



## **Wavelength-tunable laser based on nonlinear dispersive-wave generation in a tapered optical waveguide.**

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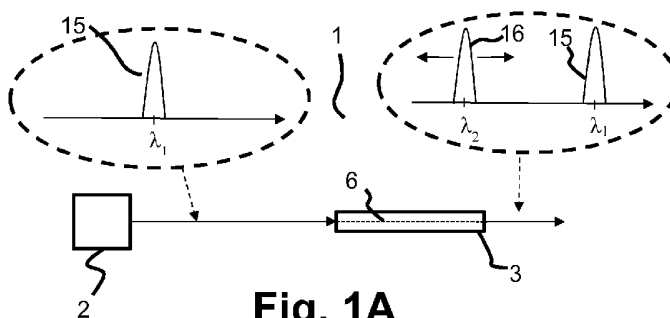
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**Fig. 1A**

(57) **Abstract:** The present invention relates to a method and a wavelength tunable laser comprising a first laser source configured to emit a first optical pulse having a pump wavelength, the first optical pulse being emitted in a first longitudinal direction. Furthermore, the wavelength tunable laser comprises a waveguide extending in the first longitudinal direction, the waveguide having longitudinally varying phase matching conditions, the waveguide being configured to generate a second optical pulse with a centre wavelength upon receiving the first optical pulse, wherein the wavelength tunable laser is configured to tune the centre wavelength of the second optical pulse by varying at least one pulse property of the first optical pulse.

## WAVELENGTH-TUNABLE LASER BASED ON NONLINEAR DISPERSIVE-WAVE GENERATION IN A TAPERED OPTICAL WAVEGUIDE

### BACKGROUND

- 5 The invention is within the field of fiber-based ultrafast laser sources. There is currently a demand for laser systems which can deliver a broad range of visible wavelengths – while at the same time being compact, robust and easy to operate – for field use in e.g. the medical sector. Low noise and short output pulses are also characteristics, which add value these laser systems.
- 10 Fiber lasers meet the demands of compactness, robust and easy operation, and possibly ultrashort pulses. The technical challenge is however that fiber lasers emit at well-defined near-infrared wavelengths, and so a wavelength conversion mechanism is needed.
- 15 Currently, this challenge is met by the so-called ‘supercontinuum’ sources in which picosecond (ps) input pulses are spectrally broadened in fibers of about 10 m length by nonlinear processes to form a spectrum spanning the whole visible range, as discussed in EP1902341-A2. If a single wavelength is
- 20 desired, it may be obtained by spectral filtering. The nonlinear processes involved are complicated and chaotic and consequently, noise properties of these sources are generally poor. Further, the temporal structure of the visible output is very complex.
- 25 An alternative technology to ‘supercontinuum’ sources is based on pumping short (few-cm) fiber pieces with femtosecond (fs) pulses. The fibers normally have anomalous dispersion at the pump wavelength, meaning that short wavelengths travel faster than long ones. In this case, the interplay of dispersion and optical nonlinearity leads to a runaway pulse compression
- 30 process. At the point of maximal compression, a dispersive wave (in some literature termed ‘Cherenkov’ radiation) at a wavelength shorter or longer

- than the pump wavelength may be emitted, provided that a certain phase-matching condition is satisfied. The wavelength of the dispersive wave is primarily determined by the dispersion properties of the fiber, i.e. the fiber structure, with a weaker dependence on pulse energy. It can span the whole visible range with current fiber technology. The disadvantage of this is that the wavelength tunability is very limited, e.g. less than 100 nm in the visible range when pumping at 1550 nm (H. Tu et al., Optics Express 21, p. 23188, 2013), for a given fiber with fixed dispersion properties.
- 10 Yet another alternative technology is based on soliton self-frequency shift (SSFS), as discussed in e.g. EP1378034-A2. The disadvantage of this is that a centre wavelength of a soliton cannot be shorter than a pump wavelength of a pump pulse, i.e. a first optical pulse. Furthermore, a second disadvantage compared to the aforementioned Cherenkov radiation
- 15 approach is that the soliton frequency shift requires a longer propagation distance in the fiber, which limits the tunability towards wavelengths where material absorption losses become a limiting factor, e.g. wavelengths larger than 2500 nm in silica-based waveguides.
- 20 Another alternative solution is a fiber-based supercontinuum (SC) source which is robust and stable, and span most of the visible wavelength range, as discussed in EP1902341-A2. The disadvantage of the fiber based SC sources is that they have issues with noise and low coherence, and furthermore, the need of tunable optical filters to generate output pulses with
- 25 narrow spectra makes the fiber-based SC source more inefficient and complicated.

#### **SUMMARY OF THE INVENTION**

- It is therefore an object of the present invention to provide a wavelength tunable laser which is simpler to build, and which improves the coherence of the generated tunable optical pulse and the wavelength range of the tunable
- 30

optical pulse towards the ultra-violet (UV) wavelength range and towards the near-infrared (NIR) wavelength range, as well as providing cleaner and shorter signal output pulses in the temporal domain.

5 Disclosed herein is therefore a wavelength tunable laser comprising a first laser source configured to emit a first optical pulse having a pump wavelength, the first optical pulse being emitted in a first longitudinal direction. Furthermore, the wavelength tunable laser comprises a waveguide extending in the first longitudinal direction, the waveguide having  
10 longitudinally varying phase matching conditions, the waveguide being configured to generate a second optical pulse with a centre wavelength upon receiving the first optical pulse, wherein the wavelength tunable laser is configured to tune the centre wavelength of the second optical pulse by varying at least one pulse property of the first optical pulse.

15 It is an advantage of the wavelength tunable laser that the centre wavelength of the second optical pulse is determined by the combination of the optical properties, i.e. phase matching conditions, of the waveguide at a compression point in the waveguide and the pulse property of the first optical  
20 pulse, i.e. a pump pulse entering the waveguide. Hereby, the wavelength tunable laser is configured to emit a second optical pulse with an improved coherence and an improved wavelength range in the visible and UV wavelength range and/or NIR wavelength range. Furthermore, the Signal-to-noise ratio is improved due to less contribution of high frequency noise  
25 components, such as quantum fluctuations provided to the first optical pulse.

It is a further advantage of the wavelength tunable laser that the tuning of the centre wavelength of the second optical pulse becomes more energy efficient and less complicated, since the tuning of the second optical pulse is  
30 generated by the combination of the waveguide and the varying of the pulse property of the first optical pulse. For a suitable fiber laser design, the pulse

properties may be varied e.g. by changing the current of the amplifier pump diodes, without the need for movement of mechanical parts.

5 A wavelength tunable laser, configured to vary a centre wavelength of a second optical pulse in UV wavelength range, opens up new markets for ultrashort optical pulse laser ( i.e. femto-second laser or a pico-second laser), such as imaging techniques within the medical sector or any other sectors.

10 The waveguide may be a single part waveguide, wherein the waveguide may comprise a single material being either non-doped or doped with a second material.

The waveguide may be a single part waveguide or a single waveguide element. It is thereby understood that the waveguide is not a combination of multiple single part waveguides. The waveguide may be a single crystal or a single photonic crystal fiber extending in the first longitudinal direction. Furthermore, the waveguide having longitudinally varying phase matching conditions may be configured to generate a second optical pulse with a centre wavelength upon receiving the first optical pulse.

20

Application to critical dimension (CD) metrology: Online monitoring of sub-micron features in a production environment is becoming increasingly important, e.g. in the semiconductor industry, and photonics industries. Monitoring systems robust against vibrations will often be necessary, see M. H. Madsen et al., *Optica* 2, p. 301 (2015). A group of common approaches, known as reflectometry, ellipsometry and scatterometry, acquires optical reflection/scattering data at multiple angles and/or wavelengths and solve an inverse problem to obtain the CD's of the fabricated structure. For multiwavelength approaches, an increasing number of wavelengths is  
30 needed as the CD scale is decreased.

The technology of the present laser and method is advantageous for multiwavelength scatterometry and related approaches because of the better brightness and spatial coherence in the present technology than lamps or high-power diodes, and better noise properties than supercontinuum sources, which may be important for accuracy, see H. Song et al., Appl. Opt. 21, p. 4000 (2011), and acquisition time. In addition, a fully fiber-integrated version of the present laser would be highly robust compared to laser systems containing bulk-optics parts (optical parametric amplifiers, systems based on second-harmonic generation). A fast wavelength scan rate, from purely electronic wavelength tuning, may also be an advantage compared to lasers with moving mechanical parts.

Application to one-photon fluorescence microscopy: One-photon fluorescence microscopy is primarily used on exogeneous fluorophores, which are introduced as labels into biological organisms, where they can be attached to specific molecules, e.g. proteins. One is interested in utilizing a large range of wavelengths, so that many different labels can be imaged simultaneously. This technique is heavily used in confocal microscopes, which contain a battery of light sources, or a commercial supercontinuum source equipped with tunable spectral filters.

The technology of the present laser and method is advantageous because it can be fully fiber integrated, like supercontinuum sources, while providing greatly superior noise properties. Depending on the desired spectrum width and suppression of unwanted wavelengths, it might also be possible to do without the tunable spectral filter, which typically eats a few dB of the visible signal.

Application to two-photon fluorescence microscopy on exogeneous fluorophores: The fluorescent labels discussed above may also be excited by intense near-IR light by two-photon absorption. This is an advantage

because near-IR light penetrates deeper into biological samples, and because the process is only efficient at the focal point, so one obtains depth resolution and reduced background. Supercontinuum sources cannot deliver the required near-IR femtosecond pulses. Instead, the main technology is bulk solid-state lasers, such as Ti:sapphire lasers, possibly in combination with optical parametric amplifiers, in particular the Coherent Chameleon lasers, see <https://www.coherent.com/products/?1557/Chameleon-Family>.

The technology of the present laser and method is advantageous because it can potentially provide wavelength-tunable femtosecond pulses with high peak power in the 700-1000 nm range, in a fully fiber-integrated laser system, which will have superior stability and reliability compared to bulk solid-state lasers. Also, a fully fiber-integrated laser with all-electrical tunability (no moving mechanical parts) could tune faster than solid-state lasers such as the Coherent Chameleon.

Application to two-photon fluorescence of endogeneous fluorophores: Endogeneous fluorophores are fluorescent molecules naturally occurring in biological tissue. Imaging based on endogeneous fluorophores avoids the cumbersome process of introducing exogeneous labels. The one-photon absorptions are typically in the 200-500 nm range, see G. A. Wagnières et al., *Photochemistry and photobiology* 68, p. 603 (1998), so two-photon excitation can be done at visible/near IR wavelengths, e.g. the 600-700 nm range in a recent demonstration, see D. Li et al., *Opt. Lett.* 34, p. 202 (2009). The advantages of two-photon excitation are similar to those discussed above, with the addition that one may avoid damage to tissue and optical components that might arise by using deep-UV light.

The technology of the present laser and method is advantageous because it could deliver smooth femtosecond pulses with high peak power across the visible spectrum, and low noise. Furthermore it could be fully fiber-integrated,



and thereby much more robust and easy to use than optical parametric oscillators/amplifiers pumped solid-state lasers such as Ti:sapphire lasers, see D. Li et al., Opt. Lett. 34, p. 202 (2009). Fiber end delivery may also be an advantage for deeper penetration into biological tissue, where visible light is strongly scattered.

Application to photothermal microscopy: Photothermal microscopy detects the distortion of a probe beam due to temperature changes induced by absorption of a pump beam. In biological tissue, the absorber can be exogeneous, such as gold nanoparticles, or endogeneous organic molecules, the latter having the advantage of not being toxic. Pump wavelengths across the visible are needed for various absorbers. Ps or even shorter pulses are of interest for time-resolved spectroscopy, as some thermal relaxation processes occur on a picosecond time scale. Noise is a serious issue, requiring advanced mitigation schemes such as balanced detection in implementations with commercial filtered supercontinuum sources, see J. He et al., Opt. Express 23, p. 9762 (2015).

The technology of the present laser and method is advantageous because it provides wavelength-tunable sub-picosecond pulses in the visible range with low noise in a laser system which can be highly robust and easy to operate in an all-fiber implementation. Fiber end delivery may also be an advantage for deeper penetration into biological tissue, where visible light is strongly scattered.

General advantages relating to power budget: A general advantage, which would apply for all applications, is that the pump power requirements of the proposed technology will be lower than that of the supercontinuum sources which are presently the only all-fiber integrated competitors for the present technology. These sources typically convert 10-20% of the input pump power into a short-wavelength band of 300-400 nm width. The conversion

efficiencies of the present technology are typically in the range 1-10% in simulations, for conversion into a much narrower band of typically 10-30 nm. It follows that the requirement of the present technology on average pump power to obtain a given average power spectral density in the visible is typically a few times lower than for the supercontinuum sources, albeit with some variations between specific implementations.

General advantages relating to lifetime: It is generally known that commercial supercontinuum sources have lifetime limitations, which are not severe for scientific research, but may well be for industrial/clinical applications, including the above. 'Photodarkening' of silica fibers under supercontinuum radiation has been discussed in terms of unwanted absorptions around 630 nm from the so-called non-bridging oxygen-hole-center defect, induced by multiphoton absorptions of the pump light, and possibly photo-induced OH absorptions at near-infrared wavelengths if the fiber contains hydrogen, see J. M. Stone et al., *Opt. Lett.* 15 p. 2717 (2013).

The technology of the present laser and method may be expected to have a lifetime advantage over picosecond-pumped supercontinuum sources, in part because the pump power of the present technology is lower (see above), but mostly because the visible radiation is generated in fiber pieces as short as 1-2 cm, compared to ~10 m for typical supercontinuum sources. Therefore, much higher induced losses (up to the dB/cm level) are tolerable before a degradation of the spectrum will be noticeable. In addition, the actual power transfer takes place over even shorter distances, around 1 mm, which may in fact be a central requirement for the method to work. Therefore, even a loss of 1 dB/cm at 630 nm would only seriously affect the output spectrum around this wavelength, and near-IR absorption from OH would have very little effect on the visible spectrum, especially for Yb-pumped systems. This is in contrast to supercontinuum sources, where visible light is continually shifted downwards in frequency by interaction with near-IR solitons, see A. V.

Gorbach and D. V. Skryabin, Nature Photonics 1, p. 653 (2007), so that absorptions at a given visible wavelength will also affect the spectrum at shorter wavelengths, and near-IR absorptions may also influence the visible spectrum.

5

In one or more embodiments, the waveguide may either be a tapered waveguide, a photonic crystal fiber infiltrated with a fluid having a high temperature sensitivity of its refractive index combined with a longitudinal temperature variation along the first longitudinal direction of the waveguide,  
10 or a waveguide comprising a photosensitive material, such as Germanium doped silica glass, having an inscribed variation of the refractive index along the first longitudinal direction of the waveguide. The inscribed variation of the refractive index may be obtained via the photosensitivity, e.g. by illumination with a light source or a laser source.

15

In one or more embodiments, the waveguide may be a tapered waveguide having at least a down-tapered part and/or at least an up-tapered part, and alternatively, at least a straight part. The down-tapered part and the up-tapered part may be denoted as an extracting part which has an extracting  
20 length along the first longitudinal direction of the waveguide.

The down-tapered may have an input side and an output side, wherein a diagonal or a diameter of the down-tapered part decreases along a first longitudinal direction from the input side to the output side.

25

The up-tapered part may have an input side and an output side, wherein a diagonal or a diameter of the up-tapered part increases along the first longitudinal direction from the input side to the output side.

Along the first longitudinal direction the up-tapered part and down-tapered part have an extracting length which may be the same or different from each other.

- 5 In one or more embodiments, the extracting length determines a tuning gradient, i.e. a ratio between a change in centre wavelength over a change in at least one pulse property of the first optical pulse, i.e. an optical pump pulse. The extracting length may be between 5 mm to 50 mm, 10 mm to 30 mm and 15 mm to 2 mm.

10

The extracting part may have a first diameter or a first diagonal, i.e. a first transverse dimension, and a second diameter or a second diagonal, i.e. a second transverse dimension, wherein a taper ratio between the first transverse dimension and the second transverse dimension may be between  
15 0.1 to 0.9, between 0.2 to 0.7, between 0.3 to 0.6 or between 0.3 to 0.9.

The straight part may have an input and an output side, and wherein a diagonal or a diameter of the straight part may be constant along the first longitudinal direction from the input side to the output side. The transverse  
20 dimension of the straight part may be equal to the first transverse dimension of the extracting part. The taper ratio of the up-tapered part and the down-tapered part may be the same or different from each other.

In one or more embodiments, the waveguide may be a tapered waveguide  
25 comprising at least an extracting tapered part, wherein the extracting tapered part may be configured to tune the centre wavelength of the second optical pulse, and wherein the extracting tapered part may be a down-tapered part or an up-tapered part.

30 In one or more embodiments, the extracting tapered part has a first transverse dimension and a second transverse dimension, wherein a taper

ratio between the first transverse dimension and the second transverse dimension may be between 0.1 and 0.9, 0.2 and 0.7, 0.3 and 0.6 or 0.3 and 0.9. By reducing the taper ratio the wavelength range of the second optical pulse increases.

5

In one or more embodiments, the extracting tapered part has an extracting length along a first longitudinal direction determining a tuning gradient, i.e. a ratio between a change in centre wavelength over a change in at least one pulse property of the first optical pulse. Thus, by increasing the extracting  
10 length a resolution of the tuning of the centre wavelength improves, i.e. the variance of the centre wavelength by varying at least one pulse property is reduced.

The tapered waveguide may be a tapered optical fiber.

15

In one or more embodiments the second optical pulse, i.e. Cherenkov radiation (CR), may be generated in an up-tapering part of the waveguide. The main limitation on generating isolated CR spectra may be the emission of secondary CR components at position  $z$  larger than compression point  
20 ( $z_c$ ). The pump pulse attains its largest bandwidth at  $z_c$ , but goes through a series of successive recompressions, where the bandwidth expands again.

In the up-tapering waveguide, the CR phase-matched wavelength moves closer to the pump wavelength with increasing  $z$ , and so efficient secondary  
25 CR emission may occur, even if the bandwidth does not expand to the same level as at  $z_c$ . The pulse recompression leads to emission of CR at the phase-matched wavelength. By making the up-tapered section longer the pump recompressions gradually becomes weaker and the secondary CR emissions becomes weaker, and thereby, the pulse quality of the CR  
30 improves.

In one or more embodiments, the compression point  $z_c$  may be shifted further into the up-tapering part of a fiber, thus moving the CR wavelength closer to the pump. By doing this, it turns out that the problem of secondary CR emission may be magnified, until a region shortly before the end of the taper, where the secondary recompressions cease to be an issue. The performance can be improved by using a nonlinear taper profile, where the taper ratio may be a decreasing function of a pitch in the up-tapering section. Furthermore, the problem is diminished as the long wavelength end of the tapered wavelength range moves away from the pump.

10

In one or more embodiments, the up-tapered part may be removed. The use of a down-tapering fiber for CR generation introduces a new issue, namely that of pump-CR re-collisions, which induce spectral changes and broadening to the CR pulse due to cross-phase modulation (XPM) effects. When CR is generated, it will in general have a lower group velocity than the pump wave, and will therefore emerge in the tail of the pump pulse, i.e. the first optical pulse. However, as the fiber down-tapers, the group velocity of a given visible wavelength relative to the pump wavelength increases. If the CR is generated early in the down-taper, the CR pulse may eventually move faster than the pump pulse and catch up with it. When passing through the pump pulse, the CR pulse experiences spectral shifts and broadening through XPM. It may be possible that a part of the CR pulse is trapped behind the pump pulse and blue-shifted.

20

This re-collision effect can be mitigated by employing a nonlinear taper profile to the down-tapered part, in which the tapering rate increases as a function of the longitudinally length of the waveguide or the length of the waveguide in the first longitudinally direction. Re-collision between pump and CR may thus be eliminated, or made to occur at a faster relative speed, which leads to a less pronounced effect of XPM, and a reduced trapping effect. In this way, the blue-shift and broadening of the CR pulse may be eliminated or reduced.

30

In one or more embodiments, the nonlinear taper profile may be provided to the waveguide either by increasing or decreasing the tapering rate as a function of the longitudinally length of the waveguide or the length of the waveguide in the first longitudinally direction.

In one or more embodiments, the nonlinear taper profile to the up-tapered part may be generated by decreasing the tapering rate as a function of the longitudinally length of the waveguide or the length of the waveguide in the first longitudinally direction.

In an up-tapered profile the wavelength of the CR wavelength, i.e. the second optical pulse, increases as a function of the longitudinally length of the waveguide or the length of the waveguide in the first longitudinally direction.

In a down-tapered profile the wavelength of the CR wavelength, i.e. the second optical pulse, decreases as a function of the longitudinally length of the waveguide or the length of the waveguide in the first longitudinally direction.

In one or more embodiments, the taper profile may be linear. A linear taper profile may be generated by keeping the tapering rate constant as a function of the longitudinally length of the waveguide or the length of the waveguide in the first longitudinally direction.

In one or more embodiments, by use of a short tapered waveguide, i.e. the length of tapered part may be between 5 mm and 10 mm, 2.5 mm and 10 mm or 5 mm and 20 mm, CR may be generated close to the waveguide end facet. In silica glass, as well as in most other optical materials, the magnitude of material dispersion increases with decreasing wavelength in the visible range. When generating CR in a down-tapering fiber, the shortest

wavelengths, having the strongest dispersion, are emitted closest to the end facet, and the magnitude of the dispersion seen by the long wavelengths generated early in the taper decreases as a pitch of the waveguide is lowered. This mitigates the difference in dispersion between short and long  
5 visible wavelengths, and in general leads to the emission of very short pulses.

On the other hand, when generating CR in an up-tapering fiber, the situation is reversed: The short wavelengths are now generated far from the end facet,  
10 and are strongly broadened by linear dispersion. The short-wavelength pulses are now strongly broadened, and there may be an order-of-magnitude difference between the FWHM durations of the longest and shortest pulses. Therefore, if short temporal CR pulses are desired, CR generation in a down-taper is strongly preferred.

15 In one or more embodiments, the waveguide having the longitudinally varying phase matching conditions may be a photonic crystal fiber infiltrated with a fluid having a high temperature sensitivity of its refractive index, i.e. a second material, combined with a longitudinal temperature variation along the first  
20 longitudinal direction of the waveguide. The temperature sensitive fluid material may be distributed in the capillaries of the photonic crystal fiber, in such a way, that the longitudinally varying phase matching condition is generated when applying a temperature variation along the first longitudinal direction. The temperature variation may be applied along the waveguide in  
25 the first longitudinal direction by multiple temperature processors (e.g. a heater, cooler or a heater-cooler system), or a wire configured to generate a temperature variation along the wire and on to the waveguide in the first longitudinal direction when a current is applied to the wire. The temperature variation may also be applied by injecting light from a secondary pump laser  
30 at a wavelength where the fluid absorbs strongly. The waveguide may be



designed so that there is a strong coupling from the waveguide core to the fluid-infiltrated regions at said wavelength.

In one or more embodiments, the waveguide may comprise a photosensitive material, such as Germanium doped silica glass, having an inscribed  
5 variation of the refractive index along the first longitudinal direction of the waveguide. Said variation may be permanently inscribed by utilizing the photosensitivity, e.g. by illumination with UV light. The waveguide may be designed so that the inscribed refractive-index variation along the first  
10 longitudinal direction generates varying phase matching conditions along the first longitudinal direction in the waveguide, as desired for the tunable light source.

The wavelength tunable laser is configured to tune a centre wavelength of  
15 the second optical pulse by varying at least one pulse property of the first optical pulse.

In one or more embodiments, the at least one pulse property may be a peak power, pulse width, pulse chirp or state of polarization of the first optical  
20 pulse. The pulse properties may be combined to further enhance the tunability of the second optical pulse if one of the pulse properties is not sufficient to utilize the dispersion profile of the waveguide for tuning the centre wavelength of the second optical pulse, or if the preferred design of the pump laser naturally leads to simultaneous variations of several  
25 parameters.

In one or more embodiments, the pulse property may be other than the wavelength of the pump pulse, i.e. the first optical pulse. It is easier to vary the peak power, pulse width, pulse chirp or state of polarization of the first  
30 optical pulse, in-order to tune the centre wavelength of the second optical pulse.

A first laser source configured to varying at least one pulse property continuously combined with the waveguide provides a continuous tuning of the centre wavelength of the second optical pulse. The first laser source may  
5 be an Ytterbium based fiber laser, an Erbium-based fiber laser, an ultrashort pulse laser, a femto-second laser, or a pico-second laser.

In one or more embodiments, the waveguide comprises a compression point having a phase matching condition, the compression point positioned along  
10 the first longitudinal direction, wherein the centre wavelength of the second optical pulse is determined by the phase matching condition at the compression point, and wherein tuning the centre wavelength of the second optical pulse by shifting the compression point along the first longitudinal direction is done by varying at least one pulse property.

15 In one or more embodiments, the waveguide comprises a phase matching condition at a compression point, wherein the compression point is positioned along the first longitudinal direction. The centre wavelength of the second optical pulse is determined by the phase matching condition at the  
20 compression point. Tuning the centre wavelength of the second optical pulse by shifting the compression point along the first longitudinal direction is done by varying at least one pulse property.

A compression waveguide may be configured to guide the first optical pulse  
25 into the waveguide, and wherein a compression point in the waveguide is provided and determined by the optical properties of the compression waveguide and at least one pulse property. The compression waveguide may be an optical fiber or a crystal having positive/negative nonlinear dispersion and positive/negative Group-Velocity-Dispersion.

30

The compression waveguide may be built into an extracting part of a tapered waveguide, or the compression waveguide may be built into the waveguide having longitudinally varying phase matching conditions.

- 5 The compression point may be a point of maximal compression of the first optical pulse.

In one or more embodiments the compression point may be a point within the waveguide having longitudinally varying phase matching conditions of  
 10 maximal peak power of the first optical pulse. The point may be a distance from an input side of a waveguide to a point, along the longitudinal direction of the waveguide, where the peak power of the second optical pulse is maximised.

- 15 The point of maximal peak power of the first optical pulse, i.e. the compression point, may be determined knowing a dispersion profile and a nonlinear coefficient profile both as a function of position  $z$  along the longitudinal direction of the waveguide.

- 20 A 'soliton number'  $N$  may be defined by the relation

$$N = \frac{P_0 \int_0^{z_c} dz \gamma(z)^{-2.0}}{0.56} \quad (1)$$

$P_0$  is the peak power of the pump pulse (i.e. the first optical pulse) at the entrance of the waveguide,  $z$  is the position along the longitudinally direction  
 25 of a waveguide,  $z_c$  is the compression point along the longitudinal direction of a waveguide,  $\gamma$  is the nonlinear coefficient and the constants 2.0 and 0.56 are determined from a numerical fit to numerical simulations (see discussion of equation 2 below).

The position of the compression point  $z_c$  in the waveguide may be approximately predicted from knowledge of the peak power  $P_0$  and Gaussian RMS width ( $t_0$ ) of the pump pulse at the entrance of the waveguide by equation 2;

5

$$f^2 \frac{t_0^2}{2P_0} = - \int_0^{z_c} dz' \int_0^{z'} dz'' \beta_2(z') \gamma(z''), \quad \beta_2 = \frac{d^2 \beta}{d\omega^2}, \quad (2)$$

$\beta_2$  is the nonlinear dispersion constant and  $f = 0.56 + \frac{2.0}{N}$  is a function obtained by fitting to results of numerical calculations for several designs of photonic crystal fibers. Our experience shows that equation 2 in almost all cases predicts  $z_c$  to an accuracy of a few per cent.

10

In one or more embodiments, the dispersion profile  $\beta_2$  may be of higher order than 2, leading to a different definition of  $f^2 \frac{t_0^2}{2P_0}$ , see equation 2.

15 In one or more embodiments, the compression point of the first optical pulse may be predicted by using equation 2 in combination with equation 1, as being the point of maximal peak power of the first optical pulse.

20 In one or more embodiments the soliton number (N) may be between 0 and 10, 5 and 10, 5 and 20, or 5 and 30, when the compression point is between 1 cm and 4 cm.

25 In one or more embodiments the soliton number (N) may increase when reducing the distance to the compression point until significant noise appears in the output of the waveguide. The relation between noise and soliton number is somewhat dependent on pulse and waveguide properties, but in general the noise level increases with increasing N.

In one or more embodiments, multiple peak power maxima of the first optical pulse may occur along the longitudinally varying phase matching conditions of a waveguide, and thereby, the waveguide may comprise multiple compression points.

5

In one or more embodiments, a waveguide may comprise a single compression point.

10 In one or more embodiments, the wavelength tunable laser is configured to tune the centre wavelength of the second optical pulse within a wavelength range comprising wavelengths being shorter and/or longer than the pump wavelength.

15 In one or more embodiments, the wavelength range of the second optical pulse is tuned by varying the pump wavelength of the first optical pulse, wherein the wavelength range of the second optical pulse is between 300 nm to 600 nm, 300 nm to 450 nm, 400 nm to 800 nm, 400 nm to 1200 nm, or 1200 nm to 7000 nm. By increasing the pump wavelength of the first optical pulse a minimum wavelength of the wavelength range may decrease to  
20 shorter wavelength. However, a coupling efficiency between the first optical pulse and the second optical pulse may be reduced resulting in lower pulse energy of the second optical pulse.

25 In one or more embodiments, the waveguide may be an optical fiber, a crystal, a segmented Photonic crystal fiber, or any other waveguide having an anomalous dispersion at least at the pump wavelength of the first optical pulse.

30 In one or more embodiments the centre wavelength of the second optical pulse may have an anomalous dispersion, thereby the anomalous dispersion regime may be divided, by a normal dispersion regime, into a first anomalous

dispersion regime with the first optical pulse and a second anomalous dispersion regime with the second optical pulse.

In one or more embodiments, the first laser source is an ultrashort optical pulse laser, such as a femto-second laser or a pico-second laser.

Disclosed herein in another aspect of the invention, is a method for tuning a centre wavelength of a second optical pulse, wherein the method comprising the steps of:

- 10       – providing a first laser source emitting a first optical pulse having a pump wavelength, the first optical pulse being emitted in a first longitudinal direction;
- generating a second optical pulse having a centre wavelength by directing the first optical pulse through a waveguide extending in the
- 15       first longitudinal direction, the waveguide having longitudinally varying phase matching conditions, and
- tuning the centre wavelength of the second optical pulse by varying at least one pulse property of the first optical pulse.

20       In one or more embodiments the at least one pulse property is a peak power, pulse width, pulse chirp or state of polarization of the first optical pulse.

In one or more embodiments, the centre wavelength of the second optical pulse is tuned within a wavelength range comprising wavelengths being

25       shorter and/or longer than the pump wavelength.

A further aspect of invention disclosed herein is a waveguide comprising longitudinal varying phase matching conditions configured to generate a second optical pulse with a centre wavelength upon receiving a first optical

30       pulse from a first laser source, wherein the waveguide is configured to tune

the centre wavelength of the second optical pulse by varying at least one pulse property of the first optical pulse.

In one or more embodiments, the method may include determining the  
5 compression point as disclosed previously.

In one or more embodiments, the phase matching may be referred as the Cherenkov phase matching. The Cherenkov phase matching criterion on a propagation constant, for a pump having a center frequency of  $\omega_0$ , may be  
10 formulated as:

$$\beta(\omega) = \beta_0 + (\omega - \omega_0)\beta_1. \quad (3)$$

The meaning may be that the second optical pulse (i.e. the Cherenkov radiation) will be emitted at frequency  $\omega$  fulfilling that the propagation constant is zero.

15

The term phase-matching is defined differently in different connections across the field of optics. For instance within harmonic generation, it is possible to convert two pump photons into one signal photon, in a second-order nonlinear material, with twice frequency (from energy conservation).

20 The conservation leads to a phase-matching requirement on the propagation constants:

$$\beta(2\omega_0) = 2\beta(\omega_0) = 2\beta_0, \quad (4)$$

where  $\omega_0$  is the pump frequency. So second-order harmonic signal generated  
25 at a frequency of  $2\omega_0$  will only be generated when the criterion in equation (4) holds.

One can note a qualitative difference between the Cherenkov radiation phase matching criterion, defined in equation 3, and the second-order harmonic

phase matching condition, defined in equation 4, in that the Cherenkov radiation signal frequency  $\omega$  is only related to  $\omega_0$  via the phase matching condition (3), whereas for the second-order harmonic signal frequency is always twice the pump frequency, and the phase matching condition (4) is an  
 5 additional requirement.

The practical consequence for second-harmonic generation may be that a given waveguide layout will typically only yield phase matching and thereby frequency conversion for one pump frequency, whereas for Cherenkov  
 10 radiation generation, a range of pump wavelengths (e.g. an ultrafast pump pulse) will yield a range of signal wavelengths. Thereby, the advantage of the waveguide, fulfilling the criterion of the Cherenkov radiation, is that the generated tuneable wavelength range of the second optical pulse becomes  
 broader.

15

The above concepts of harmonic generation can be generalized to higher-order nonlinearities, e.g. in a third-order nonlinear material, such as silica glass. E.g. the third-order nonlinear phase matching criterion may be defined  
 as;

20

$$\beta(3\omega_0) = 3\beta_0. \quad (5)$$

In third-order nonlinear materials one can have the nonlinear process of four-wave mixing (FWM), where two pump photons are annihilated to generate new photons at different frequencies (typically called signal and idler  
 25 photons). The pump photons may have different wavelengths, but for simplicity the case of one pump wavelength is considered. The Four-wave mixing phase matching criterion is

$$2\beta_0 = \beta(\omega_s) + \beta(\omega_i), \quad (6)$$



where  $\omega_s$  and  $\omega_i$  are signal and idler frequencies, respectively. Energy conservation further requires that  $\omega_s + \omega_i = 2 \omega_0$ . It is clear that the Four-wave mixing phase matching criterion is again of a different nature than the Cherenkov radiation phase matching criterion, see equation 3.

5

In one or more embodiments, a wavelength tuneable laser comprising a first laser source configured to emit a first optical pulse having a pump wavelength. The first optical pulse being emitted in a first longitudinal direction and the first optical pulse comprising at least one variable pulse property, and a single waveguide element extending in the first longitudinal direction. The single waveguide element having longitudinally varying Cherenkov radiation phase matching conditions, the single waveguide element being configured to generate a second optical pulse with a centre wavelength upon receiving the first optical pulse. The first laser source may be configured to vary the at least one variable pulse property and wherein the single waveguide element may be adapted for tuning the centre wavelength of the second optical pulse when the at least one variable pulse property may be varied.

20 In a further embodiment, the single waveguide element comprises a compression point having the Cherenkov radiation phase matching condition. The compression point may be positioned along the first longitudinal direction, wherein the centre wavelength of the second optical pulse may be determined by the Cherenkov radiation phase matching condition at the  
25 compression point

In another embodiment the compression point may be a point of maximal peak power of the second optical pulse.

In one or more embodiments, the centre wavelength of the second optical pulse may be tunable within a wavelength range comprising wavelengths being shorter and/or longer than the pump wavelength.

- 5 In one or more embodiments, the single waveguide element may either be a tapered waveguide, a photonic crystal fiber infiltrated with a fluid having a high temperature sensitivity of its refractive index combined with a longitudinal temperature variation along the first longitudinal direction of the waveguide, or a single waveguide element comprising a photosensitive
- 10 material, such as Germanium doped silica glass, having an inscribed refractive-index variation along the first longitudinal direction of the waveguide.

In one or more embodiments, the single waveguide element may be a

15 tapered waveguide comprising at least an extracting tapered part, and wherein the extracting tapered part may be a down-tapered part or an up-tapered part.

In one or more embodiments, the single waveguide element may be an

20 optical fiber, a crystal, a segmented Photonic crystal fiber, or any other waveguide having an anomalous dispersion at least at the pump wavelength of the first optical pulse.

Disclosed herein in another aspect of the invention, may be a method for

25 tuning a centre wavelength of a second optical pulse, wherein the method comprising the steps of:

- providing a first laser source emitting a first optical pulse having a pump wavelength, the first optical pulse being emitted in a first longitudinal direction;
- 30 - generating a second optical pulse having a centre wavelength by directing the first optical pulse through a single waveguide element

extending in the first longitudinal direction, the single waveguide element having longitudinally varying Cherenkov radiation phase matching conditions, and

- tuning the centre wavelength of the second optical pulse by varying at least one pulse property of the first optical pulse.

In one or more embodiments, the single waveguide element comprises a compression point having the Cherenkov radiation phase matching condition, the compression point being positioned along the first longitudinal direction, wherein the centre wavelength of the second optical pulse may be determined by the Cherenkov radiation phase matching condition at the compression point.

In one or more embodiments, the compression point may be a point of maximal peak power of the second optical pulse.

In one or more embodiments, the single waveguide element may either be:

- a tapered waveguide;
- a photonic crystal fiber infiltrated with a fluid having a high temperature sensitivity of its refractive index combined with a longitudinal temperature variation along the first longitudinal direction of the waveguide, or
- a single waveguide element comprising a photosensitive material, such as Germanium doped silica glass, having an inscribed refractive-index variation along the first longitudinal direction of the waveguide.

In one or more embodiments, the single waveguide element may be a tapered waveguide comprising at least an extracting tapered part, and wherein the extracting tapered part may be a down-tapered part or an up-tapered part.

In one or more embodiments, the extracting tapered part has a first transverse dimension and a second transverse dimension, wherein a taper ratio between the first transverse dimension and the second transverse dimension may be between 0.1 and 0.9, between 0.2 and 0.7, between 0.3 and 0.6, or between 0.3 and 0.9.

In one or more embodiments, the extracting tapered part has an extracting length along a first longitudinal direction determining a tuning gradient, i.e. a ratio between a change in centre wavelength over a change in at least one pulse property of the first optical pulse.

In one or more embodiments, the single waveguide element may be an optical fiber, a crystal, a segmented Photonic crystal fiber, or any other waveguide having an anomalous dispersion at least at the pump wavelength of the first optical pulse.

In one or more embodiments, the first laser source may be an ultrashort optical pulse laser, such as a femto-second laser or a pico-second laser.

According to an aspect, disclosed is a waveguide comprising longitudinal varying Cherenkov radiation phase matching conditions configured to generate a second optical pulse with a centre wavelength upon receiving a first optical pulse from a first laser source, wherein the waveguide may be configured to tune the centre wavelength of the second optical pulse by varying at least one pulse property of the first optical pulse.

#### **BRIEF DESCRIPTION OF THE FIGURES**

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

Fig. 1A – 1B show a wavelength tunable laser emitting a first optical pulse into a waveguide generating a second optical pulse having a centre wavelength,

- 5 Fig. 2A – 2C shows different configurations of a waveguide having longitudinal varying phase matching conditions,

Fig. 3 shows a waveguide receiving a first optical pulse at a pump wavelength, wherein varying either a peak power, pulse width, or pulse chirp  
10 of the first optical pulse provides a shift of the compression point in the waveguide,

Fig. 4A – 4D shows numerical simulations of a second optical pulse being tuned in up-tapered part or down-tapered part by varying the pulse width of  
15 the first optical pulse or by varying the peak power of the first optical pulse,

Fig. 5 shows an experimental result of a second optical pulse being tuned in the down-tapered part by varying the pulse width or by varying the peak  
20 power of the first optical pulse,

Fig. 6 shows a diagram of a method for tuning a centre wavelength of a second optical pulse,

Fig. 7 shows a spectrum of the second optical pulse generated in a linear-  
25 and a nonlinear down-tapering fiber,

Fig. 8A - 8B show a temporal spectrum, and corresponding spectrum as a function of wavelength of a nonlinear down-tapering fiber,

30 Fig. 9A – 9B show spectra of a linear taper with down- and up-tapering sections of 1 cm each and a 1mm tail at the end,

Figs. 10A - 10C show profile, spectra and noise versus output of CR power.

#### DETAILED DESCRIPTION

Figs. 1A and 1B show a wavelength tunable laser 1 being configured to tune  
5 a centre wavelength  $\lambda_2$  of a second optical pulse 16. Fig. 1A shows a  
wavelength tunable laser 1 comprising a first laser source 2 configured to  
emit a first optical pulse 15, with a pump wavelength  $\lambda_1$ , into a waveguide 3 in  
a first longitudinal direction 6. The waveguide 3 comprises a longitudinally  
10 varying phase matching condition extending in the first longitudinal direction  
6. The combination of receiving the first optical pulse 15 and the  
longitudinally varying phase matching conditions in the waveguide 3  
generates a second optical pulse 15 at a centre wavelength  $\lambda_2$ . Hereby, the  
combination of varying at least one pulse property of the first optical pulse  
15 and the variation of the phase matching conditions in the first longitudinal  
direction provides that the centre wavelength  $\lambda_2$  of the second optical pulse  
16 is able to be tuned below the pump wavelength  $\lambda_1$ .

Fig. 1B shows a wavelength tunable laser 1 comprising a compression  
waveguide 4 configured to guide the first optical pulse 15 into the waveguide  
20 3 and compress a pulse width of the first optical pulse 15. The compression  
waveguide 4 is configured to generate a compression point 17 in the  
waveguide 3 which is determined by the optical properties of the  
compression waveguide 4 and at least one pulse property. The compression  
waveguide 4 may be an optical fiber or a crystal having positive nonlinear  
25 dispersion and positive Group-Velocity-Dispersion or negative nonlinear  
dispersion and negative Group-Velocity-Dispersion.

Figs. 2A-C show different configurations of a waveguide 3 having longitudinal  
varying phase matching conditions, wherein the waveguide receives a first  
30 optical pulse 15 at a pump wavelength  $\lambda_1$  and generates and emit a second  
optical pulse 16 having a centre wavelength  $\lambda_2$ .

Fig 2A shows a waveguide having a longitudinally varying phase matching conditions, which in this particular example is a photonic crystal fiber having multiple capillaries 5 doped with a temperature sensitivity fluid material 7, i.e. a second material combined with a longitudinal temperature variation ( $T_1$ ,  $T_2$ ,  $T_3$ ) along the first longitudinal direction 6 of the photonic crystal fiber 3. The temperature sensitivity fluid material 7 may be doped and distributed in the capillaries 5 of the photonic crystal fiber 3. The longitudinally varying phase matching condition is generated when applying a temperature variation ( $T_1$ ,  $T_2$ ,  $T_3$ ), along the first longitudinal direction 6 on the waveguide 3, multiple temperature processors (e.g. a heater, cooler or a heater-cooler system), or a wire configured to generate a temperature variation along the wire and on to the waveguide in the first longitudinal direction when a current is applied to the wire. The temperature variation may also be applied by injecting light from a secondary pump laser at a wavelength where the fluid absorbs strongly. The waveguide may be designed so that there is a strong coupling from the waveguide core to the fluid-infiltrated regions at said wavelength.

Fig. 2B shows a waveguide 3 comprising a photosensitive material, such as Germanium doped silica glass, provided with an inscribed variation of a refractive index 9, i.e. variation of phase matching conditions, along the first longitudinal direction 6 in the waveguide 3. The variation of the refractive index 9 may be provided by a so-called photochemical process.

In one or more embodiments, the tapered waveguide may have at least a down-tapered part and/or at least an up-tapered part and possibly at least a straight part. Fig. 2C shows an example of such a tapered waveguide 3 having a down-tapered part 12, an up-tapered part 13, and a straight part 14. The down-tapered part 12 and the up-tapered part 13 may be denoted as an extracting part 11 which has an extracting length 18 along the first longitudinal direction 6 of the waveguide 3. The down-tapered 12 may have

an input 10A and an output side 10B, wherein a diagonal or a diameter of the down-tapered part 12 decreases along a first longitudinal direction 6 from the input side 10A to the output side 10B. The up-tapered part 13 may have an input side 10C and an output side 10D, wherein a diagonal or a diameter of the up-tapered part 13 increases along the first longitudinal direction 6 from the input side 10C to the output side 10D.

In one or more embodiments, the input side (10A, 10C) and output side (10B, 10D) may be switched, so that the down-tapered part 12 may have an input side 10A and an output side 10B, wherein a diagonal or a diameter of the down-tapered part 12 increases along a first longitudinal direction 6 from the input side 10A to the output side 10B. Furthermore, the up-tapered part 13 may have an input side 10C and an output side 10D, wherein a diagonal or a diameter of the up-tapered part 13 decreases along the first longitudinal direction 6 from the input side 10C to the output side 10D.

Along the first longitudinal direction 6, the up-tapered 13 and the down-tapered fiber 12 have an extracting length 18, which may be the same or different from each other. The extracting length 18 determines a tuning gradient, i.e. a ratio between a change in centre wavelength  $\lambda_2$  over a change in at least one pulse property of the first optical pulse  $\lambda_1$ , i.e. an optical pump pulse. The extracting length 18 may be between 5 m to 50 mm, 10 mm to 30 mm, or 15 mm to 2 mm.

The extracting part 11 may have a first diameter or a first diagonal, i.e. a first transverse dimension 19, and a second diameter or a second diagonal, i.e. a second transverse dimension 20, wherein the first transverse dimension 19 is smaller than the second transverse dimension 20. The ratio between the first transverse dimension 19 and the second transverse dimension 20 may be between 0.1 and 0.9, between 0.2 and 0.7, between 0.3 and 0.6 or between 0.3 and 0.9. The straight part may have an input and an output side, wherein



a diagonal or a diameter of the straight part 14 is constant along the first longitudinal direction from the input side to the output side. The transverse dimension of the straight part may be equal to the first transverse dimension 19 of the extracting part 11.

5

In one or more embodiments, the tapered waveguide 3 comprises at least an extracting tapered part 11, wherein the extracting tapered part 11 is configured to tune the centre wavelength  $\lambda_2$  of the second optical pulse 16, and wherein the extracting tapered part 11 is a down-tapered part 12 or an  
10 up-tapered part 13.

The extracting tapered part 11 has an extracting length 18 along a first longitudinal direction 6 determining a tuning gradient, i.e. a ratio between a change in centre wavelength  $\lambda_2$  of the second optical pulse 16 over a change  
15 in at least one pulse property of the first optical pulse 15. Thus, by increasing the extracting length 18, a resolution of the tuning of the centre wavelength  $\lambda_2$  improves, i.e. the variance of the centre wavelength  $\lambda_2$  by varying at least one pulse property is reduced.

20 The tapered waveguide 3 may be a tapered optical fiber or a tapered crystal.

Fig. 3 shows a waveguide receiving a first optical pulse 15 at a pump wavelength  $\lambda_1$ , wherein varying either a peak power ( $P_1 - P_6$ ), pulse width ( $T_{d1} - T_{d6}$ ), or pulse chirp ( $k_{c1} - k_{c6}$ ) of the first optical pulse 15 provides a  
25 shift of the compression point 17 in the waveguide 3. The shift of the compression point 17 results in a tuning of the centre wavelength ( $\lambda_{2A} - \lambda_{2C}$  or  $\lambda'_{2A} - \lambda'_{2C}$ ) of the second optical pulse (16A - 16F). In this particular example, the waveguide 3 is a tapered waveguide, wherein the shift of the compression point 17 in combination with the change in phase matching  
30 conditions along the first longitudinal direction 6 results in a shift or tuning of

the centre wavelength ( $\lambda_{2A} - \lambda_{2C}$  or  $\lambda'_{2A} - \lambda'_{2C}$ ) of the second optical pulse (16A – 16F).

In an example, the compression point 17 propagates along the first  
5 longitudinal direction 6 experiencing an increasing size of a transverse  
dimension 21, such as a diagonal or a diameter of the waveguide 3, resulting  
in a shift of the centre wavelength  $\lambda_2$  towards longer wavelengths. In another  
example, the compression point 17 propagates along the first longitudinal  
direction 6 experiencing a decreasing size of the transverse dimension 21  
10 resulting in a shift of the centre wavelength  $\lambda_2$  towards shorter wavelengths.

The tapered waveguide 3 is further configured to emit a first secondary  
optical pulse 16A generated in the down-tapered part 12 and a second  
secondary optical pulse 16F generated in the up-tapered part 13, wherein a  
15 first centre wavelength  $\lambda_{2C}$  of the first secondary optical pulse 16A is equal to  
a second centre wavelength  $\lambda'_{2C}$  of the second secondary optical pulse 16F.  
Hereby, the tapered waveguide 3 is configured to generate and emit at least  
two second optical pulses 16, wherein the centre wavelength  $\lambda_2$  of both  
second optical pulses 16 are identical.

20

Furthermore, the tapered waveguide 3 may be configured to generate and  
emit at least two second optical pulses 16, wherein the centre wavelength  $\lambda_2$   
of both second optical pulses 16 are not identical. This is provided by having  
an up-tapered part 13 and a down-tapered part 12 wherein the taper ratio  
25 and/or the extracting length 18 are not the same for the two parts 12, 13, or  
by proper selection of input pulse characteristics, so that the first and second  
compression points will have different phase matching conditions in the  
taper.

30 Figs. 4A-D show numerical simulations of a second optical pulse 16 being  
tuned in the up-tapered part 13 or the down-tapered part 12 by varying the

pulse width  $T_d$  of the first optical pulse 15 or by varying the peak power  $E_1$  of the first optical pulse 15. In these particular examples, the waveguide 3 is a tapered photonic crystal fiber.

5 Fig 4a shows the second optical pulse 16 being tuned in an up-tapered part 13 by varying the pulse width  $T_d$  at constant pulse energy  $E_1$  of the first optical pulse 15. In Fig. 4A, the pulse energy  $E_1$  is set to 32 nJ and the variation of the pulse width  $T_d$  of the first optical pulse 15 is between 303 fs and 425 fs. Furthermore, the pump wavelength  $\lambda_1$  is 1550 nm, and the  
10 waveguide 3 has a taper ratio of 0.3 and an extracting length of 2 cm. It is seen that by increasing the pulse width  $T_d$  of the first optical pulse 15, the centre wavelength  $\lambda_2$  of the second optical pulse 16 is moving towards longer wavelengths. In Fig. 4A, the wavelength range of the second optical pulse 16 is between 420 nm and 690nm.

15 Fig. 4B shows a similar example as shown in Fig. 4A, however, the pulse energy of the first optical pulse  $E_1$  is increased from 32 nJ to 36 nJ, and the variation of the pulse width  $T_d$  of the first optical pulse 15 is between 303 fs and 466 fs. By comparing Fig. 4A and 4B, it is seen that the second optical  
20 pulses 16 at  $T_d$  equal to 303 fs and 425 fs have moved towards shorter wavelengths due to increase in pulse energy  $E_1$ . Furthermore, it is seen that by increasing the pulse energy, the wavelength range of the second optical pulse 16 increases at the expenses of a more complex spectral profile of the second optical pulses being generated furthest away from the output side of  
25 the up-tapered part. The wavelength range of the second optical pulse 16 is between 385 nm and 685nm.

Fig 4C shows the second optical pulse 16 being tuned in an up-tapered part 13 of the tapered waveguide 3 by varying the pulse width  $T_d$  at constant  
30 pulse energy  $E_1$  of the first optical pulse 15. In Fig. 4D, the pulse energy, i.e. the peak power of the first optical pulse is 56 nJ, and the variation of the

pulse width  $T_d$  is between 354 fs and 531 fs. It is clearly seen that the spectra become much more complicated in this case, which is a disadvantage when controlled emission of a narrow wavelength range is desired. Simulations also show that noise and coherence properties of the visible output degrade, when comparing with the previous simulations in Fig. 4A to 4B. The wavelength range of the second optical pulse 16 is between 380 nm and 680nm.

Fig. 4D shows a numerical simulation of the second optical pulse 16 being tuned by varying the pulse width  $T_d$  between 106 fs and 202 fs at a constant peak power, i.e.  $E_1$  equal to 32 nJ, in the down-tapered part 12. It is seen that by increasing the pulse width  $T_d$ , the centre wavelength  $\lambda_2$  of the second optical pulse 16 is moving towards shorter wavelengths. It is also seen that generation of the centre wavelength  $\lambda_2$  in the down-tapered part 12 in this case leads to a more complex spectral profile of the second optical pulse 16, with the eventual appearance of multiple spectral peak as the input pulse width  $T_d$  is shortened.

From the numerical simulations in Fig. 4A to 4C the importance of finding the correct relationship between the peak power  $E_1$ , i.e. pulse energy, the pulse width  $T_d$ , the taper ratio and at least the extracting length 18 is clearly seen. Thereby, it cannot be considered to be a trivial matter to develop a wavelength tunable laser by just combining a tapered waveguide and a laser source. Furthermore, the numerical simulations in Fig. 4D compared to Fig. 4A shows that it is in this case an advantage to generate the centre wavelength  $\lambda_2$  in the up-tapered part 13 of the waveguide 3, if a narrow output spectrum around some desired value of the centre wavelength  $\lambda_2$  is desired.

Fig. 5 shows an experimental result of the second optical pulse 16 being tuned by varying the peak power  $E_1$  between 197 mW and 228 mW. The

pump wavelength  $\lambda_1$  is 1030 nm, and all spectra are normalized so the maximal spectral intensity is 1. It is seen that by increasing the peak power  $E_1$ , the centre wavelength  $\lambda_2$  of the second optical pulse 16 is moving towards longer wavelengths. The wavelength range of the second optical pulse 16 is between 420 nm and 450nm. It is noted that in straight waveguides without any longitudinal variation, an increase in pump power will shift the centre wavelength  $\lambda_2$  of the second optical pulse 16 slightly towards shorter wavelengths. Therefore, the results in Fig. 5 experimentally demonstrate the use of a tapered waveguide 3 to control the power dependence of the centre wavelength  $\lambda_2$  of the second optical pulse 16.

Fig. 6 shows a diagram of a method 30 for tuning a centre wavelength  $\lambda_2$  of a second optical pulse 16, the method comprising the steps of:

- providing a first laser source (2, 30A) emitting a first optical pulse 15 having a pump wavelength  $\lambda_1$ , the first optical pulse 15 being emitted in a first longitudinal direction (6, 30B);
- generating a second optical pulse 16 having a centre wavelength  $\lambda_2$  by directing the first optical pulse 15 through a waveguide 3 extending in the first longitudinal direction 6 being, the waveguide 3 having longitudinally varying phase matching conditions 30C, and
- tuning the centre wavelength  $\lambda_2$  of the second optical pulse 16 by varying at least one pulse property of the first optical pulse 30D.

Fig. 7 shows a spectrum of the second optical pulse generated in a linear- and a nonlinear down-tapering fiber. It is clearly seen that when applying a nonlinear profile to the down-tapering the re-collision effect is mitigated. The blue shift and broadening of the CR pulse is strongly reduced, and the magnitude of the peak at 520-550 nm is decreased by more than a factor of 5.

Fig. 8A - 8B show a temporal spectrum, and corresponding spectrum as a function of wavelength of a nonlinear down-tapering fiber. The compression point varies between 2 cm and 3.9 cm and with a corresponding variation of the soliton number between 4 and 14.

5

In Fig. 8A, an example of spectra obtained with a short nonlinear downtaper profile is shown. A large number of simulations for different values of  $N$  and target  $z_c$  were carried out, and the resulting spectra inspected visually. Simulations featuring a reasonable degree of spectral isolation for the CR peak, i.e. the power peak of the second optical pulse, were selected for the plot. The wavelength range, of the 1.9 cm long nonlinear down-tapering fiber, is between 445 nm and 670 nm.

In Fig. 8B, the output pulses, CR, whose visible spectra are shown in Fig. 8A have been short-pass filtered at 750 nm, and their temporal power profile plotted. Pulse duration between 12 and 46 fs, and peak powers around the kW level results, i.e. 0,5 kW to 2,1 kW.

Fig. 9A – 9B show spectra of a linear taper with down- and up-tapering sections of 1 cm each and a 1mm tail at the end.

Fig. 9A shows spectral profiles generated in the up-tapering section of a fiber with 1-cm down and up-tapering parts, and pitch varying from 3  $\mu\text{m}$  to 1.5  $\mu\text{m}$ . In this example, the tunable wavelength is between 415 nm and 710 nm, and within the wavelength range the spectral density varies between 1,6  $\mu\text{J}/\text{nm}$  and 5,4  $\mu\text{J}/\text{nm}$ .

Fig. 9B shows CR spectra in a linear taper with down- and up-tapering sections of 1 cm each, and a 1 mm tail at the end. Tapering from pitch equal to 10  $\mu\text{m}$  to pitch equal to 3  $\mu\text{m}$  was considered. CR generation took place in

the up-tapering part. The soliton number ( $N$ ) and the designed compression point  $z_c$  of the input pump pulses are given.

In the example of Fig. 9B, the pitch has been increased and the ratio  
5 between maximum and minimum pitch within the tapered section has increased, compared to the example in Fig. 9A. The consequence of increasing the ratio and the pitch is that the peak power and the tunable wavelength range of the generated CR pulses, i.e. the second optical pulses, has increased. The tunable wavelength range is between 382 nm and 720  
10 nm, and within the wavelength range the spectral density varies between 9  $\mu\text{J}/\text{nm}$  and 33  $\mu\text{J}/\text{nm}$ .

Fig. 10A shows an example of the profile of a tapered waveguide 3 with the fiber length in mm along the x-axis shown as ranging from 0 to 16 mm, and  
15 the fiber pitch in  $\mu\text{m}$  along the y-axis shown as ranging from 1.75 to 3.0  $\mu\text{m}$ . The dotted line represents the designed or theoretical tapered waveguide and the full line represents the measured or actual tapered waveguide. Thus fig. 10 shows the profile of a nonlinear tapered waveguide 3 which is a PCF fiber.

20

Fig. 10B shows an example of the spectrum of a generated CR pulse, Cherenkov pulse or second optical pulse tunable and tuned from 414-612 nm. The wavelength in nm is shown on the x-axis and the normalised CR spectra is shown on the y-axis. The CR pulse is generated in the non-linear,  
25 tapered waveguide 3.

Fig. 10C shows noise versus output CR power at a fixed wavelength at 560 nm. The figure shows that the noise increases when the output CR power increases. CR power in mW is shown on the x-axis as ranging from 0 to 4  
30 mW and signal-to-noise ratio (SNR) is shown on the y-axis as ranging from about 500 to about 2600. Thus an increase in the pump power causes an

increase in the CR power which causes a decrease in the SNR. The SNR is still 1-2 magnitudes better than the SNRs known today for optical tunable laser sources, e.g. of a super continuum laser source.



**REFERENCES**

- 1 Wavelength tunable laser
- 2 First laser source
- 3 Waveguide
- 4 Compression waveguide
- 5 Capillary
- 6 First longitudinal direction
- 7 temperature sensitivity fluid material
- 8 Illuminating
- 9 Inscribed variation
- 10A Input side
- 10B Output side
- 10C Input side
- 10D Output side
- 11 Extracting part
- 12 Down-tapered part
- 13 Up-tapered part
- 14 Straight part
- 15 First optical pulse
- 16 Second optical pulse
- 17 Compression point
- 18 Extracting length
- 19 First transverse dimension
- 20 Second transverse dimension
- 21 Transverse dimension
- 30 Method for tuning a centre wavelength of a second optical pulse
- 30A First step of the tuning method
- 30B Second step of the tuning method
- 30C Third step of the tuning method
- 30D Fourth step of the tuning method

**CLAIMS**

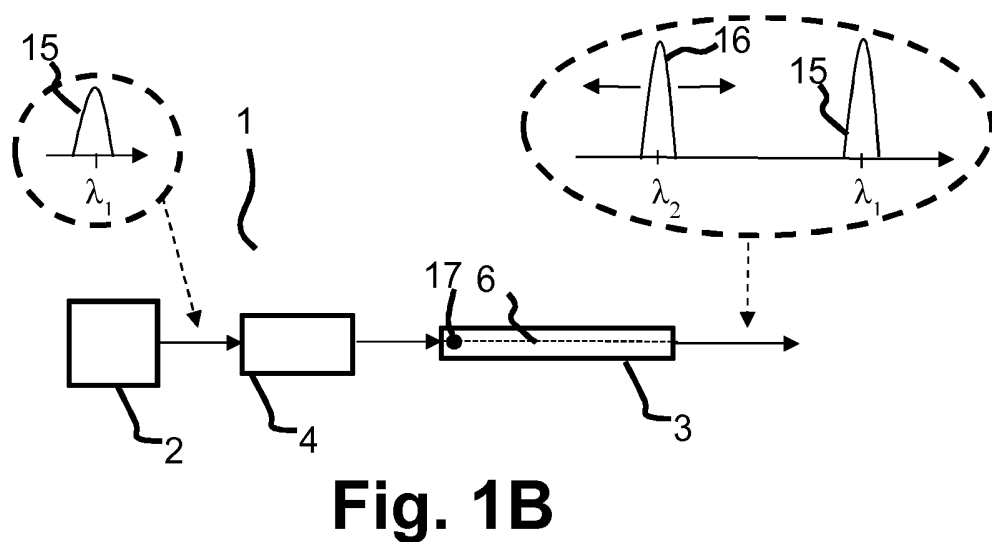
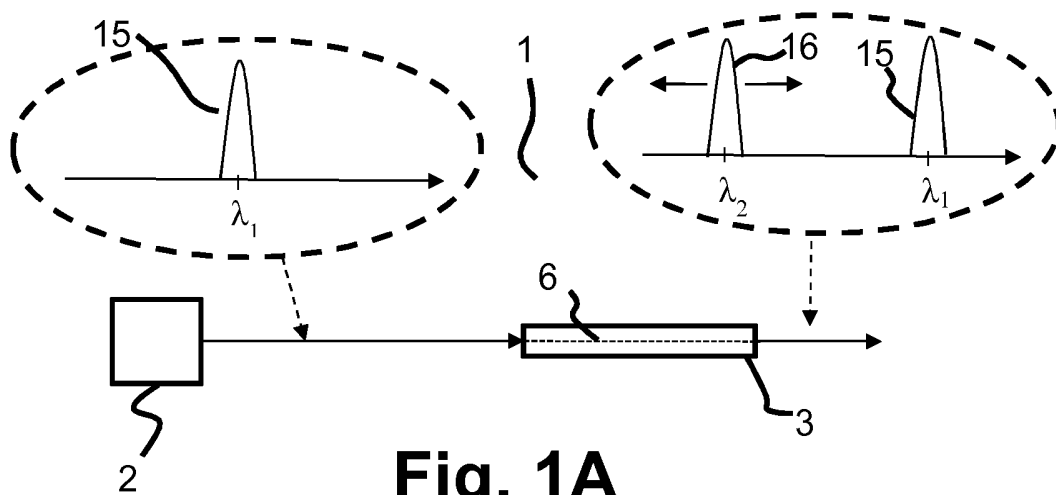
1. A wavelength tunable laser comprising:
  - a first laser source configured to emit a first optical pulse having a pump wavelength, the first optical pulse being emitted in a first longitudinal direction and the first optical pulse comprising at least one variable pulse property, and
  - a single waveguide element extending in the first longitudinal direction, the single waveguide element having longitudinally varying Cherenkov radiation phase matching conditions, the single waveguide element being configured to generate a second optical pulse with a centre wavelength upon receiving the first optical pulse,wherein the first laser source is configured to vary the at least one variable pulse property and wherein the single waveguide element is adapted for tuning the centre wavelength of the second optical pulse when the at least one variable pulse property is varied.
2. The wavelength tunable laser according to claim 1, wherein the at least one variable pulse property is a peak power, a pulse width, a pulse chirp or a state of polarization of the first optical pulse.
3. The wavelength tunable laser according to any of the preceding claims, wherein the single waveguide element comprises a compression point having the Cherenkov radiation phase matching condition, the compression point being positioned along the first longitudinal direction, wherein the centre wavelength of the second optical pulse is determined by the Cherenkov radiation phase matching condition at the compression point.

4. The wavelength tunable laser according to claim 3, wherein the compression point is a point of maximal peak power of the second optical pulse.
- 5 5. The wavelength tuneable laser according to any of the preceding claims, wherein the centre wavelength of the second optical pulse is tunable within a wavelength range comprising wavelengths being shorter and/or longer than the pump wavelength.
- 10 6. The wavelength tunable laser according to any of the preceding claims, wherein the single waveguide element is either:
- a tapered waveguide;
  - a photonic crystal fiber infiltrated with a fluid having a high temperature sensitivity of its refractive index combined with a  
15 longitudinal temperature variation along the first longitudinal direction of the waveguide, or
  - a single waveguide element comprising a photosensitive material, such as Germanium doped silica glass, having an inscribed refractive-index variation along the first longitudinal  
20 direction of the waveguide.
7. The wavelength tunable laser according to claim 6, wherein the single waveguide element is a tapered waveguide comprising at least an extracting tapered part, and wherein the extracting tapered part is a  
25 down-tapered part or an up-tapered part.
8. The wavelength tunable laser according to claim 7, wherein the extracting tapered part has a first transverse dimension and a second transverse dimension, wherein a taper ratio between the first transverse  
30 dimension and the second transverse dimension is between 0.1 and 0.9, between 0.2 and 0.7, between 0.3 and 0.6, or between 0.3 and 0.9.

9. The wavelength tunable laser according to claim 7 or 8, wherein the extracting tapered part has an extracting length along a first longitudinal direction determining a tuning gradient, i.e. a ratio between a change in  
5 centre wavelength over a change in at least one pulse property of the first optical pulse.
10. The wavelength tunable laser according to any of the preceding claims, wherein the single waveguide element is an optical fiber, a crystal, a  
10 segmented Photonic crystal fiber, or any other waveguide having an anomalous dispersion at least at the pump wavelength of the first optical pulse.
11. The wavelength tunable laser according to any of the preceding claims,  
15 wherein the first laser source is an ultrashort optical pulse laser, such as a femto-second laser or a pico-second laser.
12. A method for tuning a centre wavelength of a second optical pulse, the method comprising the steps of:  
20
- providing a first laser source emitting a first optical pulse having a pump wavelength, the first optical pulse being emitted in a first longitudinal direction;
  - generating a second optical pulse having a centre wavelength by directing the first optical pulse through a single waveguide element  
25 extending in the first longitudinal direction, the single waveguide element having longitudinally varying Cherenkov radiation phase matching conditions, and
  - tuning the centre wavelength of the second optical pulse by varying at least one pulse property of the first optical pulse.

13. The method according to claim 12, wherein the at least one pulse property is a peak power, pulse width, pulse chirp or state of polarization of the first optical pulse.
- 5 14. The method according to claim 12 or 13, wherein the centre wavelength of the second optical pulse is tuned within a wavelength range comprising wavelengths being shorter and/or longer than the pump wavelength.
- 10 15. The method according to any one of claims 12-14, wherein the single waveguide element comprises a compression point having the Cherenkov radiation phase matching condition, the compression point being positioned along the first longitudinal direction, wherein the centre wavelength of the second optical pulse is determined by the Cherenkov radiation phase matching condition at the compression point.
- 15
16. The method according to any one of claims 12-15, wherein the compression point is a point of maximal peak power of the second optical pulse.
- 20
17. The method according to any one of claims 12-16, wherein the single waveguide element is either:
- a tapered waveguide;
  - a photonic crystal fiber infiltrated with a fluid having a high temperature sensitivity of its refractive index combined with a longitudinal temperature variation along the first longitudinal direction of the waveguide, or
  - a single waveguide element comprising a photosensitive material, such as Germanium doped silica glass, having an inscribed refractive-index variation along the first longitudinal direction of the waveguide.
- 25
- 30

18. The method according to claim 17, wherein the single waveguide element is a tapered waveguide comprising at least an extracting tapered part, and wherein the extracting tapered part is a down-tapered part or an up-tapered part.
- 5
19. The method according to claim 18, wherein the extracting tapered part has a first transverse dimension and a second transverse dimension, wherein a taper ratio between the first transverse dimension and the second transverse dimension is between 0.1 and 0.9, between 0.2 and 0.7, between 0.3 and 0.6, or between 0.3 and 0.9.
- 10
20. The method according to claim 18 or 19, wherein the extracting tapered part has an extracting length along a first longitudinal direction determining a tuning gradient, i.e. a ratio between a change in centre wavelength over a change in at least one pulse property of the first optical pulse.
- 15
21. The method according to any one of claims 12-20, wherein the single waveguide element is an optical fiber, a crystal, a segmented Photonic crystal fiber, or any other waveguide having an anomalous dispersion at least at the pump wavelength of the first optical pulse.
- 20
22. The method according to any one of claims 12-21, wherein the first laser source is an ultrashort optical pulse laser, such as a femto-second laser or a pico-second laser.
- 25



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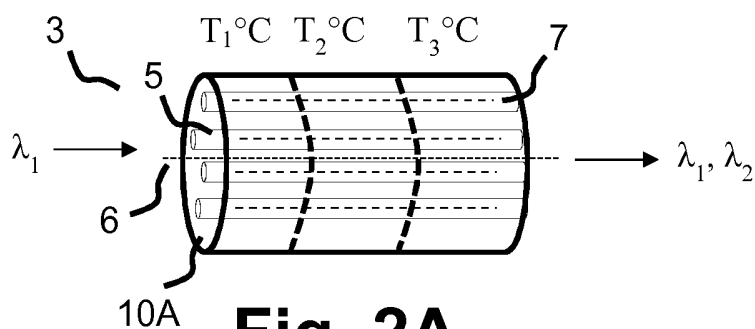


Fig. 2A



Fig. 2B

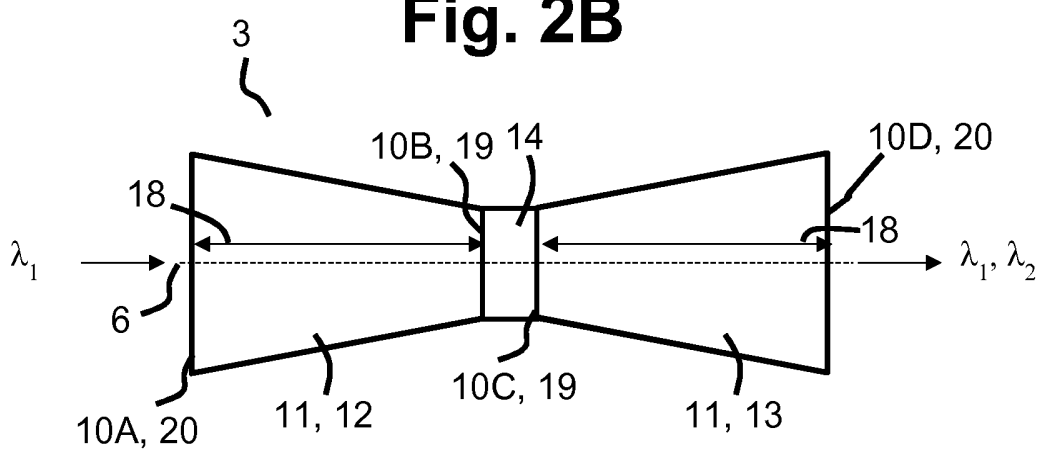


Fig. 2C



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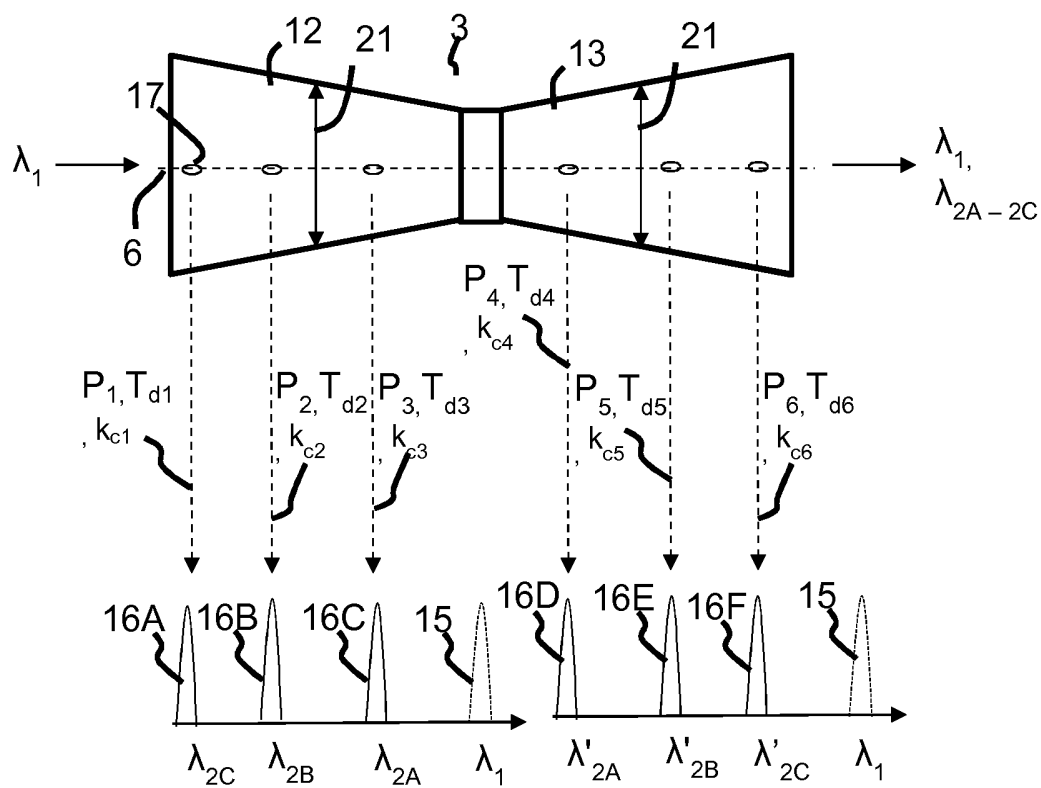


Fig. 3

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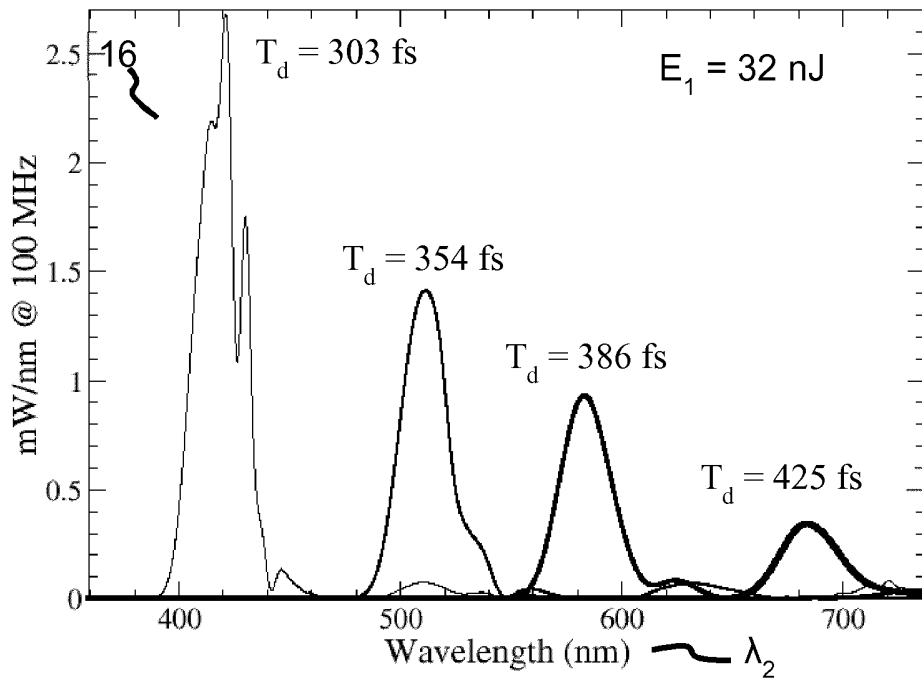


Fig. 4A

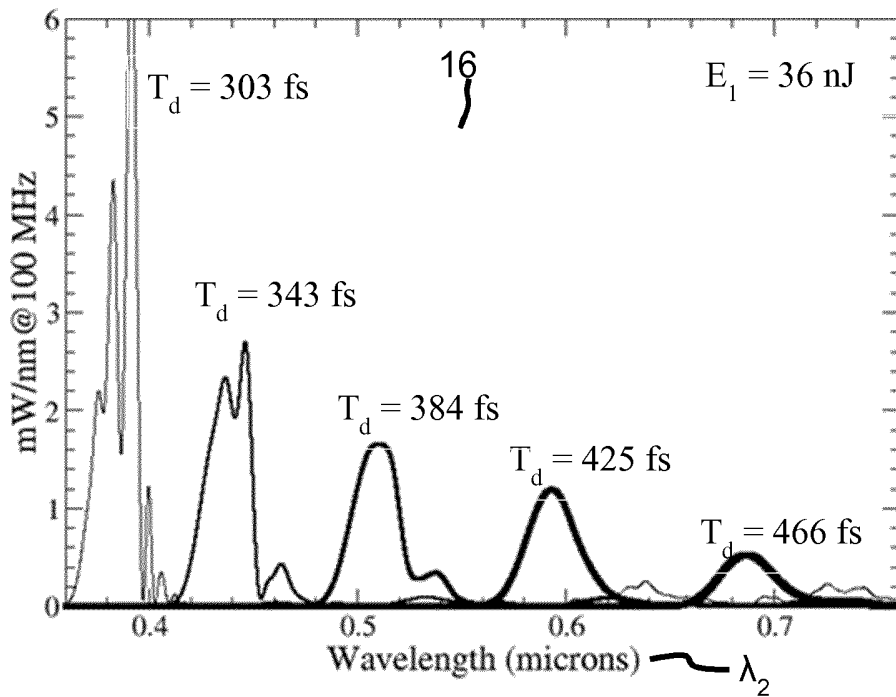


Fig. 4B

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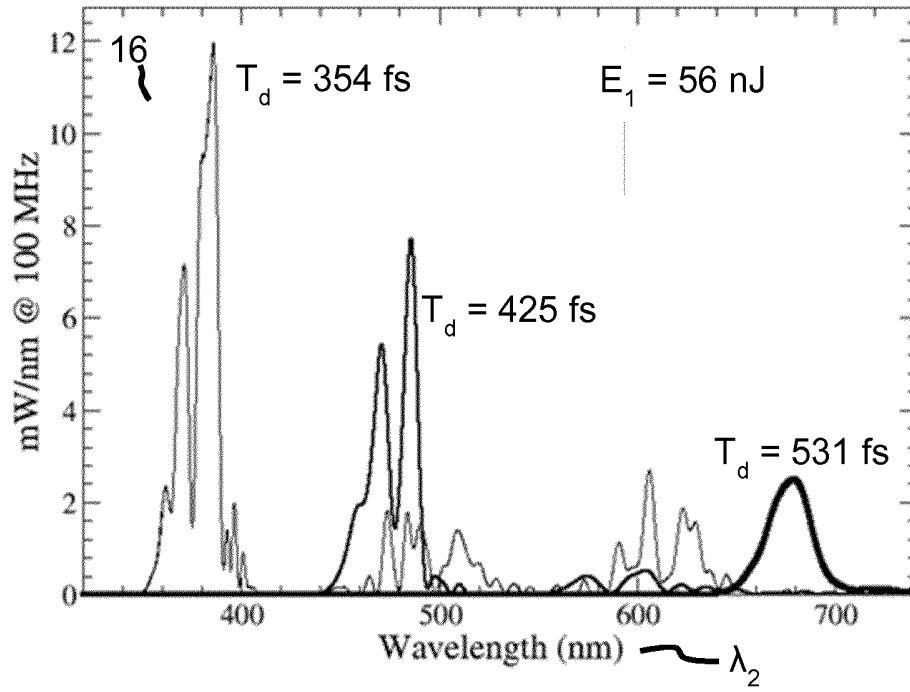


Fig. 4C

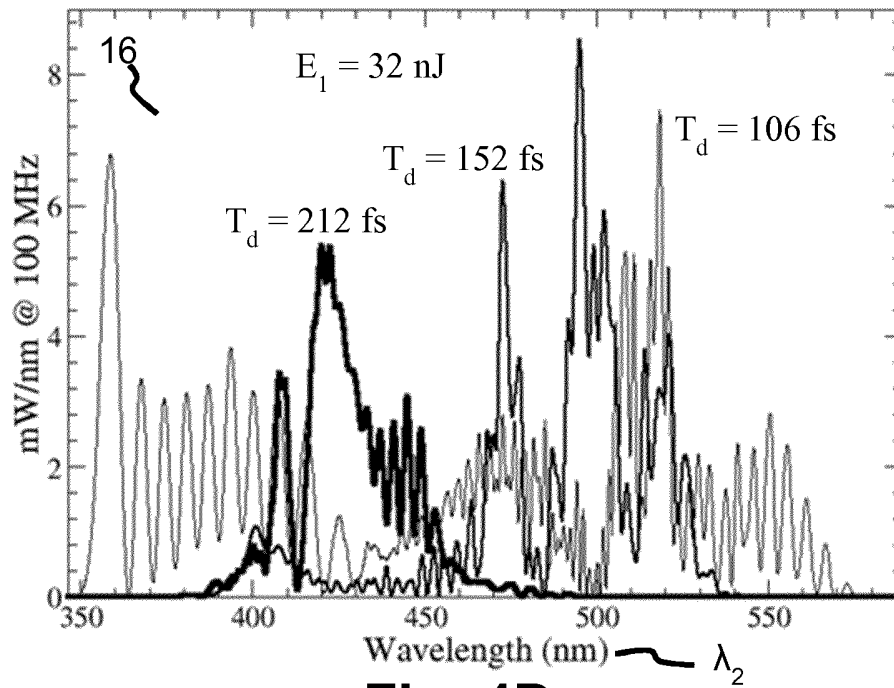


Fig. 4D

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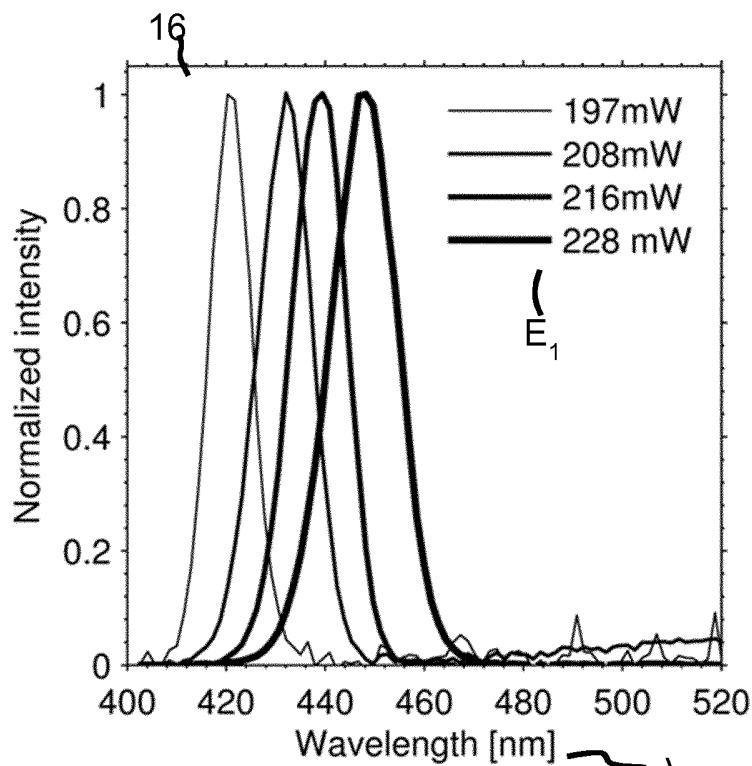


Fig. 5

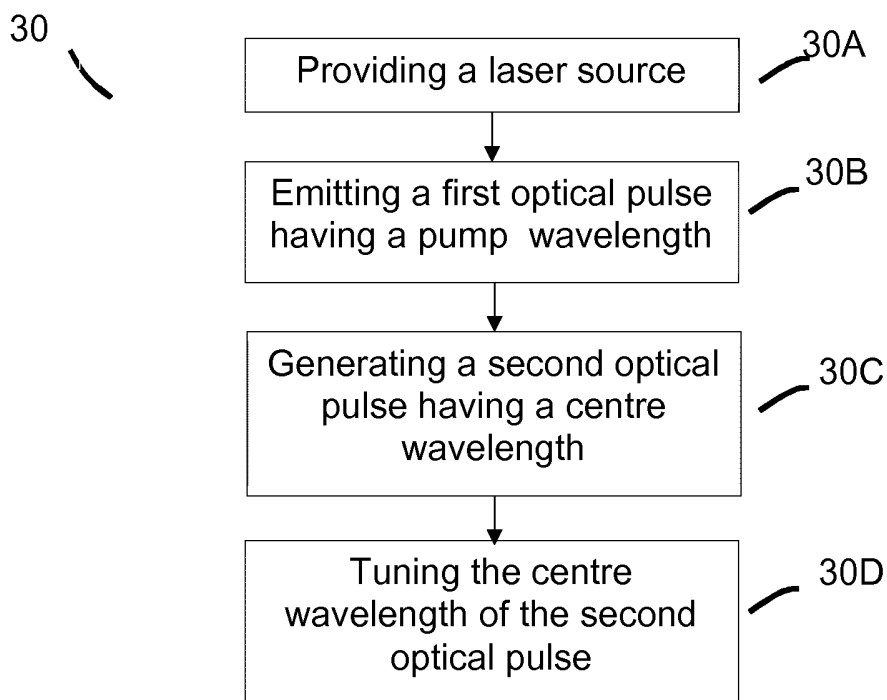


Fig. 6

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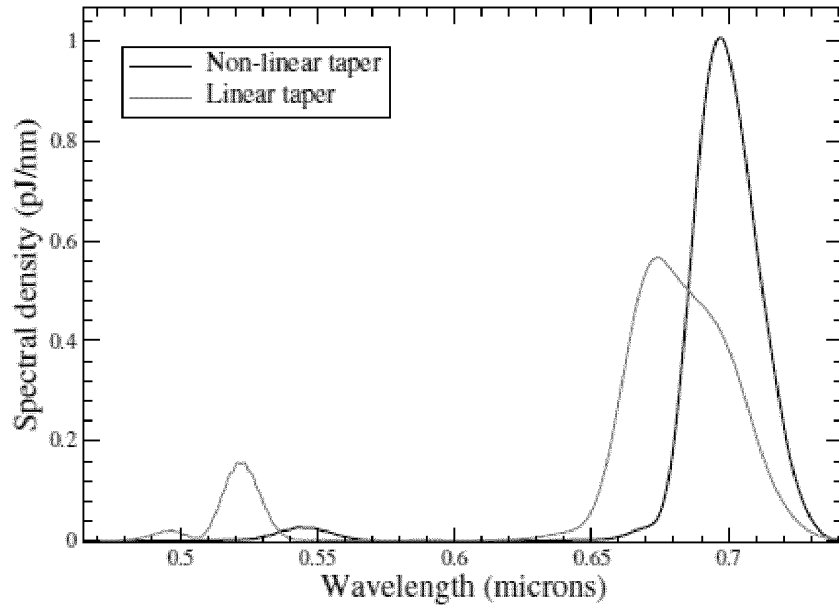


Fig.7

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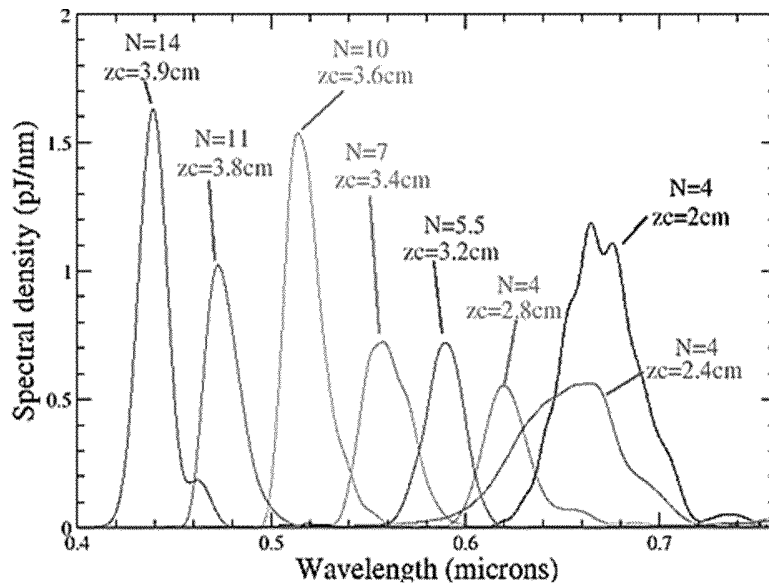


Fig. 8A

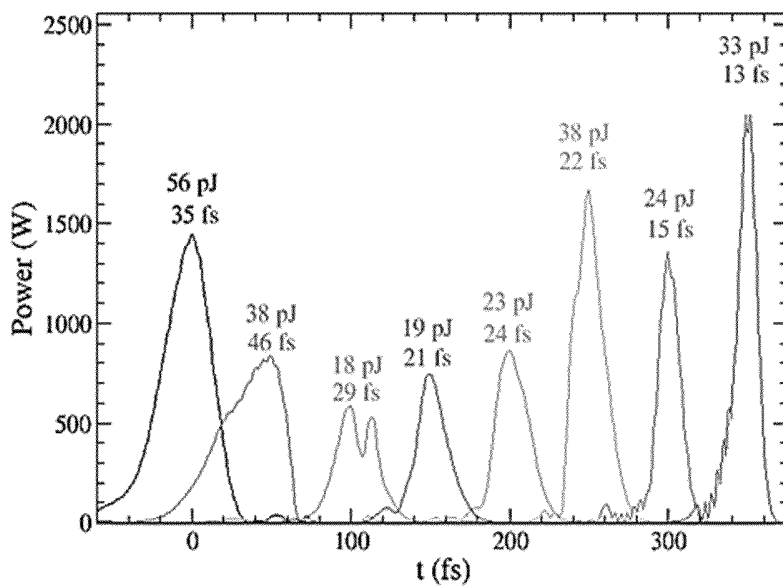


Fig. 8B

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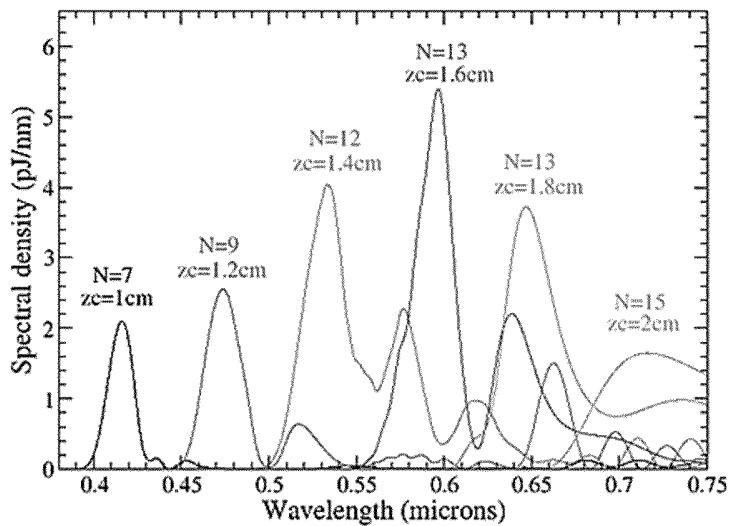


Fig. 9A

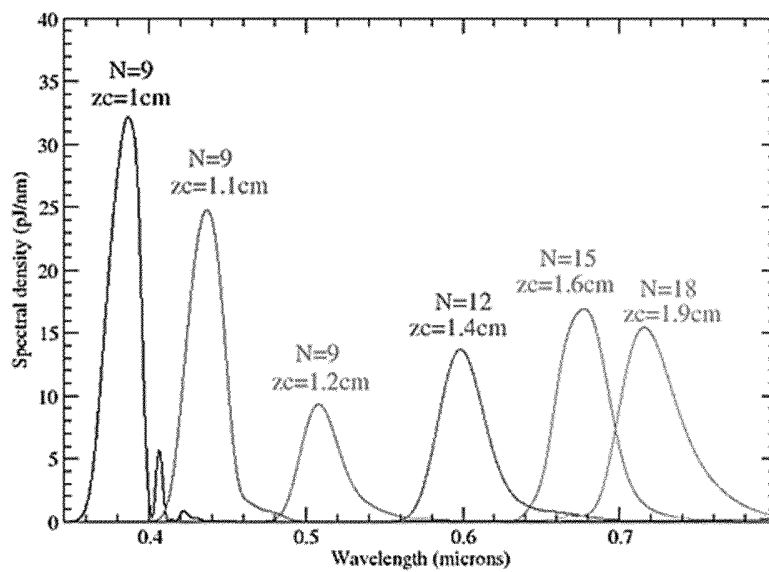
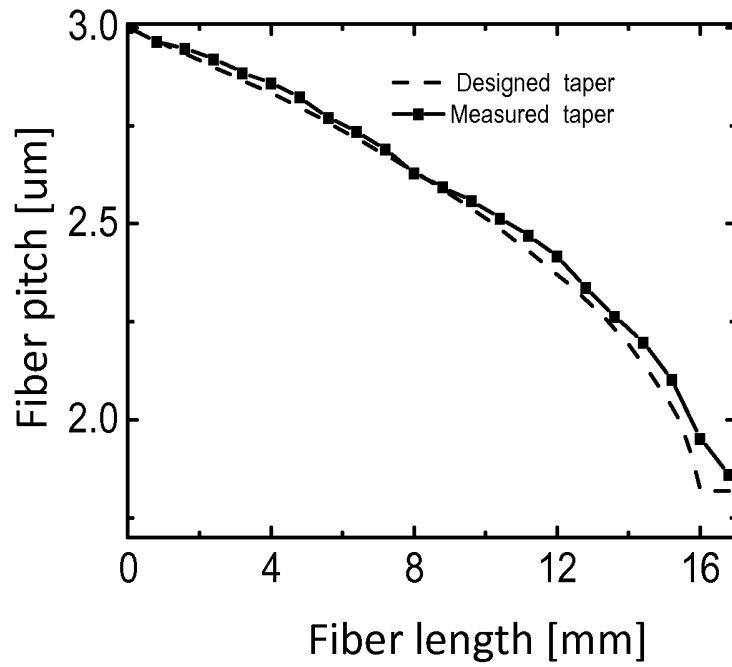


Fig. 9B

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Example of tapered PCF fiber (NL-3.0-850)

Fig. 10A



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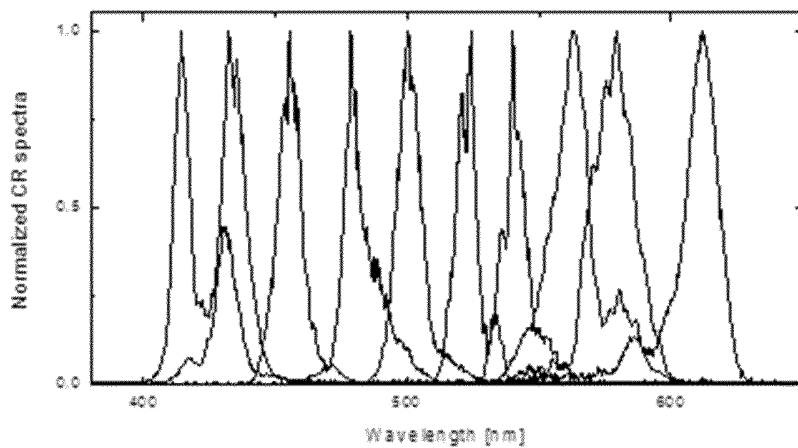


Fig. 10B

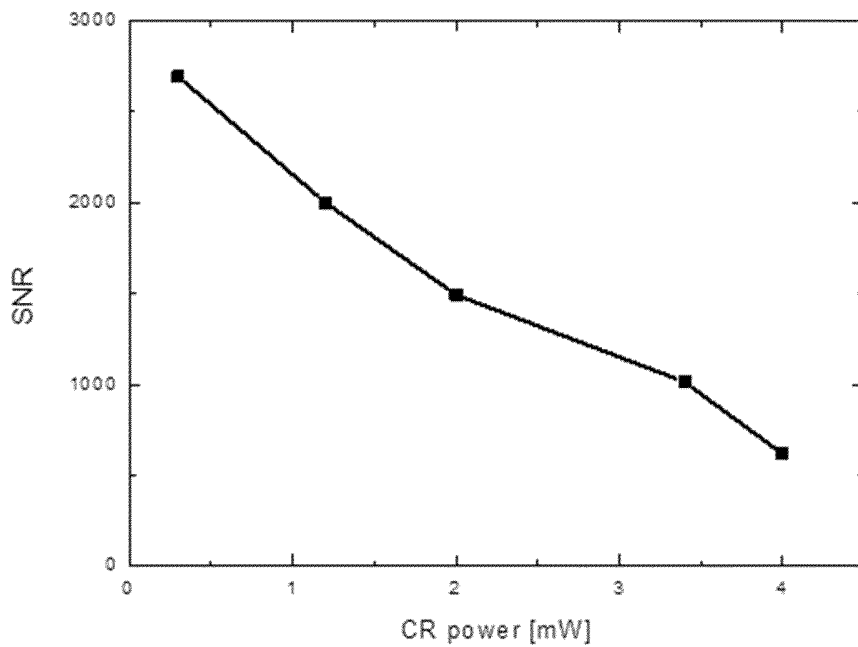


Fig. 10C

# INTERNATIONAL SEARCH REPORT

International application No PCT/EP2015/062486
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<b>A. CLASSIFICATION OF SUBJECT MATTER</b> INV. G02F1/35 H01S3/067 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b>		
Minimum documentation searched (classification system followed by classification symbols) G02F H01S		
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, INSPEC, WPI Data		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FEI LU ET AL: "Generation, characterization, and application of broadband coherent femtosecond visible pulses in dispersion micromanaged holey fibers", JOURNAL OF THE OPTICAL SOCIETY OF AMERICA B, vol. 23, no. 6, 2 June 2006 (2006-06-02), page 1221, XP055207179, ISSN: 0740-3224, DOI: 10.1364/JOSAB.23.001221 the whole document ----- -/--	1-22
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C. <span style="margin-left: 100px;"><input checked="" type="checkbox"/> See patent family annex.</span>		
* 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	
11 August 2015	18/08/2015	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer  Boubal, François	

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INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2015/062486

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>JOHN C. TRAVERS ET AL: "Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers [Invited]", JOURNAL OF THE OPTICAL SOCIETY OF AMERICA B, vol. 28, no. 12, 1 December 2011 (2011-12-01), pages A11-5210, XP055168287, ISSN: 0740-3224, DOI: 10.1364/JOSAB.28.000A11 the whole document</p> <p>-----</p>	1-22
A	<p>US 6 711 183 B1 (MIZUUCHI KIMINORI [JP] ET AL) 23 March 2004 (2004-03-23) column 16, line 25 - column 22, line 21 column 36, line 33 - column 37, line 3 figures 5, 21AQ</p> <p>-----</p>	1-22
A	<p>EP 1 118 904 A1 (JAPAN SCIENCE &amp; TECH CORP [JP] JAPAN SCIENCE &amp; TECH AGENCY [JP]) 25 July 2001 (2001-07-25) paragraph [0013] - paragraph [0035] figure 2</p> <p>-----</p>	2
A	<p>YUJUN DENG ET AL: "&lt;title&gt;Photonic crystal fiber-based broadly tunable femtosecond laser sources and applications&lt;/title&gt;", PROCEEDINGS OF SPIE, vol. 6322, 30 August 2006 (2006-08-30), page 63220H, XP055144283, ISSN: 0277-786X, DOI: 10.1117/12.681296 the whole document</p> <p>-----</p>	1-22
A	<p>DUPRIEZ P ET AL: "Tunable high energy femtosecond soliton fiber laser based on hollow-core photonic bandgap fiber", LASERS AND ELECTRO-OPTICS, 2008. CLEO 2008. CONFERENCE ON, IEEE, PISCATAWAY, NJ, USA, 4 May 2008 (2008-05-04), pages 1-2, XP031277706, ISBN: 978-1-55752-859-9 the whole document</p> <p>-----</p>	1-22
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**INTERNATIONAL SEARCH REPORT**

International application No PCT/EP2015/062486
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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>LEI ZHANG ET AL: "Paper;Simultaneous generation of tunable giant dispersive waves in the visible and mid-infrared regions based on photonic crystal fibers;Simultaneous generation of tunable giant dispersive waves in the visible and mid-infrared regions based on photonic crystal fibers",                      JOURNAL OF OPTICS, INSTITUTE OF PHYSICS PUBLISHING, BRISTOL GB,                      vol. 15, no. 7, 23 May 2013 (2013-05-23),                      page 75201, XP020247565,                      ISSN: 2040-8986, DOI:                      10.1088/2040-8978/15/7/075201                      the whole document</p> <p align="center">-----</p>	1-22

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Information on patent family members

International application No

PCT/EP2015/062486

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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EP 1118904	A1	25-07-2001	EP 1118904 A1 25-07-2001
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