index are configured to the same bulk quadratic nonlinear medium, and/or
- the intensity self-steepening nonlinear coefficient is minimized while the ratio between the cascading nonlinear refractive index and the Kerr nonlinear refractive index may be at least 1.05, at least 1.2 or at least 2.

ZGVM wavelength depends on theta, i.e. the angle that controls the Δk. Thus ZGVM is not a constant for the bulk quadratic nonlinear medium, it is only a constant if one fixes theta.

This is why ZGVM was defined for the theta that gives zero Δk in Fig. 8b, because we know that in KDP we need to be close to zero Δk to observe self-defocusing.

Fig. 11 shows the compression FOM as a function of first length (1. Length, z) for a congruent lithium niobate bulk quadratic nonlinear medium with 5 % MgO doping pumped with an optical pulse at 2.2 μm having a width of 100 fs and an intensity of 0.8 TW/cm^2. It is clearly seen that a positive FOM_c is possible to generate in a bulk quadratic nonlinear medium without applying quasi phase matching (QPM). However, applying QPM to the optical pulse the compression performance FOMc improves, and furthermore, it is possible to fine tune the compression of the optical pulse by adjusting the pitch Λ of the QPM phase matching coefficient, i.e. $\Delta k_{QPM} = \Delta k - 2\pi/\Lambda$.

Fig. 12 shows the pulse compressing method 20, wherein a further exemplary method optimizing the pump wavelength so the self-steepening effect on the optical pulse 4 propagating through a bulk quadratic nonlinear medium and the compressed optical pulse 4A may be minimized or eliminated, step 20F.

Fig. 13 show a multi-stage pulse compressor 1X comprising at least two pulse compressors (1A and 1B) and at least one beam expander 13.

In this specific example the multi-stage pulse compressor 1X comprises a first pulse compressor 1A configured to receive an optical pulse 4 and to compress the optical pulse. The compressed optical pulse 4A is forwarded to a beam expander 13, which spectrally broadens the compressed optical pulse 4A. A broadened optical pulse is then transmitted into the second pulse compressor 1B, and in the second pulse compressor 1B a second compression is then applied to the broadened optical pulse. The second pulse compressor 1B transmits a further compressed optical pulse 4B, which compared to the compressed optical pulse 4A transmitted by the pulse compressor, described in Fig. 1, the compression factor f_c is significantly increased without reducing the pulse quality Q_c.

ITEMS

1	Pulse compressor
1X	Multiple stage pulse compressor
1A	First pulse compressor
1B	Second pulse compressor
2	Bulk quadratic nonlinear medium
2A	First bulk quadratic nonlinear medium
2B	Second bulk quadratic nonlinear medium
2C	Third bulk quadratic nonlinear medium
2D	Fourth bulk quadratic nonlinear medium
2X	Other bulk quadratic nonlinear medium (s)
3	Dispersive unit
4	Optical pulse
4A	Compressed optical pulse
4B	Further compressed optical pulse
5	Dispersive control element
6	Pulse tilting
7	Laser source
8	Beam collimator
9	Propagation axis
10	Beam line
11	An input surface
12A	Intensity profile as a function of time for RDP
12B	Intensity profile as a function of time for KDP
12C	Intensity profile as a function of time for ADP
13	Beam expander
20	A pulse compressing method
Θ_i	Pulse front tilt angle
λ_{ZD}	zero order dispersion wavelength
1. length	Length
1. width	First width
2. width	Second width

CLAIMS

1. A pulse compressor (1) for compressing an optical pulse (4), the pulse compressor (1) comprising:

- a bulk quadratic nonlinear medium (2) adapted for generating a negative nonlinear phase variation and a negative group-velocity dispersion on the optical pulse (4), and
- a dispersive unit (3) with a net positive dispersion,

wherein the net positive dispersion in the dispersive unit (3) at least partially compensates for the negative nonlinear phase variation and the negative group-velocity dispersion produced by the bulk quadratic nonlinear medium (2) when the optical pulse (4) passes through the bulk quadratic nonlinear medium (2) and subsequently through the dispersive unit (3) thereby generating a temporally compressed optical pulse (4A).

2. A pulse compressor (1) according to claim 1, wherein the negative nonlinear phase variation is generated by cascaded second-harmonic generation, cascaded sum frequency generation, cascaded difference frequency generation or cascaded optical rectification.

3. A pulse compressor (1) according to claim 1, further comprising a dispersive control element (5) provided before the bulk quadratic nonlinear medium (2), the dispersive control element (5) being adapted for controlling temporal chirp of the optical pulse (4) before and/or upon entering the bulk quadratic nonlinear medium (2).

4. A pulse compressor (1) according to claim 2, wherein the dispersive control element (5) is a tilting element for tilting (6) a front of the optical pulse (4) before and/or upon entering the bulk quadratic nonlinear medium (2).

5. A pulse compressor (1) according to any preceding claim, wherein the bulk quadratic nonlinear medium (2) is configured to have a cascading nonlinear refractive index and a Kerr nonlinear refractive index, and wherein the cascading refractive index is negative and its absolute value larger than the Kerr nonlinear refractive index.

6. A pulse compressor (1) according to any preceding claim, wherein the bulk quadratic nonlinear medium (2) is configured to operate in a wavelength range between 0.7 µm to 1.4 µm, 1.1 µm to 2.5 µm, 1.7 µm to 3.5 µm, 1.5 µm to 3 µm, 3 µm to 5.5 µm, 3 µm to 7 µm, 4 µm to 9 µm, 5 µm to 10 µm, or 6 µm to 12 µm.

7. A pulse compressor (1) according to any preceding claim, wherein the bulk quadratic nonlinear medium (2) comprises:

- a wide-gap dielectric or bulk quadratic nonlinear media, such as BBO (beta-BaB_2O_4), $LiNbO_3$, KDP (KH_2PO_4), DKDP (KD_2PO_4), ADA ($NH_4H_2AsO_4$), KDA ($NH_4H_2AsO_4$), DKDA ($ND_4D_2AsO_4$), ADP ($NH_4H_2PO_4$), DADP ($ND_4D_2PO_4$), RDP (RbH_2PO_4), KTP ($KTiOPO_4$), KTA ($KTiOAsO_4$), $LiTaO_3$, $BaGa_4S_7$, $LiInS_2$, $LiGaS_2$, $LiGaSe_2$ or any other kind of bulk quadratic nonlinear media exhibiting an quadratic $\chi^{(2)}$ optical nonlinearity, or
- a semiconductor material, such as GaSe, ZnSe, AlGaAs, $CdSiP_2$, $ZnGeP_2$, $CdGa_2S_4$, ZnTe, $LiGaTe_2$, $CdGeP_2$, or any other kind of a semiconductor material exhibiting a quadratic $\chi^{(2)}$ optical nonlinearity.

8. A pulse compressor (1) according to any preceding claim, wherein the optical pulse (4) is generated by a laser source (7) configured with a pulse shaper and/or by a laser source (7) being a Ti:sapphire laser, an InGaAs laser, an AlGaIn laser, an AsSb laser, a Xe-He laser, a CO_2 laser, a GaAlAs laser, a dye laser, a Cr:ZnS laser, a Cr:ZnSe laser, a Cr:forsterite laser, an Er-doped laser, a Tm-doped laser, a Ho-doped laser, an Yb-doped laser or any kind of laser parametric amplifiers.

9. A pulse compressor (1) according to any preceding claim, wherein the dispersive unit (3) includes at least one or more of the following combinations:

a pair of diffraction gratings with an inverting telescope between them,

a pair of prisms,

one or more dispersive mirrors,

a pair of double-pass diffraction gratings with an inverting telescope between them, and/or

a pair of double-pass prisms.

10. A pulse compressor (1) according to any preceding claim, wherein the bulk quadratic nonlinear medium (2) operates in an anomalous group velocity dispersion regime, where the negative group velocity dispersion and the negative nonlinear phase variation contribute to a linear and negative chirp across the optical pulse (4).

11. A laser system configured with a pulse compressor (1) according to any preceding claim.

12. A pulse compressing method (20) comprising the following steps:

- guiding an optical pulse (4) from a laser source (7) through a bulk quadratic nonlinear medium (2) with negative nonlinear phase variation and negative group-velocity dispersion (20A) thereby obtaining a self-defocusing pulse (4) that is spectrally broadened due to the self-defocusing nonlinearity (20B), and
- guiding the self-defocusing pulse (4) through a dispersive unit (3) with a net positive dispersion for compensating negative nonlinear phase variation and negative group-velocity dispersion generated in the bulk quadratic nonlinear medium (2), and thereby, obtaining a temporally compressed pulse (4A, 20D).

13. A pulse compressing method (20) according to claim 12, wherein guiding the optical pulse (4) into the bulk quadratic nonlinear medium (2) is obtained by using a dispersive control element (3).

14. A pulse compressing method (20) according to claims 12 or 13, wherein guiding the optical pulse (4) into a dispersive control element (3) or the bulk quadratic nonlinear medium (2) is obtained by using a beam collimator (8).

15. A pulse compressing method (20) according to claims 12 to 14, wherein a pump wavelength of the optical pulse (4) is optimized so that a self-steepening effect on the temporally compressed pulse (4A) is minimized or eliminated.

16. A pulse compressor method (20) according any one of claims 12-15, further comprises generating an optical pulse (4), wherein the optical pulse (4) is generated

by a laser source (7) configured with a pulse shaper and/or by a laser source (7) being a Ti:sapphire laser, an InGaAs laser, an AlGaIn laser, an AsSb laser, a Xe-He laser, a CO2 laser, a GaAlAs laser, a dye laser, a Cr:ZnS laser, a Cr:ZnSe laser, a Cr:forsterite laser, an Er-doped laser, a Tm-doped laser, a Ho-doped laser, an Yb-doped laser (20E) or any kind of laser parametric amplifiers.

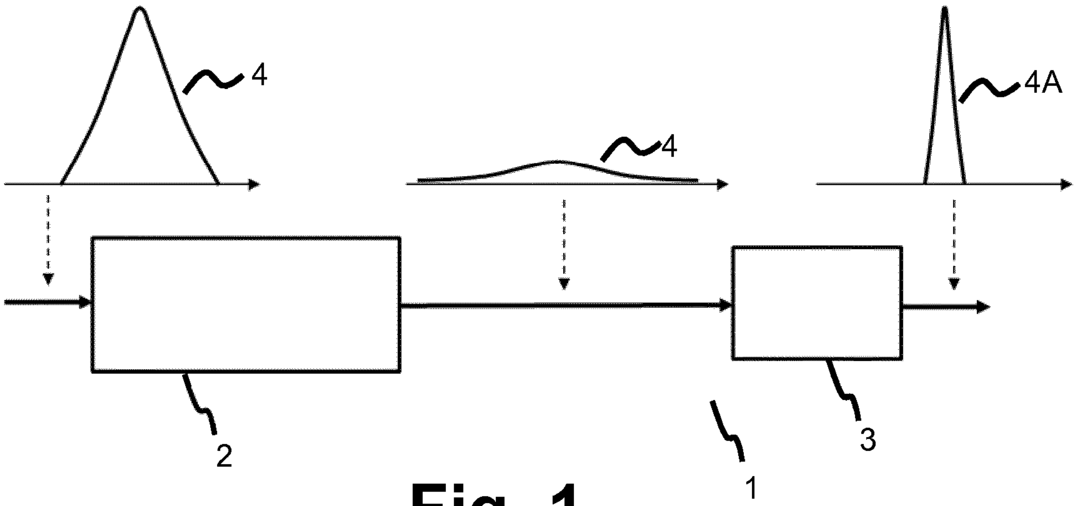

Fig. 1

Fig. 2A

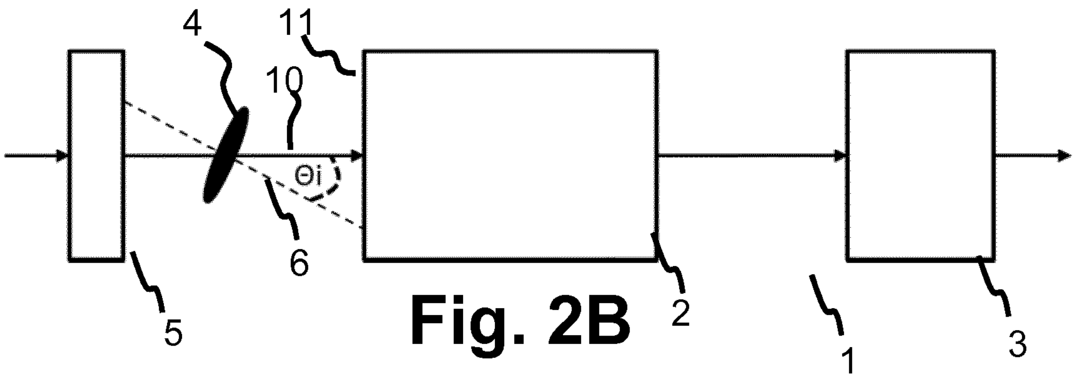

Fig. 2B

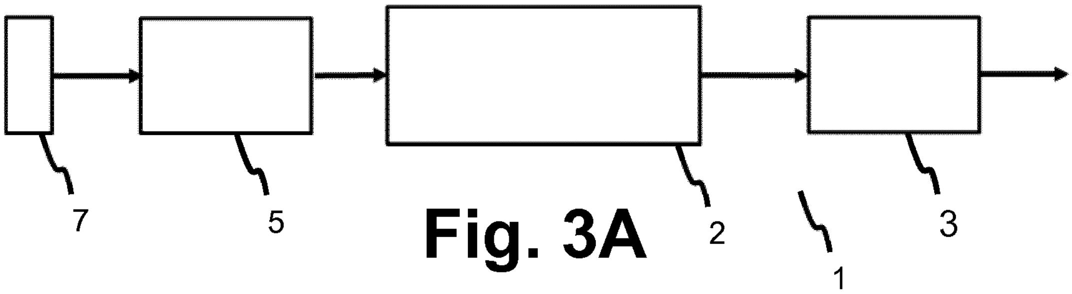

Fig. 3A

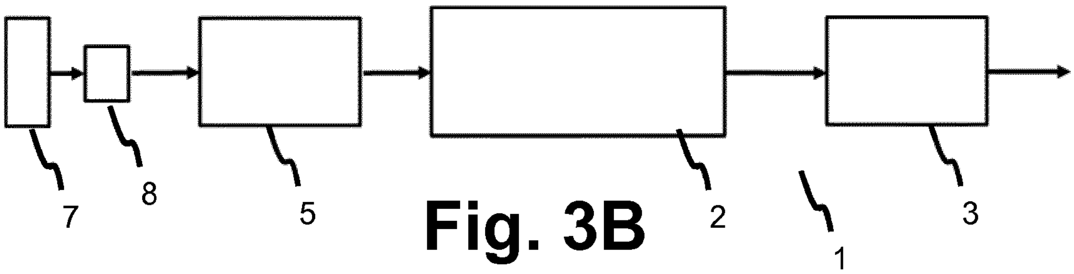

Fig. 3B

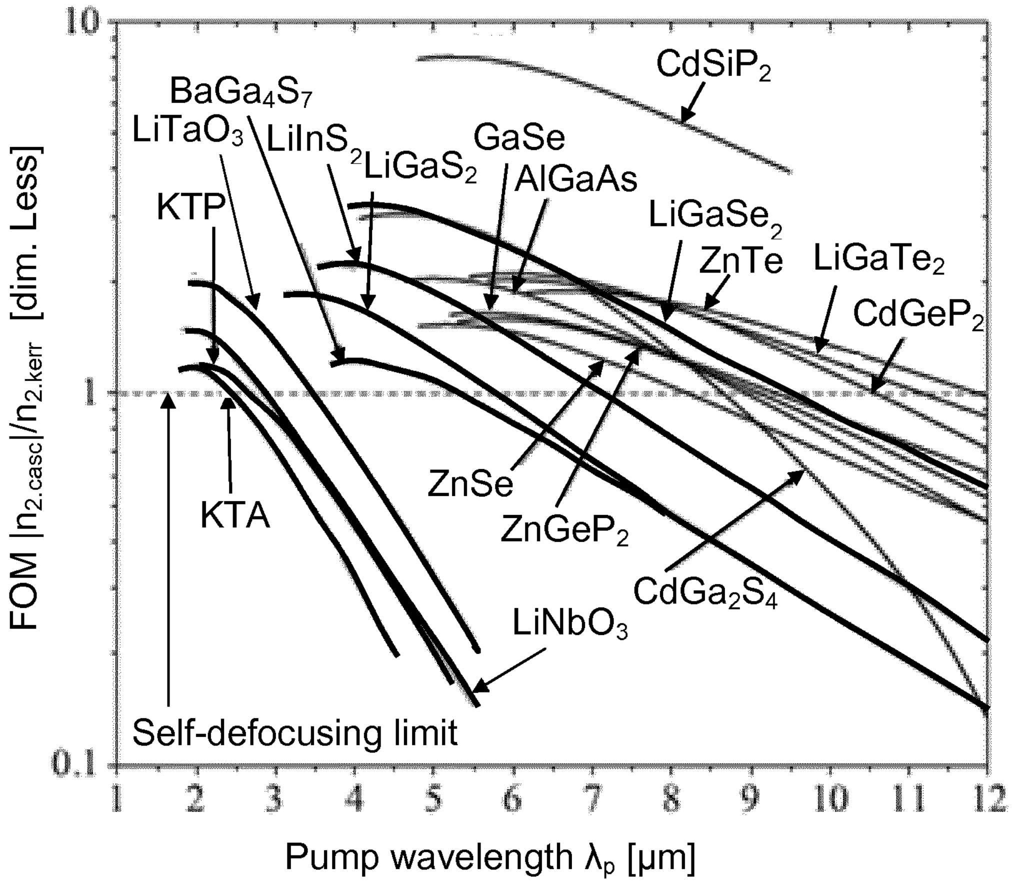
10
1
0.1
1 2 3 4 5 6 7 8 9 10 11 12
FOM |n2.casc|/n2.kerr [dim. Less]
Pump wavelength λp [μm]
CdSiP2
BaGa4S7
LiTaO3
LiInS2
LiGaS2
GaSe
AlGaAs
KTP
LiGaSe2
ZnTe
LiGaTe2
CdGeP2
ZnSe
ZnGeP2
KTA
CdGa2S4
LiNbO3
Self-defocusing limit

Fig. 4

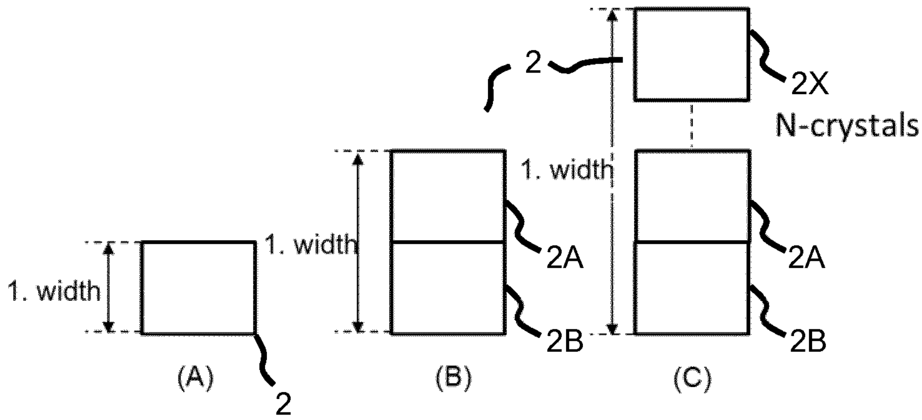

Fig. 5A

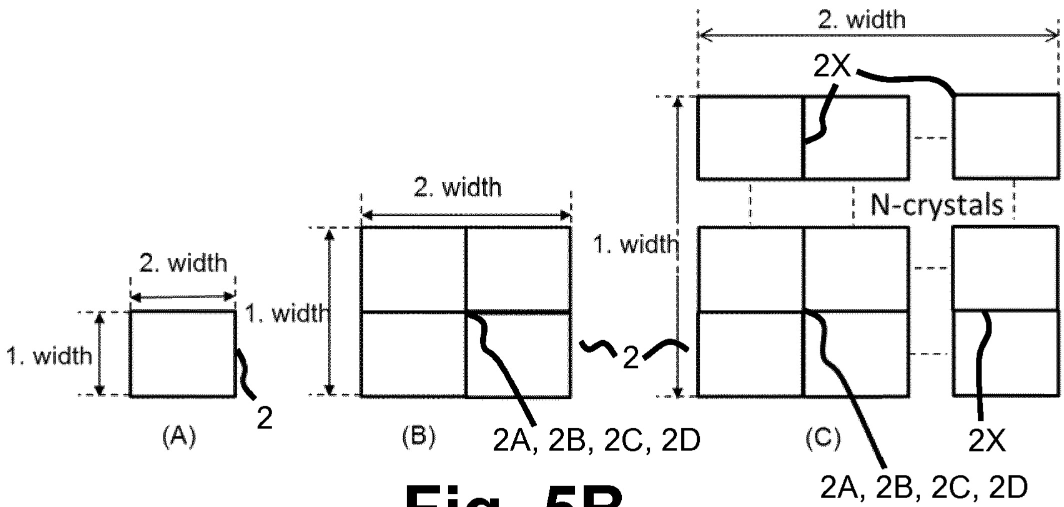

Fig. 5B

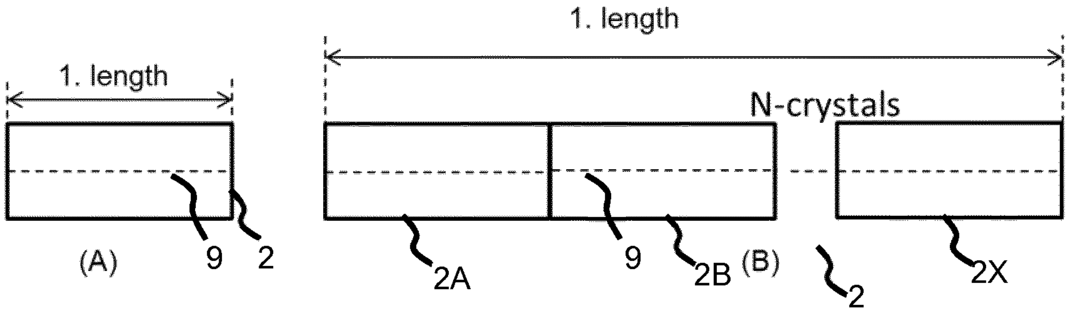

Fig. 5C

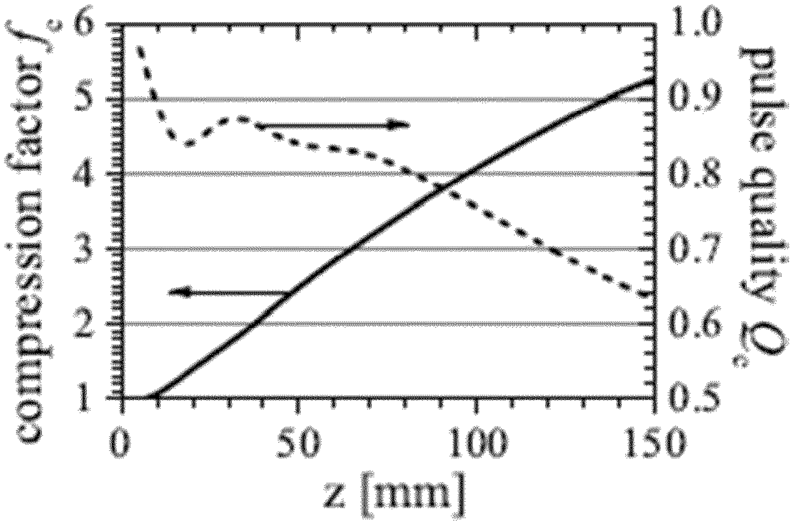
compression factor f_c
pulse quality Q_c
z [mm]
1
2
3
4
5
6
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150

Fig. 6A

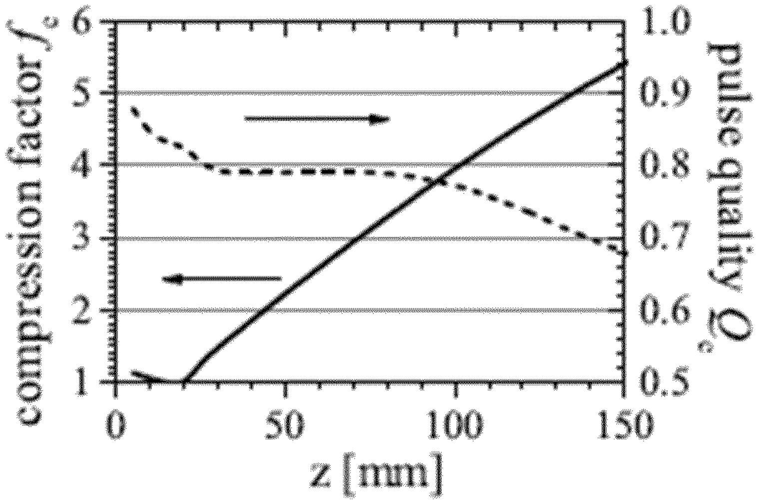
compression factor f_c
pulse quality Q_c
z [mm]
1
2
3
4
5
6
0.5
0.6
0.7
0.8
0.9
1.0
0
50
100
150

Fig. 6B

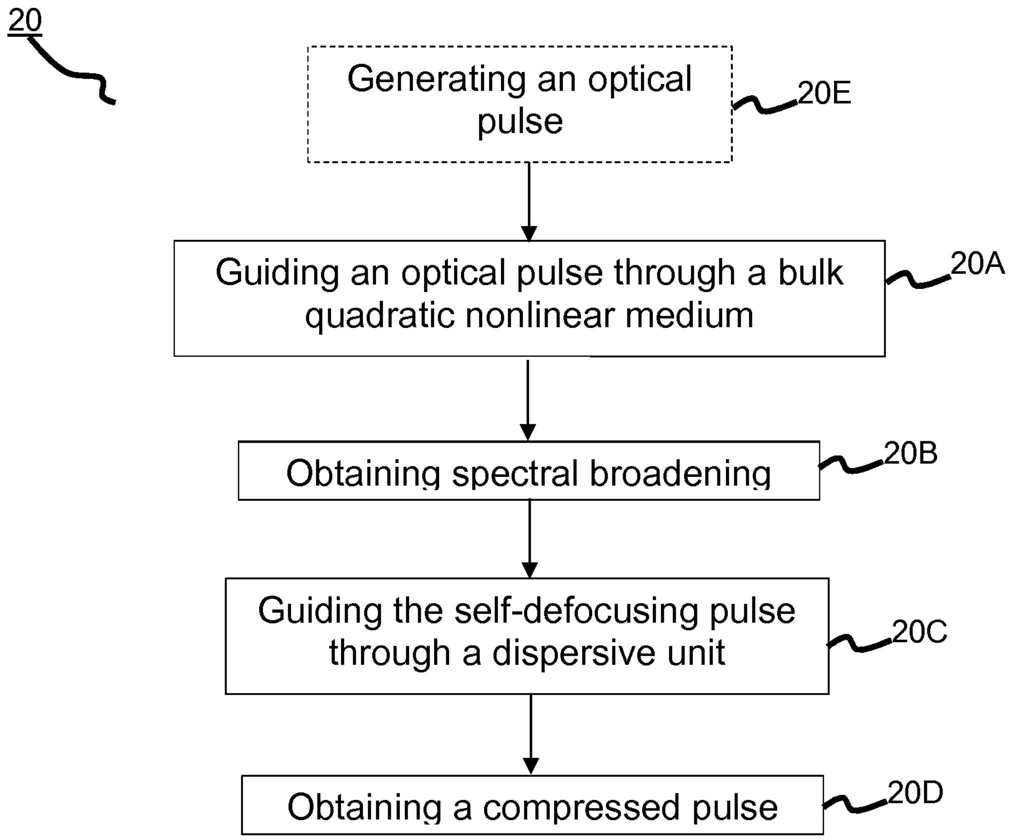
20
Generating an optical pulse
20E
Guiding an optical pulse through a bulk quadratic nonlinear medium
20A
Obtaining spectral broadening
20B
Guiding the self-defocusing pulse through a dispersive unit
20C
Obtaining a compressed pulse
20D

Fig. 7

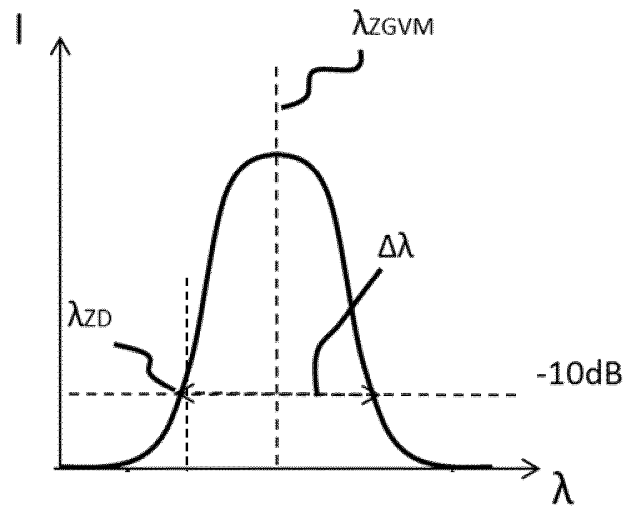

Fig. 8A

	KDP	DKDP	ADP	DADP	ADA	DADA	RDA	DRDA	RDP	DRDP	CDA	DCDA	KDA
λ_{ZD} [nm]	1010[2]	1122	938[3]	1086	1070	1286	1130	1291	1011	1131	1157	1262	1117
λ_{ZGVM} [nm]	1046	1202	1011	1174	1145	1365	1188	1365	1054	1181	1209	1322	1181
d_{36}@1064 nm [pm/V]	0.39	0.37	0.46	0.46	0.43	0.4	0.39[1]	0.31	0.36	0.38	0.402	0.402	0.41
UV edge [nm]	176	200	184	220	220	?	260	260	220	220	260	270	216
IR edge [nm]	1400	1800	1500	1700	1200	?	1460	1700	1500	1500	1430	1660	1670
cutoff -10 dB													
Δλ [nm]	73	160	144	176	150	156	116	146	86	100	104	120	128
T_{FWHM} [fs]	40	24	19	21	23	32	32	34	35	38	37	39	29
N_{cycle}	11	6	6	5	6	7	8	7	10	10	9	9	7

Fig. 8B

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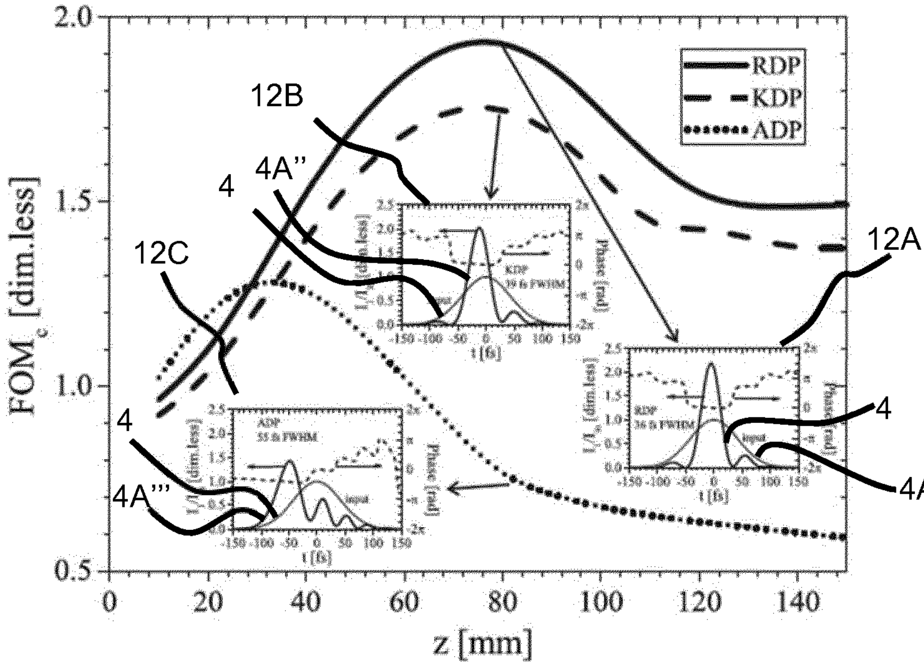

Fig. 9A

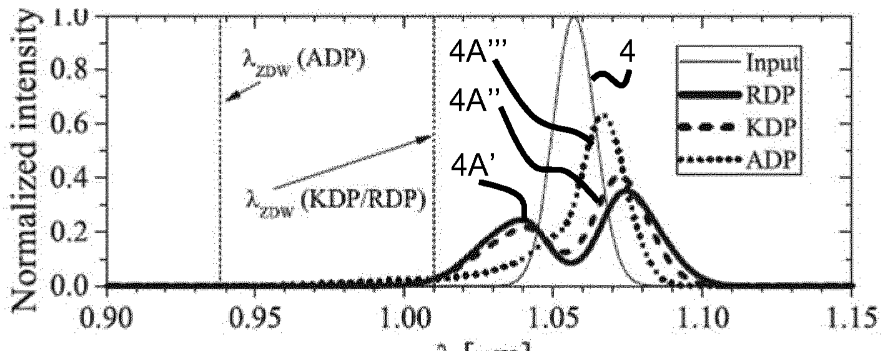

Fig. 9B

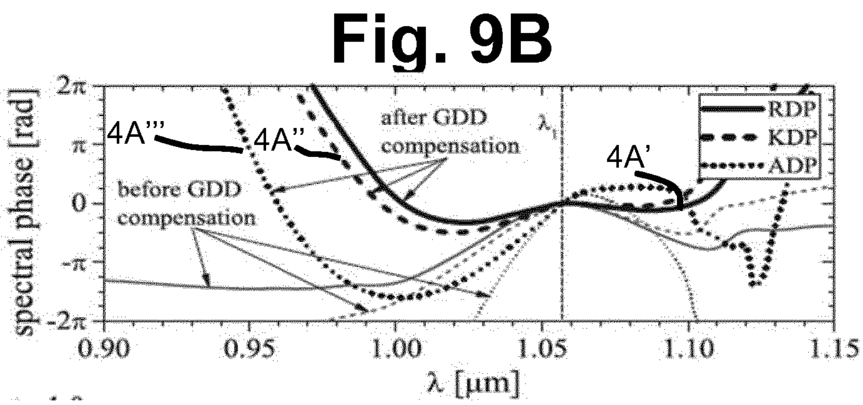

Fig. 9C

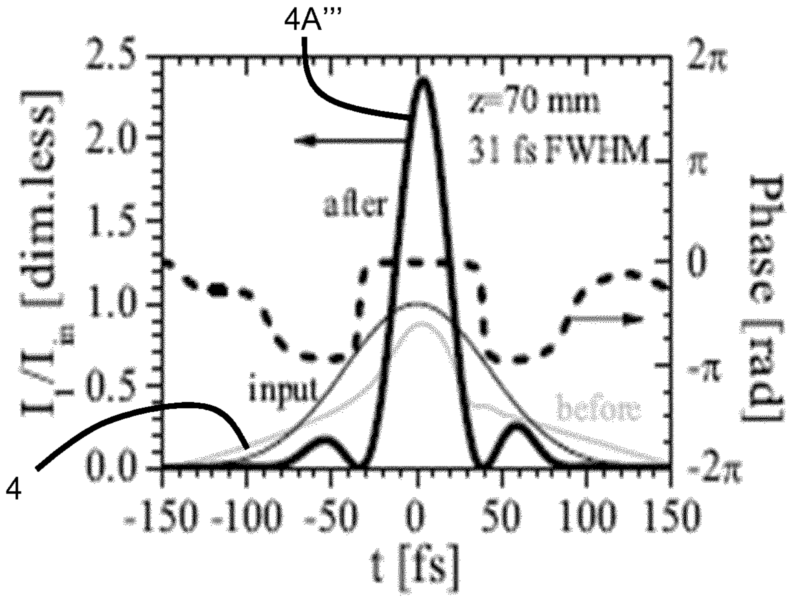

Fig. 10A

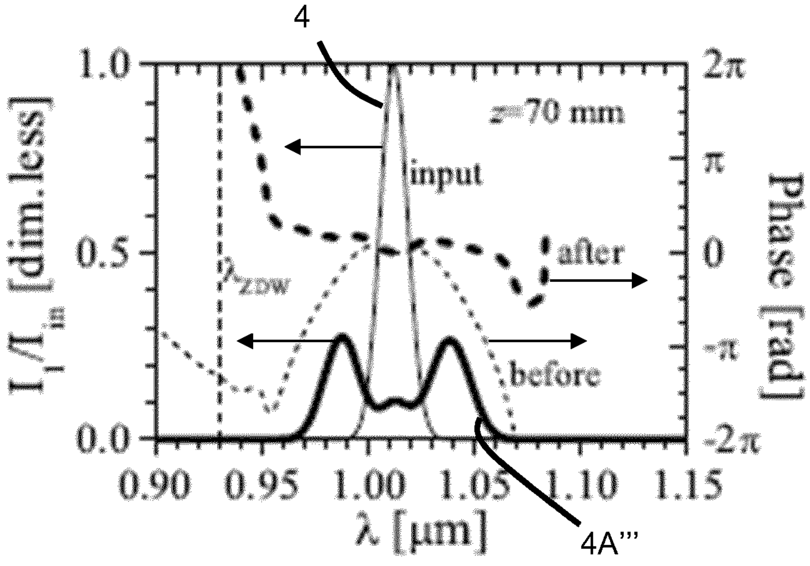

Fig. 10B

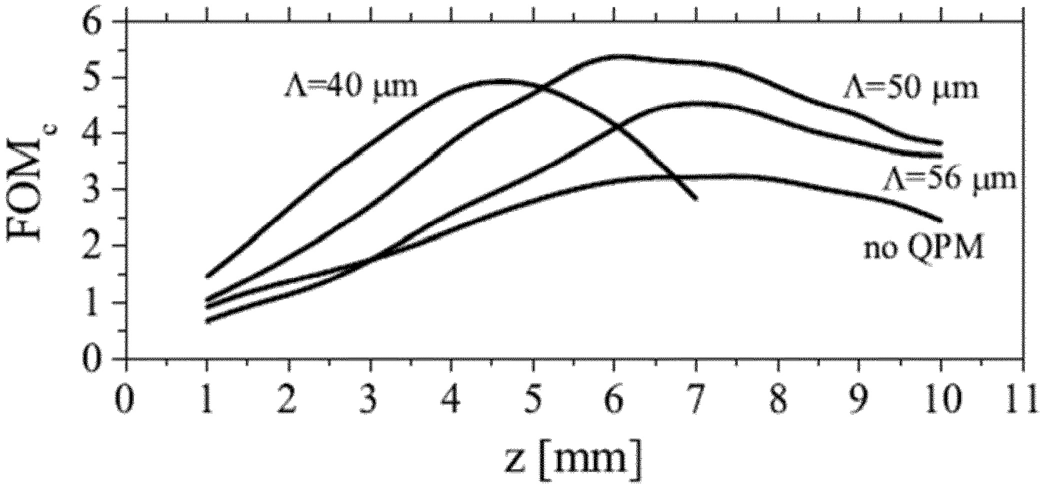

Fig. 11

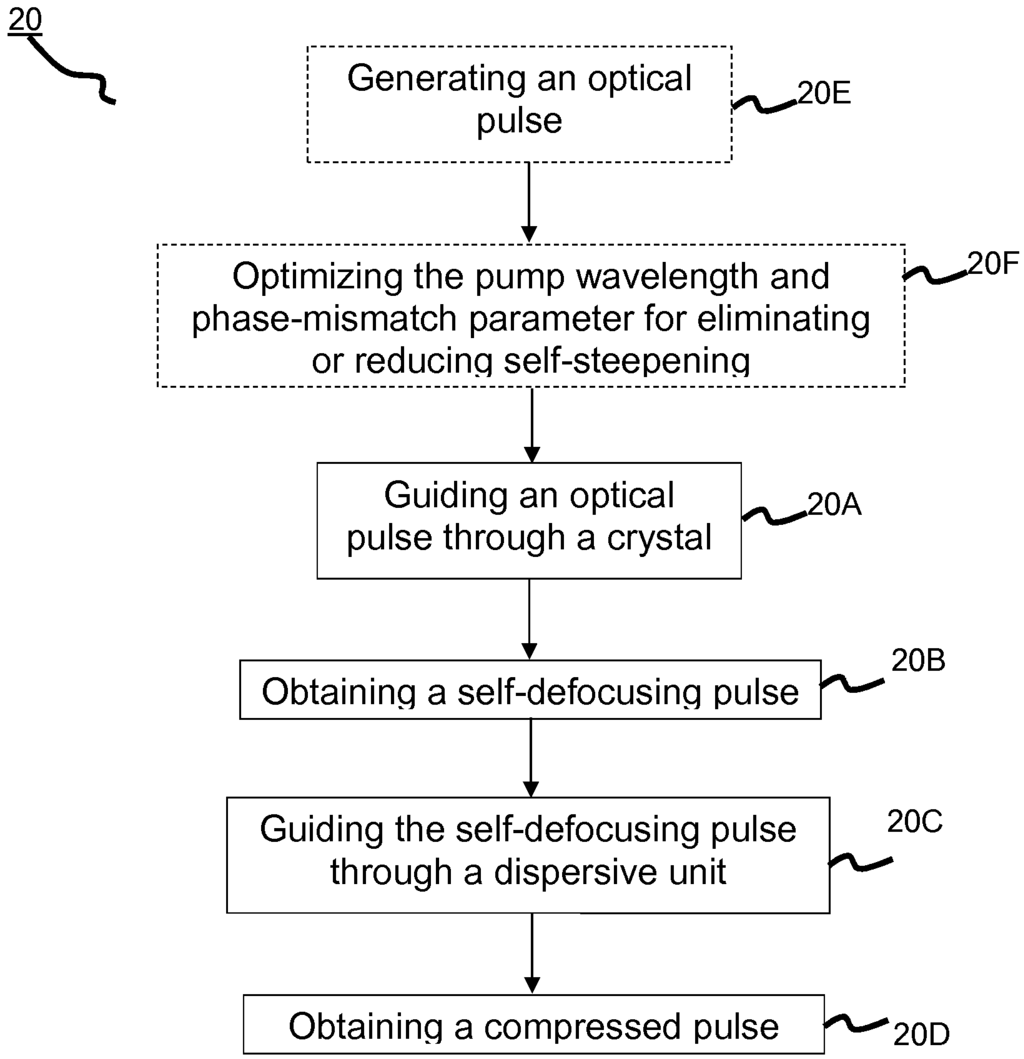
20
Generating an optical pulse
20E
Optimizing the pump wavelength and phase-mismatch parameter for eliminating or reducing self-steepening
20F
Guiding an optical pulse through a crystal
20A
Obtaining a self-defocusing pulse
20B
Guiding the self-defocusing pulse through a dispersive unit
20C
Obtaining a compressed pulse
20D

Fig. 12

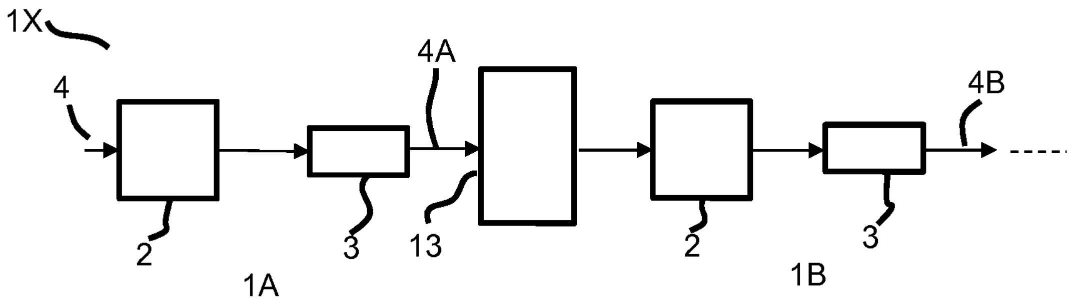

Fig. 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/059156

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01S3/00 G02F1/35 G02F1/37
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01S G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	XIANG LIU ET AL: "High-energy pulse compression by use of negative phase shifts produced by the cascade k^(2):k^(2) nonlinearity", OPTICS LETTERS, vol. 24, no. 23, 1 December 1999 (1999-12-01), page 1777, XP055145278, ISSN: 0146-9592, DOI: 10.1364/OL.24.001777	1,2, 5-12, 14-16
Y	page 1777, left-hand column, paragraph 1 - page 1779, right-hand column, paragraph 4; figures 1-3	3,4,13

	-/--	

[X] Further documents are listed in the continuation of Box C.

[ ] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
3 September 2015	15/09/2015

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Laenen, Robert

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	XIE ET AL: "Multi-stage pulse compression by use of cascaded quadratic nonlinearity", OPTICS COMMUNICATIONS, NORTH-HOLLAND PUBLISHING CO. AMSTERDAM, NL, vol. 273, no. 1, 12 March 2007 (2007-03-12), pages 207-213, XP005923362, ISSN: 0030-4018, DOI: 10.1016/J.OPTCOM.2006.12.011	1,2, 5-12, 14-16
Y	page 207, left-hand column, paragraph 1 - page 212, right-hand column, paragraph 1; figures 1-6 -----	3,4,13
Y	S. ASHIHARA ET AL: "Spectrum broadening in femtosecond pulses by cascaded second-order nonlinearities and the influence of temporal walk-off", LEOS 2000. 2000 IEEE ANNUAL MEETING CONFERENCE PROCEEDINGS. 13TH ANNUAL MEETING. IEEE LASERS AND ELECTRO-OPTICS SOCIETY 2000 ANNUAL MEETING (CAT. NO.00CH37080), vol. 2, 1 January 2000 (2000-01-01), pages 517-518, XP055145150, DOI: 10.1109/LEOS.2000.893943 ISBN: 978-0-78-035947-5 page 517, paragraph 1 - page 518, paragraph 2; figures 1-3 -----	3,4,13
X,P	BACHE MORTEN ET AL: "High-energy pulse compressor using self-defocusing spectral broadening in anomalously dispersive media", 2014 CONFERENCE ON LASERS AND ELECTRO-OPTICS (CLEO) - LASER SCIENCE TO PHOTONIC APPLICATIONS, THE OPTICAL SOCIETY, 8 June 2014 (2014-06-08), pages 1-2, XP032708327, [retrieved on 2014-12-16] pages 1-2; figures 1,2 -----	8,16

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