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A method of generating supercontinuum light and a supercontinuum light source

Pu, Minhao; Kim, Chanju; Zhao, Yanjing; Yvind, Kresten

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

(72) Inventors: **PU, Minhao**; c/o DTU, Anker Engelunds Vej 101, 2800 Kongens Lyngby (DK). **KIM, Chanju**; c/o DTU, Anker Engelunds Vej 101, 2800 Kongens Lyngby (DK). **ZHAO, Yanjing**; c/o DTU, Anker Engelunds Vej 101, 2800 Kongens Lyngby (DK). **YVIND, Kresten**; c/o DTU, Anker Engelunds Vej 101, 2800 Kongens Lyngby (DK).

(74) Agent: **INSPICOS P/S**; Agern Alle 24, 2970 Hørsholm (DK).

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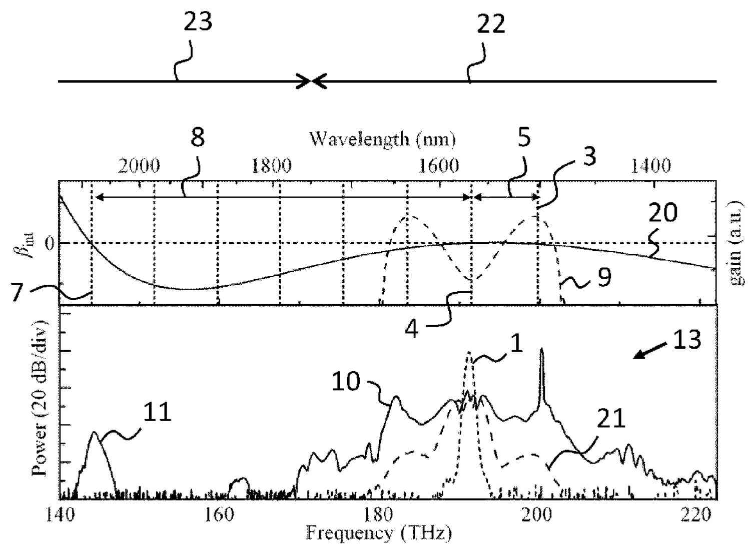

Fig. 4

(57) Abstract: The invention relates to a method of generating supercontinuum light comprising : providing frequency comb pump light and auxiliary pump light, wherein an auxiliary centre frequency is spectrally detuned with respect to a comb centre frequency by an auxiliary pump detuning; pumping a nonlinear medium associated with dispersive wave generation at a dispersive wave frequency shifted by a dispersive wave detuning relative to the comb centre frequency; spectrally translating the frequency comb pump light via a cascaded four-wave mixing process induced by the auxiliary pump light to thereby generate cascaded comb light; generating a dispersive wave at the dispersive wave frequency, wherein the generation of the dispersive wave is induced by the cascaded comb light due to an integer multiple of the auxiliary pump detuning lying within a spectral range of the dispersive wave detuning; and outputting the cascaded comb light and the dispersive wave to thereby provide the supercontinuum light.

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A METHOD OF GENERATING SUPERCONTINUUM LIGHT AND A SUPERCONTINUUM LIGHT SOURCE

FIELD OF THE INVENTION

The present invention relates to a method of generating supercontinuum light. The invention further relates to a supercontinuum light source.

BACKGROUND OF THE INVENTION

Nonlinear optical processes can be utilized to generate new frequencies of light. In a simple picture, pump light can be used to pump a nonlinear medium, and a nonlinear interaction between the pump light and the nonlinear medium can, e.g., generate frequencies of light not present in the pump light. Accordingly, nonlinear optical processes offer a host of possibilities to provide new types of light and light sources.

One type of light which may be established via nonlinear processes is supercontinuum light, which can be formed by nonlinear processes acting on pump light to cause spectral broadening. Conventionally, supercontinuum light can be provided with various spectral widths, but generally, it is desirable to have a very broad supercontinuum. A broad supercontinuum can be used to study a broader range of phenomena and may permit optical stabilization of the light through f-2f interferometry.

Due to the nonlinearity of nonlinear optical processes, a fundamental constraint is that high-intensity pumping light is most often required. For example, broad supercontinuum light is typically generated by pumping a nonlinear medium with a femtosecond laser having a peak power of several kilowatts.

The constraint that high-intensity light is typically required to generate broad spectrum light significantly restraints utilization of supercontinuum light in practical applications. Most often, a bulky table-top or fibre-based system is required to provide adequate pump power.

Accordingly, there is a need for new approaches which permit generation of broad supercontinuum light using limited input power or alternative pump light sources.

SUMMARY

On the above background, it is an object of preferred embodiments of the invention to provide an approach for generating broad supercontinuum light using reduced optical power in comparison with conventional solutions. It is further an object of some embodiments of the invention to provide broadband supercontinuum light based on alternative pump light sources. An additional object of some embodiments is to provide miniaturized systems capable of generating supercontinuum light, which in turn may be enabled by reduced power and/or alternative pump light sources.

A first aspect of the present disclosure relates to a method of generating supercontinuum light, the method comprising the steps of:

providing frequency comb pump light and auxiliary pump light, wherein an auxiliary centre frequency of the auxiliary pump light is spectrally detuned with respect to a comb centre frequency of the frequency comb pump light by an auxiliary pump detuning, wherein a peak power of the frequency comb pump light is at most 30 Watt;

pumping a nonlinear medium with the frequency comb pump light and the auxiliary pump light simultaneously, wherein the frequency comb pump light is associated with a phase matching criterion for dispersive wave generation in the nonlinear medium at a dispersive wave frequency shifted by a dispersive wave detuning relative to the comb centre frequency;

spectrally translating the frequency comb pump light via a cascaded four-wave mixing process in the nonlinear medium induced by the auxiliary pump light to thereby generate cascaded comb light;

generating a dispersive wave in the nonlinear medium at the dispersive wave frequency, wherein the generation of the dispersive wave is induced by the cascaded comb light due to an integer multiple of the auxiliary pump detuning lying within a spectral range of the dispersive wave detuning, wherein the spectral range is centred at the dispersive wave detuning and has a width of at most half of the auxiliary pump detuning; and

outputting the cascaded comb light and the dispersive wave from the nonlinear medium to thereby provide the supercontinuum light.

Supercontinuum light is typically generated by pumping a nonlinear medium with a very powerful laser, such as a femtosecond laser with a peak optical power of several kilowatts, to thereby generate spectrally broad supercontinuum light.

Generally, conventional teachings provide that spectrally broad supercontinuum light cannot be generated when the power is reduced, due to the constraints offered by nonlinear processes. However, the inventors of the present disclosure have realized that a specific combination of input light sources and nonlinear phenomena can be utilized to generate supercontinuum light without the necessity of high-power pump light.

A general aim of examples of the present disclosure is to generate a dispersive wave in a nonlinear medium.

When pump light enters a nonlinear medium, a dispersive wave can be generated if the conditions are adequate. The pump light and the nonlinear medium defines a phase matching criterion for dispersive wave generation at a dispersive wave frequency detuned from the centre frequency of the pump light. However, the dispersive wave is only generated if some light is provided at the dispersive wave frequency. Conventionally, a high-power femtosecond laser is typically used, which initially provides a broad spectrum and a high optical peak power, which can ensure the generation of the dispersive wave. If no light is present at the dispersive wave frequency from the femtosecond laser itself, a host of nonlinear processes induced by the high-power laser can collectively generate at least some light at the dispersive wave frequency, thereby triggering the generation of a dispersive wave.

If low-power pump light is used, conventional teachings provide that no light is provided to or generated at the dispersive wave frequency, and consequently, dispersive wave generation is not triggered.

The present disclosure therefore suggests a specific combination of input light sources which utilize nonlinear phenomena to provide light to the dispersive wave frequency to trigger generation of a dispersive wave. If a dispersive wave is generated, a broad supercontinuum is generally ensured.

Examples of the present disclosure utilize two different input lights: frequency comb pump light and auxiliary pump light.

By simultaneously pumping the nonlinear medium with both frequency comb pump light and auxiliary pump light, a nonlinear process referred to as four-wave mixing can be induced. In a four-wave mixing process, interactions between two or three frequencies of light produce two or one new frequencies of light. Using two pump frequency components f_1 and f_2 as examples, new frequencies may be generated according to energy conservation: $f_3 = f_1 - (f_2 - f_1) = 2f_1 - f_2$ and $f_4 = f_2 + (f_2 - f_1) = 2f_2 - f_1$. Thereby, the frequency components can be spectrally translated based on the detuning between them.

When new frequency components are generated, these can in turn induce additional four-wave mixing processes, thereby spectrally translating light even further. Such consecutive four-wave mixing is referred to as cascaded four-wave mixing.

When frequency comb pump light is used, the presence of an auxiliary pump light can spectrally translate the spectrum of the frequency comb pump light. The frequency comb pump light can be spectrally translated by a cascaded four-wave mixing process to generate cascaded comb light. Such cascaded comb light can potentially constitute at least a part of supercontinuum light.

The spectral spacing of the cascaded comb light is determined by the auxiliary pump detuning. That is, the distance between two neighbouring sub-envelopes of the cascaded comb light is given by the auxiliary pump detuning. However, sub-envelopes are not necessarily visible in the spectrum near the wavelength close to the comb centre frequency.

Examples of the present disclosure utilize a cascaded four-wave mixing process to provide light to the dispersive wave frequency to thereby induce generation of a dispersive wave. In practice, this can be performed by properly selecting the spectral detuning between the frequency comb pump light and the auxiliary pump light relative to the dispersive wave detuning between the dispersive wave frequency and the frequency comb pump light. By selecting these frequencies such that an integer multiple of the auxiliary pump detuning corresponds to the dispersive wave detuning, the cascaded four-wave mixing process can provide light specifically to the dispersive wave frequency, thereby efficiently inducing dispersive wave generation.

In practice, it is not needed that an integer multiple of the auxiliary pump detuning exactly equals the dispersive wave detuning. Generally, it is sufficient that an integer multiple of the auxiliary pump detuning lies within a spectral range centred at the dispersive wave detuning. A width of the spectral range being at most of the auxiliary pump detuning is typically sufficient to ensure that if the integer multiple of the auxiliary pump detuning lies within this spectral range, efficient dispersive wave generation is provided. Nevertheless, dispersive wave generation is typically more efficient the closer the integer multiple of the auxiliary pump detuning is to the dispersive wave detuning.

Hence, by simultaneously pumping a nonlinear medium with frequency comb pump light and auxiliary pump light detuned by an auxiliary pump detuning, a dispersive wave can be efficiently generated. In turn, this permit using a low peak power of the frequency comb pump light. Conventional teachings provide that dispersive wave generation cannot be properly induced using low-power input light. However, the inventors have realized that dispersive wave generation can indeed be performed at low peak powers if the pump light, consisting of the frequency comb pump light and auxiliary pump light, is carefully selected. These insights may generally permit generation of supercontinuum light using reduced power and narrower bandwidth or alternative pump light sources in comparison with conventional solutions. Further, these insights may provide miniaturized systems capable of generating broad supercontinuum light, for example, a chip-based supercontinuum light source.

Generally, the frequency comb pump light consists of a series of discrete, equally spaced frequency lines. Having frequency comb pump light ensures that a supercontinuum is actually generated, which would not be the case if only continuous wave (CW) light pumped the nonlinear medium. Further, it may typically provide adequate peak power. The frequency comb pump light has a comb centre frequency, for example corresponding to the frequency of the spectral peak of the frequency comb pump light, the average frequency of the frequency comb pump light, or a centre (of an envelope) of the frequency comb pump light. In an example, viable frequency comb pump light has a pulse duration of 5 picoseconds.

The auxiliary pump light can be, for example, CW light or pulsed light. It typically has a peak power smaller than the peak power of the frequency comb pump light. Pulsed light may ensure that the auxiliary pump light provides sufficient power to induce the cascaded four-wave mixing process. In case CW light is used, it can be advantageous to amplify this light to ensure that the cascaded four-wave mixing process is efficient. Such amplification may for example be implemented via a parametric gain established by the frequency comb pump light in the nonlinear medium. The auxiliary pump light has an auxiliary centre frequency, for example corresponding to the frequency of the spectral peak of the auxiliary pump light, the average frequency of the auxiliary pump light, or a centre (of an envelope) of the auxiliary pump light. In an example, viable auxiliary pump light is CW light with a power of 10 mW.

The comb centre frequency f_{comb} and the auxiliary centre frequency f_{aux} thereby defines an auxiliary pump detuning $\Delta_{aux} = f_{aux} - f_{comb}$.

Generation of dispersive waves in a nonlinear medium is described in [Gaeta, Alexander L., Michal Lipson, and Tobias J. Kippenberg. "Photonic-chip-based frequency combs." nature photonics 13.3 (2019): 158-169] and [Dudley, John M., Goëry Genty, and Stéphane Coen. "Supercontinuum generation in photonic crystal fiber." Reviews of modern physics 78.4

(2006): 1135], which are hereby incorporated by reference in their entirety. The first of these references describes that dispersive waves are a result of a phase-matched process in the presence of dispersion that is of a higher order than the group-velocity dispersion, and that the process can result in the transfer of energy from the region near the pump wave to spectral components that can be far away.

The reference provides an expression for the dispersion function:

$$D(\delta) = \sum_{n-2,3,\ldots} \frac{\beta_n}{n!}\delta^n$$

where δ is the frequency detuning from the frequency ω_0 of the pump light (in this case the centre comb frequency of the frequency comb pump light), $\beta_n = \partial^n k/\partial\omega^n\big|_{\omega=\omega_0}$ is the nth-order dispersion parameter, and $k(\omega) = n(\omega)\omega/c$ and $n(\omega)$ are the propagation constant and effective refractive index, respectively, for the waveguide mode of the nonlinear medium and include dispersion contributions that are both intrinsic to the material and from waveguide confinement. Zeros-crossings of the dispersion function provides a phase matching criterion for dispersive wave generation.

In the present disclosure, the dispersion function $D(\delta)$ corresponds to the integrated dispersion.

The dispersive wave frequency f_{DW} in combination with the comb centre frequency f_{comb} thereby defines a dispersive wave detuning $\Delta_{DW} = f_{DW} - f_{comb}$.

Typically, one or more dispersive wave frequencies can arise when a nonlinear medium is pumped, for example one dispersive wave frequency on either side of the frequency comb pump light. Some examples of the present disclosure rely on generation of one dispersive wave at one of these frequencies. However, some examples other examples utilize both dispersive waves frequencies to generate a first and a second dispersive wave.

Four wave mixing in a nonlinear medium is described in [Fukuda, Hiroshi, et al. "Four-wave mixing in silicon wire waveguides." Optics express 13.12 (2005): 4629-4637], which is hereby incorporated by reference in its entirety.

The number of times by which light is spectrally translated may a cascaded four-wave mixing process may be referred to as the order of the four-wave mixing process. For example, if the integer multiple of the auxiliary pump detuning corresponding to the dispersive wave detuning is eight, the corresponding four-wave mixing process is an eighth order four-wave mixing process.

In examples of the present disclosure, cascaded comb light and the dispersive wave is typically outputted from the nonlinear medium to thereby provide the supercontinuum light. Subsequently, this light can then be used in an application. The supercontinuum light may comprise spectral components in addition to the cascaded comb light and the dispersive wave. However, in examples of the present disclosure, the generation of the dispersive wave is typically a significant spectral feature in the spectrum of the supercontinuum of light.

In examples of the present disclosure, a pulse duration of the frequency comb pump light is at least 0.5 picosecond, for example at least 1.0 picosecond, for example at least 2.0 picoseconds, such as at least 5.0 picoseconds.

Conventionally, short pulses are preferable, but also more difficult to provide, since they generally provide broad spectrum and high optical peak power. However, the concepts of the present disclosure may advantageously permit low power in combination with relatively long pulse durations of the frequency comb pump light.

In examples of the present disclosure, a pulse duration of the frequency comb pump light is at most 40 picoseconds, for example at most 30 picoseconds, such as at most 20 picoseconds.

An upper boundary of the pulse duration as exemplified above may ensure that a dispersive wave is efficiently generated.

In examples of the present disclosure, the peak power of the frequency comb pump light is at most 20 Watt, for example at most 10 Watt, for example at most 5.0 Watt, for example at most 2.0 Watt, such as at most 1.0 Watt.

Conventionally, such lower powers have not been viable for dispersive wave generation, but may be viable according to the present disclosure due to the efficient dispersive wave generation.

In examples of the present disclosure, the peak power of the frequency comb pump light is at least 0.010 Watt, for example at least 0.030 Watt, for example at least 0.10 Watt, such as at least 0.3 Watt.

A lower boundary of the peak power as exemplified above may ensure that a dispersive wave is efficiently generated.

In examples of the present disclosure, a repetition rate of the frequency comb pump light is at most 200 GHz, for example at most 150 GHz, such as at most 100 GHz.

An upper boundary of the repetition rate of the frequency comb light as exemplified above can enable a detectable repetition rate, which in turn may enable optical stabilization of the light through f-2f interferometry.

In examples of the present disclosure, the auxiliary pump light is continuous wave light.

The concepts of the present disclosure advantageously permit the auxiliary pump light to be based on simple CW light. This CW light may be combined with a parametric gain established by the frequency comb pump light in the nonlinear medium.

In examples of the present disclosure, the frequency comb pump light is established by pumping a nonlinear resonator medium, such as a nonlinear micro-ring resonator or a nonlinear Fabry-Perot resonator, with primary continuous wave light.

Optionally, the frequency comb pump light can thereby be based on CW light, referred to as primary CW light, different from any auxiliary CW light. The primary CW light can then be converted into frequency comb pump light via a nonlinear resonator medium. For example, the primary CW light can pump a nonlinear micro-ring resonator in which the CW light is converted into frequency comb pump light by utilizing the Kerr effect within the nonlinear micro-ring resonator.

By generating the frequency comb pump light by pumping a nonlinear resonator medium via primary CW light, it is possible to provide frequency comb light via relatively simple and/or small-sized means, which compliments some concepts of the present disclosure which at least aim to provide broad supercontinuum light by miniaturized systems.

In examples of the present disclosure, the nonlinear resonator medium comprises at least a part of the nonlinear medium.

In examples of the present disclosure, the nonlinear resonator medium is separate from the nonlinear medium.

That is, the medium in which four-wave mixing and the dispersive wave generation takes place can either, at least partly, be the same medium as the medium in which the frequency comb pump light is established, or it can be a separate medium.

Having the nonlinear resonator medium comprising at least a part of the nonlinear medium can enable a simplification of a final implemented system. For example, it may be possible to realize the method using only one nonlinear element instead of two.

Having the nonlinear resonator medium separate from the nonlinear medium allows a clear separation of processes, which in turn can enable improved control and simplified modification of the system.

In examples of the present disclosure, the nonlinear medium has a nonlinear refractive index of at least 1.0×10^{-19} m^2/W, for example at least 3.0×10^{-19} m^2/W, such as at least 10×10^{-19} m^2/W.

A relatively large nonlinear refractive index as exemplified here may provide improved conditions for dispersive wave generation.

Generally, it is possible to enhance nonlinear effects by extending the length of the nonlinear medium, such that pump light spends more time within the nonlinear medium. However, in relation to dispersive wave generation, the length of the nonlinear medium affects the phase matching criterion and thereby the dispersive wave frequency and the dispersive wave detuning. Increasing the length of the nonlinear medium arbitrarily will shift the dispersive wave frequency to frequency regimes which are inaccessible. In other contexts, whether it is the length or the nonlinear refractive index which is increased does not matter, but in the context of the present disclosure, increasing the nonlinear refractive index is preferable.

With respect to different frequencies, the relevant nonlinear refractive index is the nonlinear refractive index at the comb centre frequency.

In examples of the present disclosure, the nonlinear medium is a nonlinear waveguide comprising silicon nitride, lithium niobate, aluminium nitride, silica, aluminium gallium arsenide, silicon carbide, tantalum pentoxide, amorphous silicon, silicon, or gallium phosphide, preferably aluminium gallium arsenide.

The nonlinear waveguide may be a waveguide on an insulator, for example an aluminium gallium arsenide-on-insulator (AlGaAsOI) waveguide.

Although many materials are viable, aluminium gallium arsenide has been found to be particularly suitable for dispersive wave generation according to the present disclosure.

In examples of the present disclosure, the nonlinear waveguide has a length of at most 12 mm, for example at most 10 mm, for example at most 8 mm, such as at most 6 mm.

Such lengths can potentially ensure efficient dispersive wave generation, for example in combination with the nonlinear medium comprising aluminium gallium arsenide and/or the nonlinear medium having a nonlinear refractive index of at least 10×10^{-19} m^2/W.

In examples of the present disclosure, the dispersive wave is spectrally separate from a main envelope of the supercontinuum light.

In conventional dispersive wave generation, the dispersive wave is typically spectrally located at a flank or border of a main envelope of an output spectrum. In such situations, the dispersive wave is typically induced or triggered by light within this main envelope.

In contrast, the concepts of the present disclosure can provide an efficient spectral translation to induce the dispersive wave generation. Thereby, the dispersive wave can be spectrally separate from a main envelope of the supercontinuum light.

Such a spectrally separate dispersive wave can implicitly be associated with an efficient usage of the light in terms of spectral broadness. Inducing a dispersive wave which lies within a main envelope does not necessarily broaden the spectrum significantly.

A dispersive wave being spectrally separate from a main envelope of the supercontinuum light can be quantified as follows.

In examples of the present disclosure, the dispersive wave has a relative spectral peak amplitude which is at least 5 dB greater than a local spectral minimum between the dispersive wave frequency and the comb centre frequency, for example at least 10 dB greater, such as at least 15 dB greater.

A local minimum between the dispersive wave frequency and the comb centre frequency is indicative of the dispersive wave being spectrally separate from a main envelope of the supercontinuum light.

In examples of the present disclosure, the dispersive wave has a relative spectral peak amplitude, wherein the spectral amplitude of the supercontinuum light at the comb centre frequency is at most 50 dB greater than the relative spectral peak amplitude of the dispersive wave, for example at most 45 dB greater, such as at most 40 dB greater.

Thereby, a minimal amplitude of the dispersive wave is ensured. A dispersive wave having an arbitrarily small peak amplitude may not be suitable for various application.

In examples of the present disclosure, the method comprises a step of establishing a parametric gain spectrum in the nonlinear medium, wherein the parametric gain spectrum is established by the frequency comb pump light via the step of pumping the nonlinear medium, wherein the auxiliary centre frequency is spectrally located in the parametric gain spectrum such that a parametric gain is applied to the auxiliary pump light.

The cascaded four-wave mixing process can be enhanced by utilizing a parametric gain spectrum established in the nonlinear medium by the frequency comb pump light. By spectrally locating the auxiliary centre frequency within the parametric gain spectrum, a parametric gain is applied to the auxiliary pump light, which in turn increases the spectral amplitude of this light. Given the greater amplitude, the nonlinear cascaded four-wave mixing process can be improved. This is especially relevant if the auxiliary pump light is CW light, which can have a lower peak amplitude than pulsed light.

Thus, the cascaded four-wave mixing process in the nonlinear medium may be induced by the auxiliary pump light subject to or based on the parametric gain of the parametric gain spectrum at the auxiliary centre frequency.

Since the establishment of a parametric gain spectrum can be performed using frequency comb pump light and a nonlinear medium, the utilization of this parametric gain spectrum constitutes a simple and efficient approach for improving dispersive wave generation without necessarily having to implement major modifications or new components.

In examples of the present disclosure, the auxiliary centre frequency is spectrally located within a 15-dB bandwidth of a side lobe of the parametric gain spectrum, for example within a 10-dB bandwidth, such as within a 5-dB bandwidth.

Typically, a parametric gain spectrum has two side lobes, with one of these located on either side of the comb centre frequency, and each of the two side lobes having a spectral peak. Improved four-wave mixing may be achieved by spectrally locating the auxiliary centre frequency near such a spectral peak. This can be quantified by, e.g., a 15-dB bandwidth of such a side lobe, the 15-dB bandwidth corresponding to a spectral extent between levels of the side lobe 15 dB below its spectral peak. Alternatively, a 10-dB or a 5-dB bandwidth can be used, corresponding to a spectral extent between levels of the side lobe 10 dB or 5 dB below its spectral peak.

An auxiliary pump frequency close to a spectral peak of the parametric gain spectrum applies a greater gain to the auxiliary pump light which is advantageous. Nevertheless, the auxiliary pump detuning should also be considered when selecting the auxiliary pump detuning to ensure that an integer multiple of the auxiliary pump detuning lies within the spectral range of the dispersive wave detuning.

In examples of the present disclosure, the integer multiple of the auxiliary pump detuning corresponding to the dispersive wave detuning is from 2 to 15.

Although many different physical effects can affect four-wave mixing, higher-order four-wave mixing generally tends to be less efficient than lower-order four wave mixing.

The provision of an upper limit to the integer multiple of the auxiliary pump detuning can ensure that a sufficient amount of light is actually translated to the dispersive wave frequency.

In examples of the present disclosure, the spectral range of the dispersive wave detuning has a width of at most 40 % of the auxiliary pump detuning, for example a width of at most 30 % of the auxiliary pump detuning, such as a width of at most 20 % of the auxiliary pump detuning.

By modifying the auxiliary pump detuning and the dispersive wave detuning such that the integer multiple of the auxiliary pump detuning lies closer to the dispersive wave detuning, dispersive wave generation is enhanced.

In examples of the present disclosure, the dispersive wave detuning is at least 25 THz, for example at least 30 THz, such as at most 35 THz.

In examples of the present disclosure, the dispersive wave detuning is at most 120 THz, for example at most 110 THz, such as at most 100 THz.

Upper and/or lower boundaries of the dispersive wave detuning may ensure that a sufficiently broad supercontinuum can be feasibly provided.

In examples of the present disclosure, the auxiliary pump detuning is at least 2.0 THz, for example at least 4.0 THz, such as at least 6.0 THz

In examples of the present disclosure, the auxiliary pump detuning is at most 30 THz, for example at most 25 THz, such as at most 20 THz.

Upper and/or lower boundaries of the auxiliary pump detuning may ensure efficient and distant spectral translation of light.

In examples of the present disclosure, a relative peak amplitude of the dispersive wave is reduced by at least 20 dB when the nonlinear medium is not pumped by the auxiliary pump light.

In typical conventional supercontinuum generation, a significant dispersive wave may be generated without auxiliary pump light, for example due to broad and/or powerful frequency comb pump light, or alternatively due to other nonlinear broadening effects. Such a dispersive wave may for example be generated if the dispersive wave frequency is located at within a main envelope of supercontinuum light. Even in such situations, auxiliary pump light may potentially amplify the dispersive wave.

In contrast, some examples of the present disclosure rely dispersive wave generation in which no substantial dispersive wave is present without auxiliary pump light. In practice, this can be quantified by a comparison of a relative peak amplitude of the dispersive wave with or without auxiliary pump light.

Examples in which the relative peak amplitude is reduced by at least 20 dB when the nonlinear medium is not pumped by the auxiliary pump light are typically associated with a significant broadening of the spectrum of the supercontinuum light when the auxiliary pump light is actually utilized, which is advantageous.

In examples of the present disclosure, a 40-dB bandwidth of the supercontinuum light is at least 80 THz, for example at least 100 THz, such as at least 120 THz.

In this context, a 40-dB bandwidth corresponds to a spectral extent between levels of the supercontinuum light 40 dB below a peak amplitude of the supercontinuum light, preferably a peak amplitude of the supercontinuum light at the comb centre frequency (thereby disregarding any spectral peak from the auxiliary pump light at the auxiliary centre frequency).

Examples of the present disclosure preferably has a broad 40-dB bandwidth as exemplified above.

In examples of the present disclosure, the 40-dB bandwidth spans at least one octave.

A span of at least one octave may permit optical stabilization of the light through f-2f interferometry.

In examples of the present disclosure, the 40-dB bandwidth is reduced by at least 50 % when the nonlinear medium is not pumped by the auxiliary pump light, for example at least 65 %, such as at least 80 %.

In typical conventional supercontinuum generation, a broad supercontinuum may be generated without auxiliary pump light, for example due to broad and/or powerful frequency comb pump light and other nonlinear broadening effects.

However, some examples of the present disclosure are not able to provide a broad supercontinuum without auxiliary pump light. Thereby, the provision of auxiliary pump light is associated with a significant broadening of the spectrum of the supercontinuum light. In turn, this is indicative of an efficient use of energy, since a broad supercontinuum spectrum established without auxiliary pump light is most likely established using relatively more power.

In examples of the present disclosure, a spectral contribution to the supercontinuum light from the cascaded comb light and the dispersive wave is greater than spectral contributions to the supercontinuum light from other nonlinear processes in the nonlinear medium.

In examples of the present disclosure, the nonlinear medium exhibits anomalous dispersion at the comb centre frequency and exhibits normal dispersion at the dispersive wave frequency.

Anomalous dispersion is characterized by a positive derivative of the refractive index with respect to wavelength $dn/d\lambda > 0$. This can provide adequate conditions for required nonlinear effects. The dispersion of the nonlinear medium can be engineered by controlling the waveguide cross-section of the nonlinear medium and spatially varying the refractive index of the surrounding material or the nonlinear material.

In examples of the present disclosure, the dispersive wave frequency is a first dispersive wave frequency, the dispersive wave detuning is a first dispersive wave detuning, the dispersive wave is a first dispersive wave, the integer multiple of the auxiliary pump detuning is a first integer multiple, the spectral range is a first spectral range,

wherein the frequency comb pump light is associated with the phase matching criterion for dispersive wave generation at the first dispersive wave frequency and a second dispersive wave frequency, wherein the first dispersive wave frequency is shifted by the first dispersive wave detuning relative to the comb centre frequency, wherein the second dispersive wave frequency is shifted by a second dispersive wave detuning relative to the comb centre frequency,

wherein the method further comprises a step of generating a second dispersive wave in the nonlinear medium at the second dispersive wave frequency, wherein the generation of the second dispersive wave is induced by the cascaded comb light due to a second integer multiple of the auxiliary pump detuning lying within a second spectral range of the second dispersive wave detuning, wherein the second spectral range is centred at the second dispersive wave detuning and has a width equal to the width of the first spectral range,

wherein the step of outputting the cascaded comb light and the first dispersive wave is a step of outputting the cascaded comb light, the first dispersive wave, and the second dispersive wave from the nonlinear medium to thereby provide the supercontinuum light.

The phase matching criterion for dispersive wave generation can be fulfilled at two separate frequencies, for example on either side of the comb centre frequency. Such two separate frequencies can then be referred to as a first dispersive wave frequency and a second dispersive wave frequency.

By correctly selecting the auxiliary pump detuning, the first dispersive wave detuning, and the second dispersive wave detuning, it is possible to generate cascaded comb light at both the first dispersive wave frequency and the second dispersive wave frequency to thereby generate both a first dispersive wave and a second dispersive wave. This is obtained by tuning parameters such that a first integer multiple of the auxiliary pump detuning corresponds to the first dispersive wave detuning and such that a second integer multiple of the auxiliary pump detuning corresponds to the second dispersive wave detuning. The first integer and the second integer can be the same (with opposite signs) or they can be different.

By inducing generation of both a first and a second dispersive wave, the spectral width of the supercontinuum light can be improved even further.

In examples of the present disclosure, the supercontinuum light of the first aspect is generated using the supercontinuum light source according to any examples of the second aspect of the present disclosure.

A second aspect of the present disclosure relates to a supercontinuum light source comprising:

> a frequency comb light source configured to provide frequency comb pump light having a comb centre frequency and a peak power of at most 30 Watt;

> an auxiliary light source configured to provide auxiliary pump light having an auxiliary centre frequency which is spectrally detuned with respect to the comb centre frequency by an auxiliary pump detuning;

> a nonlinear medium, wherein the frequency comb light source and the auxiliary light source are optically coupled to the nonlinear medium, wherein the frequency comb pump light is associated with a phase matching criterion for dispersive wave generation in the nonlinear medium at a dispersive wave frequency shifted by a dispersive wave detuning relative to the comb centre frequency,

wherein the nonlinear medium is configured to spectrally translate the frequency comb pump light via a cascaded four-wave mixing process induced by the auxiliary pump light to thereby generate cascaded comb light,

wherein the cascaded comb light is configured to induce generation of a dispersive wave in the nonlinear medium at the dispersive wave frequency due to an integer multiple of the auxiliary pump detuning lying within a spectral range of the dispersive wave detuning, wherein the spectral range is centred at the dispersive wave detuning and has a width of at most half of the auxiliary pump detuning,

wherein the nonlinear medium is configured to output the cascaded comb light and the dispersive wave to provide supercontinuum light.

Generally, a supercontinuum light source according to the second aspect of the present disclosure may provide improvements and advantages similar to those provided by methods according to the first aspect of the present disclosure.

In examples of the present disclosure, the frequency comb light source comprises a primary continuous wave light source and a nonlinear resonator medium, such as a nonlinear micro-ring resonator or a Fabry-Perot resonator, which is pumped by the primary continuous wave light source to establish the frequency comb pump light.

By generating the frequency comb pump light by pumping a nonlinear resonator medium via primary CW light from a primary CW light source, it is possible to provide frequency comb light via relatively simple and/or small-sized means, which compliments some concepts of the present disclosure which at least aim to provide broad supercontinuum light by miniaturized systems.

In examples of the present disclosure, the frequency comb light source is integrated on a chip.

In examples of the present disclosure, an electrical power consumption of the frequency comb light source is at most 8.0 W, for example at most 5.0 W, such as at most 3.0 W.

In examples of the present disclosure, the supercontinuum light source is integrated on a chip.

Providing components integrated on a chip and/or components having a low electrical power consumption may permit integration of the supercontinuum light source into a wide range of applications, such as wearable or portable applications and/or a fully chip-integrated broadband light source. Such a light source can in turn be used for personalized measurements such as glucose monitoring, portable high-precision measurements, and satellite timekeeping.

In examples of the present disclosure, the frequency comb light source and the auxiliary light source are serially coupled to the nonlinear medium such that the frequency comb pump light passes through the auxiliary light source prior to entering the nonlinear medium.

In examples of the present disclosure, the auxiliary light source comprises two mirrors which are arranged to define a laser cavity of the auxiliary light source, wherein a respective transmission coefficient for each of said two mirrors is greater for light at the comb centre frequency than for light at the auxiliary centre frequency.

In conventional systems in which two light sources are coupled into a nonlinear medium, light from these light sources is often guided via separate waveguides portions which are then merged into a single waveguide portion prior to entering the nonlinear medium. Such a Y-merging point in an optical waveguide results in a significant loss of light when transitioning form the separate waveguide portions to the single waveguide portion.

By coupling two light sources serially or sequentially into the nonlinear medium, instead of in parallel, the loss of light from merging separate waveguide portions can be avoided. In turn, this may ensure more efficient nonlinear effects in the nonlinear medium and/or may lower the requirements for the light sources pumping the nonlinear medium.

This is particular advantageous in the context of the present invention, since it may allow the provision of miniaturized systems capable of generating supercontinuum light, such as a chip-based supercontinuum light source.

A straightforward approach to implement such a serial coupling of light sources into the nonlinear medium is to use mirrors in one of the light sources which have a frequency-dependent transmission and reflection.

For example, the auxiliary light source may have two mirrors which define a laser cavity for generation of auxiliary pump light. These two mirrors generally have a reflection coefficient for the auxiliary pump light which is close to 1. Typically, one of the mirrors have a reflection coefficient which is slightly lower to thereby constitute an output coupler from which the auxiliary pump light of the auxiliary light source is outcoupled. For example, such a mirror may have a reflection coefficient for the auxiliary pump light in the range from 0.80 to 0.99, such as 0.95. However, for the frequency comb pump light, these mirrors have a significantly lower reflection coefficient, and a correspondingly greater transmission coefficient.

Preferably, the reflection coefficient of each of the two mirrors for the auxiliary pump light is at least 0.70, for example at least 0.75, for example at least 0.80, for example at least 0.85, for example at least 0.90. Preferably, the transmission coefficient of each of the two mirrors for the frequency comb pump light is at least 0.50, for example at least 0.60, for example at least 0.70, for example at least 0.80 such as at least 0.90.

In examples of the present disclosure, the supercontinuum light source is configured to generate supercontinuum light according to any examples of the first aspect of the present disclosure.

The concept of serially coupling two light sources into a nonlinear medium can also be utilized in other systems, not necessarily relying on, e.g., generation of a dispersive wave induced by cascaded comb light due to an integer multiple of the auxiliary pump detuning lying within a certain spectral range of the dispersive wave detuning.

Accordingly, a third aspect of the present disclosure relates to an optical system comprising:

a first light source configured to provide first pump light having a first centre frequency;

a second light source configured to provide second pump light having a second centre frequency; and

a nonlinear medium, wherein the first light source and the second light source are serially coupled to the nonlinear medium such that the first pump light passes through the second light source prior to entering the nonlinear medium.

In examples of the present disclosure, the second light source comprises two mirrors which are arranged to define a laser cavity of the second light source, wherein a respective transmission coefficient for each of said two mirrors is greater for light at the first centre frequency than for light at the second centre frequency.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be further described by reference to the accompanying drawings, in which:

Figs. 1a-e illustrate elements of an exemplary method according to the present disclosure;

Figs. 2a-e illustrate elements of another exemplary method in which the frequency comb pump light establishes a parametric gain spectrum such that a parametric gain is applied to the auxiliary pump light,

Figs. 3a-d schematically illustrates various examples of supercontinuum light sources according to the present disclosure,

Fig. 4 illustrates a measured spectrum of supercontinuum light in comparison with a calculated integrated dispersion,

Fig. 5 illustrates measured dispersive wave amplitudes at various relative detunings,

Fig. 6 illustrates a measured spectrum of supercontinuum light displaying a distinct series of frequency conversions of the frequency comb pump light,

Fig. 7 illustrates a measured spectrum of supercontinuum light in which two dispersive waves are generated, and

Fig. 8 schematically illustrates another example of a supercontinuum light source according to the present disclosure.

DETAILED DESCRIPTION

Figs. 1a-e illustrates elements of an exemplary method according to the present disclosure. The method is explained in the following with reference to these figures. The horizontal axis of each of the figures corresponds to the same frequency axis.

Fig. 1a illustrates frequency comb pump light 1 and auxiliary pump light 2. The vertical axis is indicative of intensity. The frequency comb pump light 1 consists of a series of discrete frequency lines, and the curve of the frequency comb pump light 1 illustrated in Fig. 1a is the envelope of these frequency lines.

The frequency comb pump light 1 has a comb centre frequency 4, and the auxiliary pump light 2 has an auxiliary centre frequency 3. These centre frequencies 3,4 correspond to average frequency of the respective light (linearly) weighted by intensity. Alternatively, the centre frequencies 3 and 4 can be defined as the frequencies of the discrete frequency components with the highest intensity within the frequency comb pump light 1 and auxiliary pump light 2, respectively.

The auxiliary centre frequency 3 is spectrally detuned with respected to the comb centre frequency 4 by an auxiliary pump detuning 5, which is indicated in Fig. 1a by a horizontal arrow between the two centre frequencies 3,4.

In a first step of the exemplary method, the frequency comb pump light 1 and the auxiliary pump light 2 is provided, for example from a frequency comb light source and an auxiliary light source.

In a next step of the exemplary method, a nonlinear medium is pumped with the frequency comb pump light 1 and the auxiliary pump light 2 simultaneously. In this nonlinear medium, the frequency comb pump light 1 is associated with a phase matching criterion for dispersive wave generation in that nonlinear medium, which is illustrated in Fig. 1b. The figure illustrates the integrated dispersion 20 as a dashed line. The vertical axis provides the value of this integrated dispersion. At the horizontal short-dashed line, the integrated dispersion 20 is zero. This is the case at the comb centre frequency 4, also illustrated in Fig. 1b. Moving slightly away from the comb centre frequency, the integrated dispersion 20 departs from zero. However, at sufficiently low frequencies, moving away from the comb centre frequency 4, the integrated dispersion 20 curves upwardly and crosses zero, thereby defining a dispersive wave frequency 7 for dispersive wave generation in the nonlinear medium. The integrated dispersion 20 and its value thereby constitutes a phase matching criterion for dispersive wave generation in the nonlinear medium at the dispersive wave frequency 7. This dispersive wave frequency 7 is shifted by a dispersive wave detuning 8 relative to the comb centre frequency 4, which is indicated in Fig. 1b by a horizontal arrow between the comb centre frequency 4 and the dispersive wave frequency 7.

In a next step of the exemplary method, the frequency comb pump light is spectrally translated via a cascaded four-wave mixing process in the nonlinear medium induced by the auxiliary pump light. This process generates cascaded comb light 10 which is illustrated in Fig. 1c, where the vertical axis is indicative of intensity.

The spectrum of the generated cascaded comb light 10 is determined by the light used to pump the nonlinear medium, i.e., the frequency comb pump light 1 and the auxiliary pump light 2. The cascaded comb light 10 typically comprises a series of frequency conversions of the frequency comb pump light, wherein these frequency conversions are evenly spaced by the auxiliary pump detuning 5. In the exemplary illustration of Fig. 1c, the frequency conversions of the frequency comb light are clearly visible as peaks in the illustrated spectrum. However, given that other nonlinear processes may occur in the nonlinear medium, this may not always be the case. The spectral width of the frequency comb pump light may also be comparable to or larger than the auxiliary pump detuning 5, and accordingly, the series of frequency conversions of the frequency comb light may not be distinct in the spectrum of the cascaded comb light 10.

In case the nonlinear medium is only pumped with frequency comb pump light 1, and not auxiliary pump light 2, substantial cascaded four-wave mixing does typically not occur. Fig. 1c illustrates an exemplary output spectrum 21 for this scenario. Here, there is no series of frequency conversions of the frequency comb pump light spaced by the auxiliary pump detuning. Other nonlinear processes can broaden this output light spectrum 21, but according to preferred embodiments, the spectral width of the output light spectrum 21 when not pumping with auxiliary pump light is significantly less broad than the spectral width of the cascaded comb light 13 when pumping with the auxiliary pump light.

Fig. 1d illustrates how the auxiliary pump detuning and the dispersive wave detuning relate according to the present example. In particular, an integer multiple of the auxiliary pump detuning 5 lies within a spectral range 12 of the dispersive wave detuning 8. As illustrated, this spectral range 12 is spectrally centred at the dispersive wave detuning 8. Further, the spectral range 12 has a width of at most half the dispersive auxiliary pump detuning 5.

As an example, the dispersive wave detuning (8) is −62 THz and the auxiliary pump detuning (5) is 12 THz, by which the width of the spectral range (12) is at most 6 THz. The spectral range (12) of the dispersive wave detuning thereby covers (at most) the range from −65 THz to −59 THz. Following this, −60 THz is a multiple of the auxiliary pump detuning (5), the number by which the auxiliary pump detuning is multiplied being −5. This multiple of the auxiliary pump detuning (5) lies within the spectral range from −65 THz to −59 THz. Hence, an integer multiple of the auxiliary pump detuning lies within a spectral range of the dispersive wave detuning.

Since the frequency comb pump light 1, the auxiliary pump light 2, and the nonlinear medium has been adapted such that this criterion is fulfilled, cascaded comb light may be generated at the dispersive wave frequency, and in turn, generation of a dispersive wave is induced.

Fig. 1e illustrates the resulting output spectrum, i.e., the resulting supercontinuum light 13 which is emitted or outputted from the nonlinear medium. In addition to the cascaded comb light 10, the supercontinuum light 13 comprises the dispersive wave 11 generated at the dispersive wave frequency.

The output spectrum may comprise additional spectral components or elements, especially given that nonlinear processes often do not occur in isolation.

Note that typically, the steps of the method are performed simultaneously. That is, light is provided to pump the nonlinear medium, by which light is spectrally translated to generate cascaded comb light, thereby inducing generation of a dispersive wave which is outputted from the nonlinear medium together with the cascaded comb light in a continuous and simultaneous manner.

Figs. 2a-e illustrate elements of another exemplary method in which the frequency comb pump light establishes a parametric gain spectrum such that a parametric gain is applied to the auxiliary pump light. The figures are illustrated in a style which is substantially similar to Figs. 1a-e.

In this example, when the frequency comb pump light pumps the nonlinear medium, it establishes a parametric gain spectrum 9, which is drawn in Fig. 2b together with the integrated dispersion 20 (albeit on different vertical scales). The parametric gain spectrum 9 is centred on the comb centre frequency 4 that has two side lobes, with one located on either side of the comb centre frequency 4, and each of the two side lobes having a spectral peak.

Light in the nonlinear medium is amplified based on the parametric gain spectrum 9.

In comparison with the exemplary method described with reference the Figs. 1a-e, the exemplary method illustrated in Figs. 2a-e employs auxiliary pump light 2 having a lower amplitude. This can be seen by comparison of the auxiliary pump light illustrated in Fig. 1a and in Fig. 2a. Such lower intensity can severely hamper nonlinear processes.

Yet, due to the parametric gain spectrum 9, the auxiliary pump light is amplified, and accordingly, four-wave mixing process between the frequency comb pump light 1 and the auxiliary pump light 2 still occurs, despite the low input intensity of the auxiliary pump light 2. The amplification is most efficient if the auxiliary centre frequency 3 is located near a spectral peak of one of the side lobes of the parametric grain spectrum 9, as is the case in the illustrated example.

In the illustrations, the parametric gain applied to the auxiliary pump light 2 is qualitatively evident from the peak at the auxiliary centre frequency in Figs. 2c and 2e.

Note further that the output light spectrum 21 when not pumping with auxiliary pump light source can be affected by the parametric gain spectrum 9. This is evident in Fig. 2c in which this output light spectrum 21 has two side lobes which resembles the parametric gain spectrum. Due to the absence of auxiliary pump light, the resulting output light spectrum 21 bandwidth is narrower than the case in which the nonlinear medium is also pumped by auxiliary pump light.

Figs. 3a-d schematically illustrates various examples of supercontinuum light sources 14 according to the present disclosure.

Both the frequency comb pump light 1 and the auxiliary pump light 2 can be provided using different concepts.

In Fig. 3a, a first concept is schematically illustrated, in which a frequency comb light source 15 and an auxiliary light source 16 are provided as separate stand-alone light sources. For example, the frequency comb light source may be integrated on a chip, for example configured to provide frequency comb pump light in the form of picosecond pulses having a peak power of 1 W. The auxiliary light source can optionally also be integrated on a chip, for example the same chip, and configured to provide auxiliary pump light in the form of picosecond pulses having a peak power of 1 W (but spectrally detuned by an auxiliary pump detuning) or it could be a continuous wave light source.

The frequency comb light source 15 is configured to provide frequency comb pump light 1, and the auxiliary light source 16 is configured to provide auxiliary pump light 2.

Both light sources 15,16 are optically coupled to a nonlinear medium 6. Such an optical coupling may for example be facilitated by an optical waveguide such as an optical fibre, or implemented via free-space propagation, for example aided by a lens assembly configured to focus the frequency comb pump light and/or the auxiliary pump light into an input end of the nonlinear medium 6.

In Fig. 3b, a second concept is schematically illustrated. In comparison with the first concept illustrated in Fig. 3a, the frequency comb light source 15 is implemented as a (primary) continuous wave light source 18 in combination with a nonlinear resonator medium, namely a nonlinear micro-ring resonator 17.

The frequency comb pump light 1 can then be generated via the Kerr nonlinearity by pumping the nonlinear micro-ring resonator 17 with continuous wave light from the continuous wave light source 18. This frequency comb pump light 1 can then be optically transmitted to the nonlinear medium 6.

In Fig. 3c, a third concept is schematically illustrated. In similarity with the second concept, the frequency comb pump light is generated by pumping a nonlinear micro-ring resonator 17 with light from a continuous wave light source. However, in contrast to the second concept, the nonlinear micro-ring resonator 17 is located in parallel with the nonlinear medium 6 such that the nonlinear micro-ring resonator 17 and the nonlinear medium 6 optically couple to each other, for example via evanescent fields. As a result, the frequency comb light is once again established in the micro-ring resonator 17. However, the continuous wave light from the primary continuous wave light source 18 enters the nonlinear medium 6 before it enters the micro-ring resonator 17. Nevertheless, the nonlinear medium 6 is still pumped by the frequency comb light, and the frequency comb light source 15 still comprises a primary continuous wave light source 18 and a nonlinear resonator medium 17 which is pumped by the primary continuous wave light source 18.

In Fig. 3d, a fourth concept is schematically illustrated. In similarity with the second and third concepts, the frequency comb pump light is generated by pumping a nonlinear micro-ring resonator 17 with light from a continuous wave light source. However, under this concept, the nonlinear micro-ring resonator is also the nonlinear medium 6 in which the four-wave mixing process occurs, and in which the dispersive wave is generated.

Fig. 4 illustrates a measured spectrum of supercontinuum light 13 in comparison with a calculated integrated dispersion 20.

The top panel of the figure illustrates the integrated dispersion 20 and the parametric gain spectrum 9. The bottom panel of the figure illustrates the frequency comb pump light 1, generated supercontinuum light 13, and output light spectrum without pumping with auxiliary pump light 21.

The bottom horizontal axis of the figure provides frequency in units of THz, and the top horizontal axis of the figure provides the corresponding wavelength (in vacuum). The vertical axis of the bottom panel provides power on a logarithmic scale with 20 dB per axis tick. On the top panel, the right-hand side vertical axis provides integrated dispersion 20, and the left-hand side indicates the gain of the parametric gain spectrum in arbitrary units.

The illustrated results were obtained by using an AlGaAs-on-insulator (AlGaAsOI) waveguide with a cross-sectional dimension of 290 nm × 520 nm and a length of 11 mm as a nonlinear medium. This waveguide provides a frequency range 23 of normal dispersion, and a frequency range 22 of anomalous dispersion, which is indicated by horizontal arrows at the top of the figure.

The frequency comb pump light 1 has a comb centre frequency 4 of 191.1 THz, lying within the range 22 of anomalous dispersion, a peak power of 14.4 W, and a pulse length of 1 picosecond.

Pumping the nonlinear medium with the frequency comb pump light 1 provides the integrated dispersion 20 illustrated in the figure, which provides a dispersive wave frequency 7 at its zero-crossing at 144.3 THz. Accordingly, the dispersive wave detuning 8 is -46.8 THz. Further, the pumping establishes the illustrated parametric gain spectrum 9.

The nonlinear medium is further pumped with continuous wave auxiliary pump light having a centre frequency of 198.9 THz and a (peak) power of 12.8 mW. Accordingly, the auxiliary pump detuning 5 is 7.8 THz, lying at the peak of a side-lobe of the parametric gain spectrum 9.

Simultaneously pumping the nonlinear medium with the frequency comb light 1 and the auxiliary pump light 2 induces a cascaded four-wave mixing process in the nonlinear medium in which the frequency comb pump light 1 is spectrally translated. Since an integer multiple, i.e. a multiple of six, of the auxiliary pump detuning 5 lies within a spectral range (not shown) of the dispersive wave detuning 8, a dispersive wave is efficiently generated. The dotted vertical lines in the top panel of the figure indicate frequency spacing corresponding to the auxiliary pump detuning 5.

The bottom panel of Fig. 4 provides the output spectrum of supercontinuum light 13 measured therefrom. The supercontinuum light exhibits a distinct dispersive wave at the dispersive wave frequency 7.

In contrast, if the nonlinear medium is only pumped with the frequency comb pump light 1 and not the auxiliary pump light 2, measurements show that an output light spectrum 21 having a significantly smaller width is provided.

Fig. 5 illustrates measured dispersive wave powers at various relative detunings. The measurements were performed based the nonlinear medium and pump light outlined in relation to Fig. 4., while varying the auxiliary centre frequency.

The right-hand side panel illustrates the power 24 of a dispersive wave when varying the auxiliary pump detuning relative to the dispersive wave detuning. The top horizontal axis indicates the auxiliary centre frequency in units of wavelength, while the bottom horizontal axis provides the corresponding ratio of the dispersive wave detuning to the auxiliary pump detuning in absolute values. The left-hand side axis indicates dispersive wave power in arbitrary units. The panel additionally illustrates the parametric gain spectrum and the right-hand side axis provides its power on a logarithmic scale of 10 dB per axis tick.

The left-hand side panel illustrates frequency spectra 11a-11d of the dispersive wave measured at various relative detunings. The relative detunings at which the spectra are measured are indicated in the right-hand side panel by dots on the curve of the dispersive wave power 24 and by reference numerals 24a-24d. The top horizontal axis indicates wavelength and the bottom horizontal axis provides the corresponding frequency. The vertical axis is power on a logarithmic scale of 5 dB per axis tick.

A first auxiliary pump wavelength is 1498.5 nm, the corresponding dispersive wave power is indicated by reference numeral 24a, and its spectrum is indicated by reference numeral 11a. A second auxiliary pump wavelength is 1500 nm, the corresponding dispersive wave power is indicated by reference numeral 24b, and its spectrum is indicated by reference numeral 11b. A third auxiliary pump wavelength is 1501.5 nm, the corresponding dispersive wave power is indicated by reference numeral 24c, and its spectrum is indicated by reference numeral 11c. And a fourth auxiliary pump wavelength is 1504 nm, the corresponding dispersive wave power is indicated by reference numeral 24d, and its spectrum is indicated by reference numeral 11d.

The measurements presented in the right-hand side panel exhibit a clear oscillatory behaviour of the dispersive wave power 24, with peaks located at integer values of the ratio of the dispersive wave detuning to the auxiliary pump detuning.

These measurements evidently provides that a dispersive wave is efficiently generated when an integer multiple of the auxiliary pump detuning lies within a spectral range of the dispersive wave detuning.

The measurements additionally indicate that efficiency of dispersive wave generation is most prominent when the auxiliary centre frequency is spectrally located near a peak of a side lobe of the parametric gain spectrum 9.

Fig. 6 illustrates a measured spectrum of supercontinuum light 13 displaying a distinct series of frequency conversions of the frequency comb pump light. Further, this spectrum provides a dispersive wave 11 generated at a frequency which is greater than the comb centre frequency, in contrast to the measurements illustrated in Fig. 4.

The measurements illustrated in the figure were obtained using an AlGaAsOI waveguide as a nonlinear medium. The frequency comb light 1 has a comb centre frequency of 191.1 THz, a peak power of 14.4 W, and a pulse length of 1 picosecond. The auxiliary pump light is continuous wave light having a (peak) power of 11.5 mW and a centre frequency of 200 THz. The dispersive wave frequencies are at 143 THz and 278 THz.

The nonlinear medium is pumped with the frequency comb pump light and the auxiliary pump light to induce a four-wave mixing process spectrally translating the frequency comb pump light 1 to the dispersive wave frequency, thereby generating a dispersive wave 11. The output spectrum displays a distinct series of frequency conversions of the frequency comb pump light having a spacing corresponding to the auxiliary pump detuning.

Fig. 7 illustrates a measured spectrum of supercontinuum light 13 in which two dispersive waves 11, 25 are generated.

The measurements illustrated in the figure were obtained using an AlGaAsOI waveguide as a nonlinear medium. The frequency comb light 1 has a comb centre frequency of 194 THz, a peak power of 1455 mW, and a pulse length of 1 picosecond. The auxiliary pump light 2 is also a pulsed light having a (peak) power of 744 mW, a pulse length of 1 picosecond, and a centre frequency of 189.7 THz.

When pumping the nonlinear medium with the frequency comb pump light, the frequency comb pump light is associated with a phase matching criterion for dispersive wave generation at a first dispersive wave frequency of 148.3 THz and at a second dispersive wave frequency of 260 THz. The first dispersive wave frequency is thereby shifted by a first dispersive wave detuning of -45.7 THz relative to the comb centre frequency, and the second dispersive wave frequency is shifted by a second dispersive wave detuning of 66 THz relative to the comb centre frequency.

The nonlinear medium is pumped by the frequency comb pump light 1 and the auxiliary pump light 2 to induce a four-wave mixing process which spectrally translated the frequency comb pump light to generate cascaded comb light 10.

The light and nonlinear medium has been configured such that a first integer multiple of the auxiliary pump detuning lies within a first spectral range of the first dispersive wave detuning, and such that a second integer multiple of the auxiliary pump detuning lies with a second spectral range of the second dispersive wave detuning. Accordingly, the cascaded comb light induces generation of a first dispersive wave 11 and the first dispersive wave frequency, and of a second dispersive wave 25 at the second dispersive wave frequency.

The cascaded comb light 10, the first dispersive wave 11, and the second dispersive wave 25 is outputted to thereby provide the supercontinuum light 13.

Fig. 8 schematically illustrates another example of a supercontinuum light source 14 according to the present disclosure.

In comparison with the supercontinuum light sources illustrated in Figs. 3a-3d, in which the frequency comb light source and the auxiliary light source are coupled in parallel into the nonlinear medium, the frequency comb light source 15 and the auxiliary light source 16 of the supercontinuum light source 14 illustrated in Fig. 8 are serially coupled into the nonlinear medium 6.

The frequency comb light source 15 is arranged to provide frequency comb pump light 1, which in turn passes through the auxiliary light source 16. Thereby, both frequency comb pump light 1 and auxiliary pump light 2 passes from the auxiliary light source 16 into the nonlinear medium 6

The auxiliary light source 16 comprises a first mirror 26a and a second mirror 26b which collectively establish a laser cavity of the auxiliary light source 16. Each of these two mirrors 26a, 26b has a reflection coefficient of at least 0.90 for light at the auxiliary centre frequency, wherein the reflection coefficient is greater for the first mirror 26a than for the second mirror 26b for light at the auxiliary centre frequency such that the second mirror 26b allows extraction of a portion of the light from the laser cavity to provide the auxiliary pump light 2.

Further, each of these two mirrors 26a, 26b has a transmission coefficient of at least 0.50 for light at the comb centre frequency, thereby allowing frequency comb pump light 1 of the frequency comb light source 15 to pass through the auxiliary light source 16.

List of figure references:

1	frequency comb pump light
2	auxiliary pump light
3	auxiliary centre frequency
4	comb centre frequency
5	auxiliary pump detuning
6	nonlinear medium
7	dispersive wave frequency
8	dispersive wave detuning
9	parametric gain spectrum
10	cascaded comb light
11	dispersive wave
12	spectral range of the dispersive wave detuning
13	supercontinuum light
14	supercontinuum light source
15	frequency comb light source
16	auxiliary light source
17	nonlinear micro-ring resonator
18	primary continuous wave light source
19	auxiliary continuous wave light source
20	integrated dispersion
21	output light spectrum without pumping with auxiliary pump light

22	anomalous dispersion range
23	normal dispersion range
24	dispersive wave power
25	second dispersive wave
26	mirror

CLAIMS

1. A method of generating supercontinuum light (13), the method comprising the steps of:

providing frequency comb pump light (1) and auxiliary pump light (2), wherein an auxiliary centre frequency (3) of the auxiliary pump light (2) is spectrally detuned with respect to a comb centre frequency (4) of the frequency comb pump light by an auxiliary pump detuning (5), wherein a peak power of the frequency comb pump light is at most 30 Watt;

pumping a nonlinear medium (6) with the frequency comb pump light (1) and the auxiliary pump light (2) simultaneously, wherein the frequency comb pump light (1) is associated with a phase matching criterion for dispersive wave generation in the nonlinear medium (6) at a dispersive wave frequency (7) shifted by a dispersive wave detuning (8) relative to the comb centre frequency (4);

spectrally translating the frequency comb pump light (1) via a cascaded four-wave mixing process in the nonlinear medium (6) induced by the auxiliary pump light (2) to thereby generate cascaded comb light (10);

generating a dispersive wave (11) in the nonlinear medium (6) at the dispersive wave frequency (7), wherein the generation of the dispersive wave (11) is induced by the cascaded comb light (10) due to an integer multiple of the auxiliary pump detuning (5) lying within a spectral range (12) of the dispersive wave detuning (8), wherein the spectral range (12) is centred at the dispersive wave detuning (8) and has a width of at most half of the auxiliary pump detuning (5); and

outputting the cascaded comb light (10) and the dispersive wave (11) from the nonlinear medium (6) to thereby provide the supercontinuum light (13).

2. The method according to claim 1, wherein the peak power of the frequency comb pump light is at most 20 Watt, for example at most 10 Watt, for example at most 5.0 Watt, for example at most 2.0 Watt, such as at most 1.0 Watt.

3. The method according to any of the preceding claims, wherein the nonlinear medium is a nonlinear waveguide comprising silicon nitride, lithium niobate, aluminium nitride, silica,

aluminium gallium arsenide, silicon carbide, tantalum pentoxide, amorphous silicon, silicon, or gallium phosphide, preferably aluminium gallium arsenide.

4. The method according to any of the preceding claims, wherein the dispersive wave has a relative spectral peak amplitude which is at least 5 dB greater than a local spectral minimum between the dispersive wave frequency and the comb centre frequency, for example at least 10 dB greater, such as at least 15 dB greater.

5. The method according to any of the preceding claims, wherein the method comprises a step of establishing a parametric gain spectrum in the nonlinear medium, wherein the parametric gain spectrum is established by the frequency comb pump light via the step of pumping the nonlinear medium, wherein the auxiliary centre frequency is spectrally located in the parametric gain spectrum such that a parametric gain is applied to the auxiliary pump light.

6. The method according to claim 5, wherein the auxiliary centre frequency is spectrally located within a 15-dB bandwidth of a side lobe of the parametric gain spectrum, for example within a 10-dB bandwidth, such as within a 5-dB bandwidth.

7. The method according to any of the preceding claims, wherein the integer multiple of the auxiliary pump detuning corresponding to the dispersive wave detuning is from 2 to 15.

8. The method according to any of the preceding claims, wherein a relative peak amplitude of the dispersive wave is reduced by at least 20 dB when the nonlinear medium is not pumped by the auxiliary pump light.

9. The method according to any of the preceding claims, wherein a 40-dB bandwidth of the supercontinuum light is at least 80 THz, for example at least 100 THz, such as at least 120 THz.

10. The method according to claim 9, wherein the 40-dB bandwidth is reduced by at least 50 % when the nonlinear medium is not pumped by the auxiliary pump light, for example at least 65 %, such as at least 80 %.

11. The method according to any of the preceding claims, wherein the dispersive wave frequency is a first dispersive wave frequency, the dispersive wave detuning is a first dispersive wave detuning, the dispersive wave is a first dispersive wave, the integer multiple of the auxiliary pump detuning is a first integer multiple, the spectral range is a first spectral range,

wherein the frequency comb pump light is associated with the phase matching criterion for dispersive wave generation at the first dispersive wave frequency and a second dispersive wave frequency, wherein the first dispersive wave frequency is shifted by the first dispersive wave detuning relative to the comb centre frequency, wherein the second dispersive wave frequency is shifted by a second dispersive wave detuning relative to the comb centre frequency,

wherein the method further comprises a step of generating a second dispersive wave in the nonlinear medium at the second dispersive wave frequency, wherein the generation of the second dispersive wave is induced by the cascaded comb light due to a second integer multiple of the auxiliary pump detuning lying within a second spectral range of the second dispersive wave detuning, wherein the second spectral range is centred at the second dispersive wave detuning and has a width equal to the width of the first spectral range,

wherein the step of outputting the cascaded comb light and the first dispersive wave is a step of outputting the cascaded comb light, the first dispersive wave, and the second dispersive wave from the nonlinear medium to thereby provide the supercontinuum light.

12. A supercontinuum light source (14) comprising:

a frequency comb light source (15) configured to provide frequency comb pump light (1) having a comb centre frequency and a peak power of at most 30 Watt;

an auxiliary light source (16) configured to provide auxiliary pump light (2) having an auxiliary centre frequency which is spectrally detuned with respect to the comb centre frequency by an auxiliary pump detuning;

a nonlinear medium (6), wherein the frequency comb light source and the auxiliary light source are optically coupled to the nonlinear medium, wherein the frequency comb pump light is associated with a phase matching criterion for dispersive wave generation in the nonlinear medium at a dispersive wave frequency shifted by a dispersive wave detuning relative to the comb centre frequency,

wherein the nonlinear medium is configured to spectrally translate the frequency comb pump light via a cascaded four-wave mixing process induced by the auxiliary pump light to thereby generate cascaded comb light, wherein the cascaded comb light is configured to induce generation of a dispersive wave in the nonlinear medium at the dispersive wave frequency due to an integer multiple of the auxiliary pump detuning lying within a spectral range of the dispersive wave detuning, wherein the spectral range is centred at the dispersive wave detuning and has a width of at most half of the auxiliary pump detuning,

wherein the nonlinear medium is configured to output the cascaded comb light and the dispersive wave to provide supercontinuum light (13).

13. The supercontinuum light source according to claim 12, wherein the frequency comb light source comprises a primary continuous wave light source and a nonlinear resonator medium, such as a nonlinear micro-ring resonator or a Fabry-Perot resonator, which is pumped by the primary continuous wave light source to establish the frequency comb pump light.

14. The supercontinuum light source according to any of claims 12-13, wherein the frequency comb light source is integrated on a chip.

15. The supercontinuum light source according to any of claims 12-14, wherein an electrical power consumption of the frequency comb light source is at most 8.0 W, for example at most 5.0 W, such as at most 3.0 W.

16. The supercontinuum light source according to any of claims 12-15, wherein the frequency comb light source and the auxiliary light source are serially coupled to the nonlinear medium such that the frequency comb pump light passes through the auxiliary light source prior to entering the nonlinear medium.

17. The supercontinuum light source according to claim 16, wherein the auxiliary light source comprises two mirrors which are arranged to define a laser cavity of the auxiliary light source, wherein a respective transmission coefficient for each of said two mirrors is greater for light at the comb centre frequency than for light at the auxiliary centre frequency.

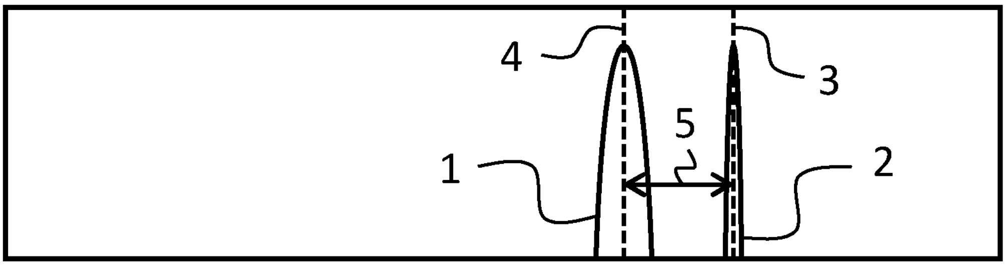

Fig. 1a

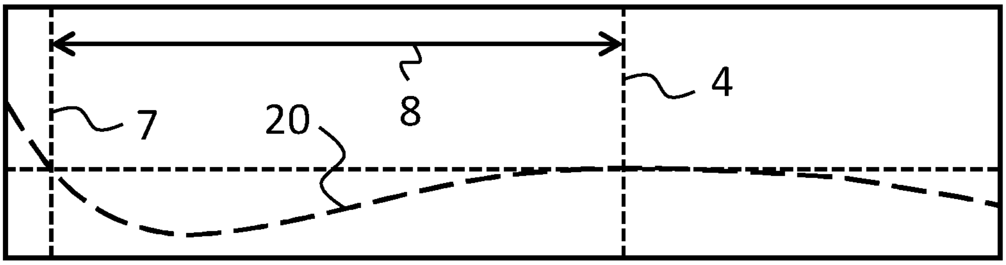

Fig. 1b

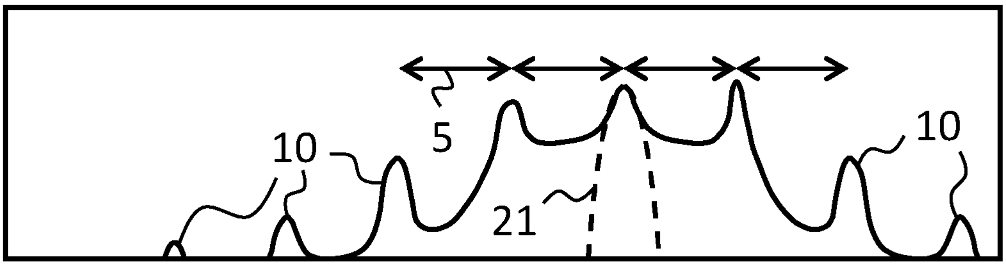

Fig. 1c

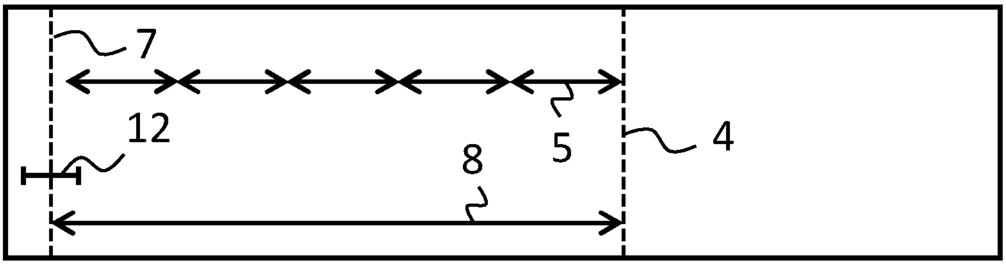

Fig. 1d

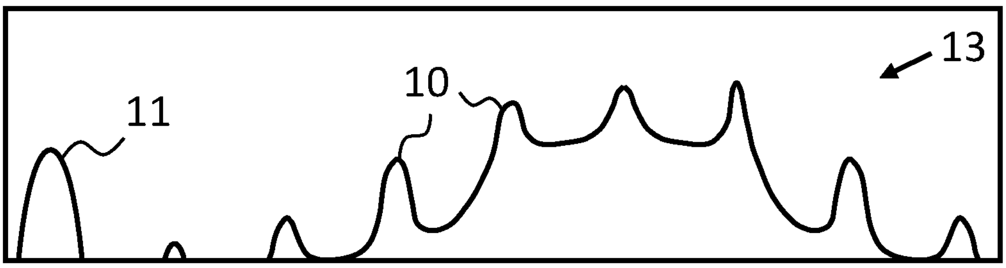

Fig. 1e

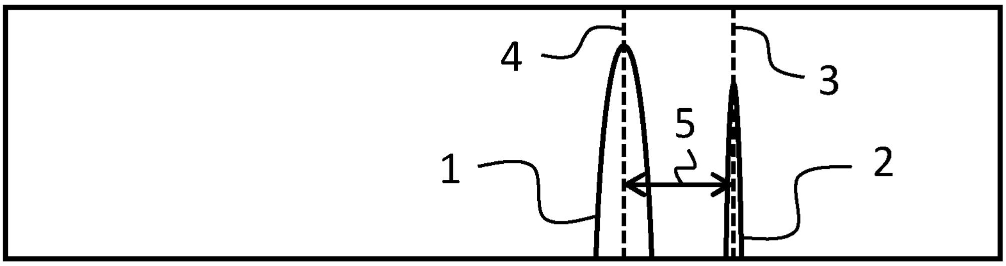

Fig. 2a

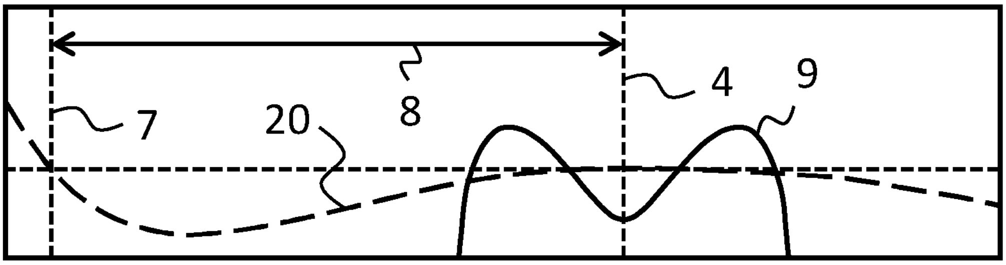

Fig. 2b

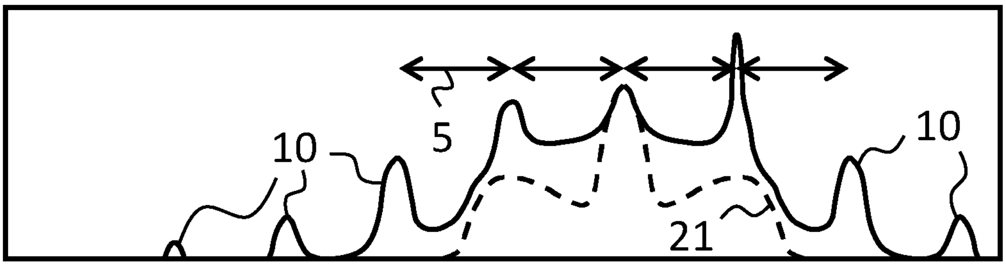

Fig. 2c

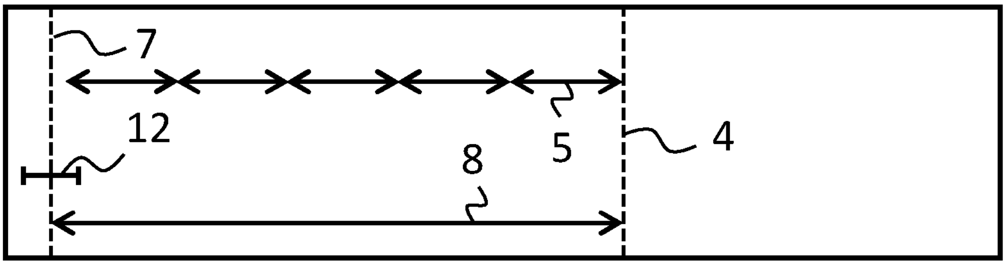

Fig. 2d

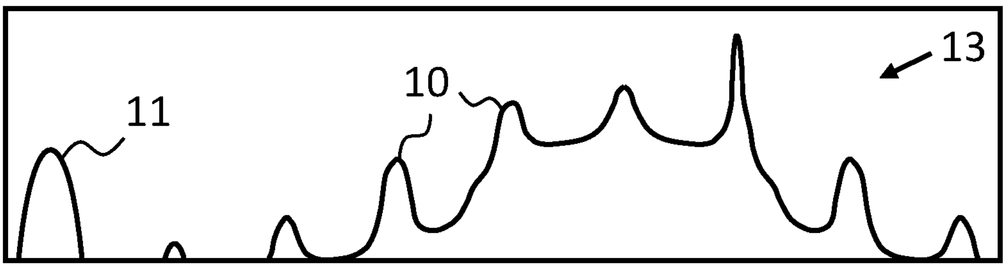

Fig. 2e

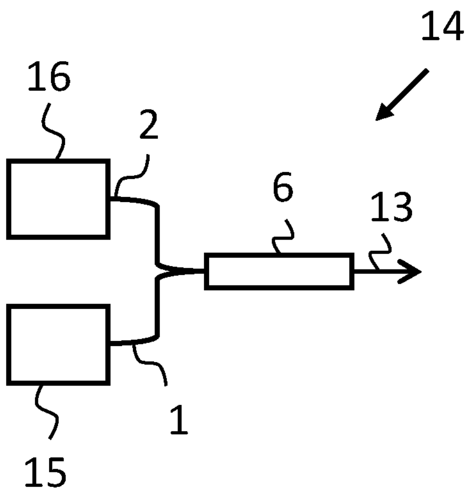

Fig. 3a

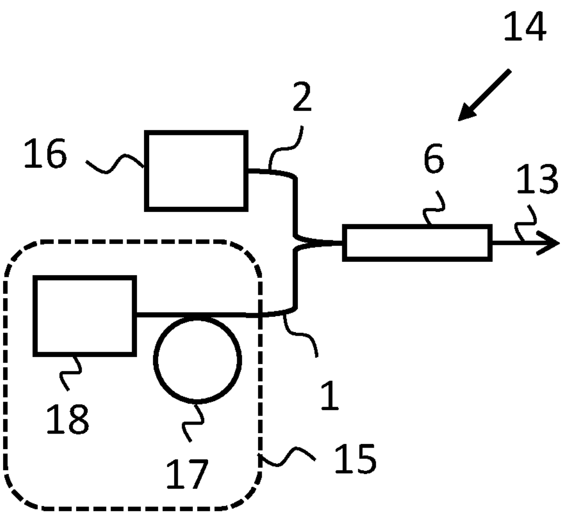

Fig. 3b

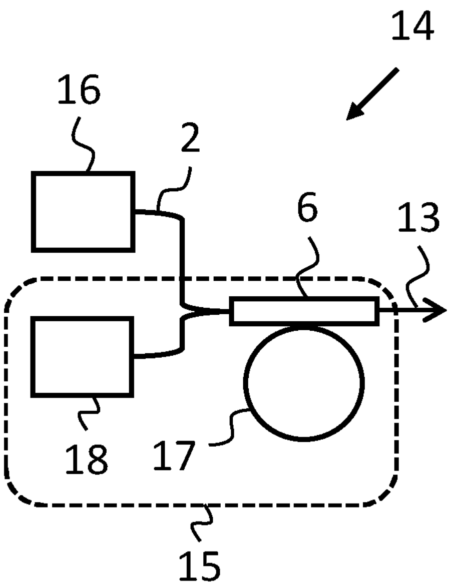

Fig. 3c

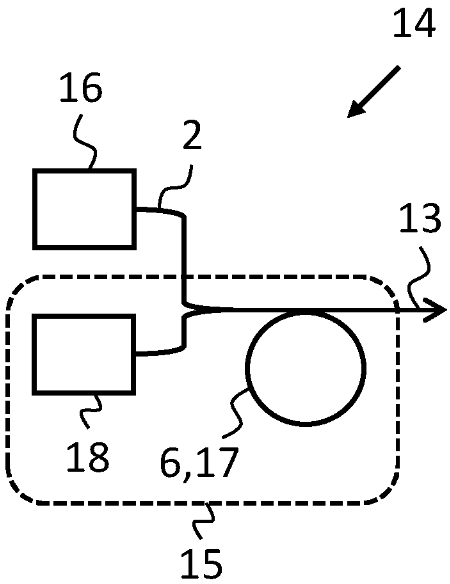

Fig. 3d

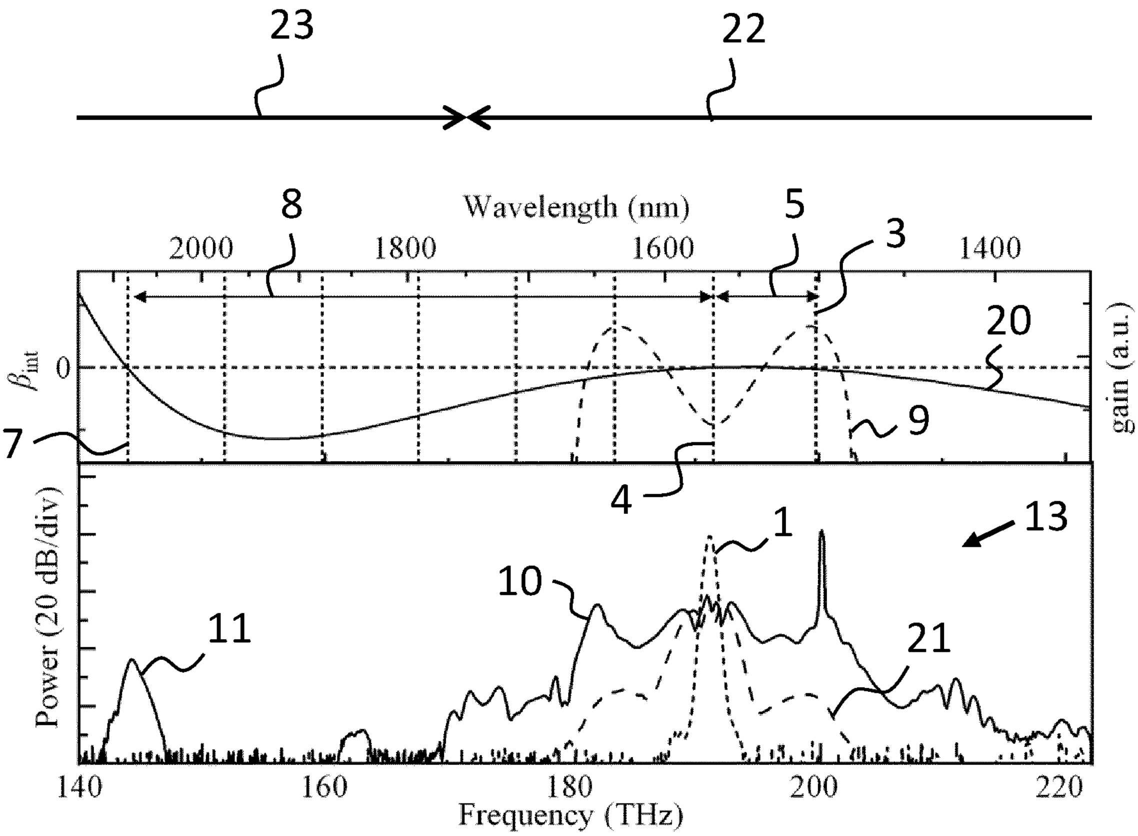
23
22
Wavelength (nm)
8
5
3
2000
1800
1600
1400
β_{int}
0
20
gain (a.u.)
7
9
4
1
13
10
11
21
Power (20 dB/div)
140
160
180
200
220
Frequency (THz)

Fig. 4

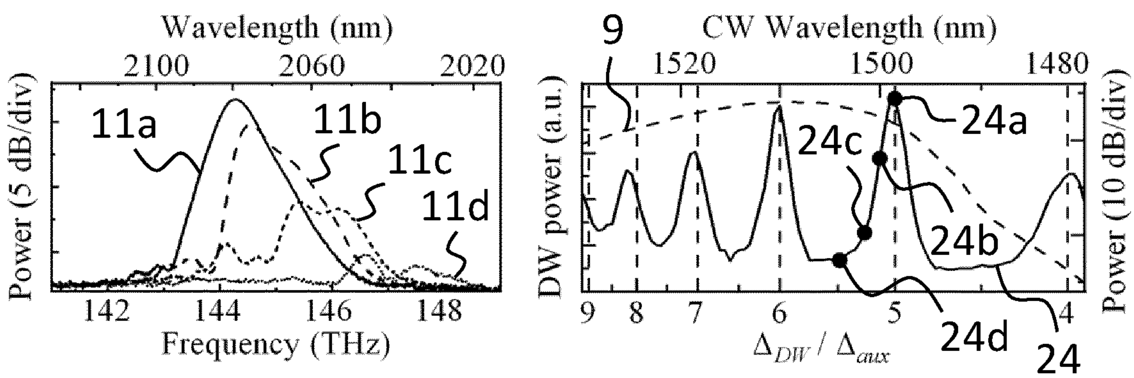
Wavelength (nm)
2100
2060
2020
11a
11b
11c
11d
Power (5 dB/div)
142
144
146
148
Frequency (THz)
9
CW Wavelength (nm)
1520
1500
1480
24a
24c
24b
24d
24
DW power (a.u.)
Power (10 dB/div)
9
8
7
6
5
4
$\Delta_{DW} / \Delta_{aux}$

Fig. 5

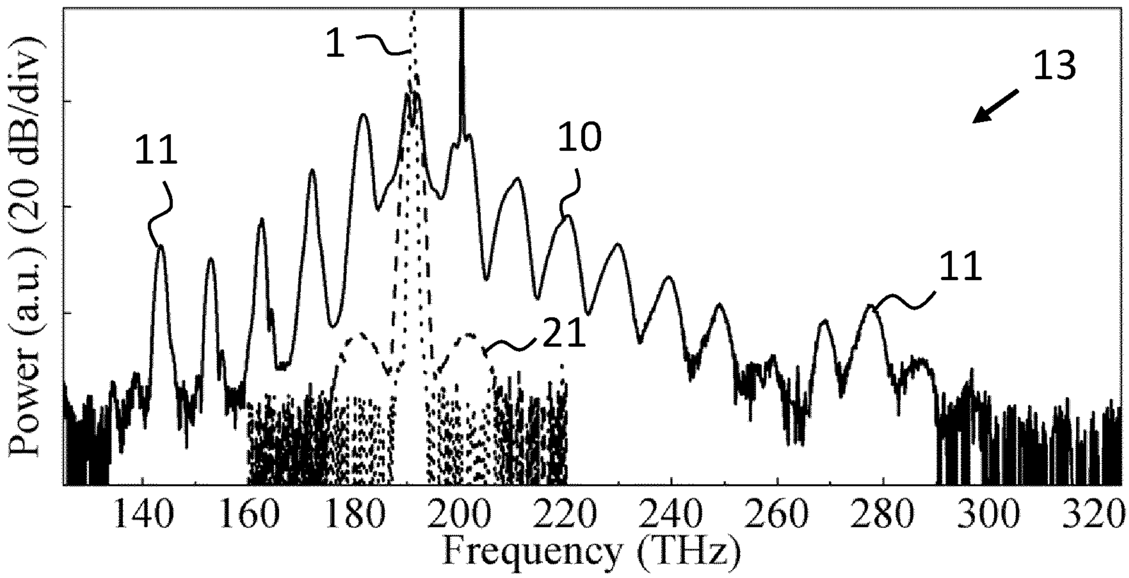
Power (a.u.) (20 dB/div)
Frequency (THz)
140
160
180
200
220
240
260
280
300
320
1
11
10
11
13
21

Fig. 6

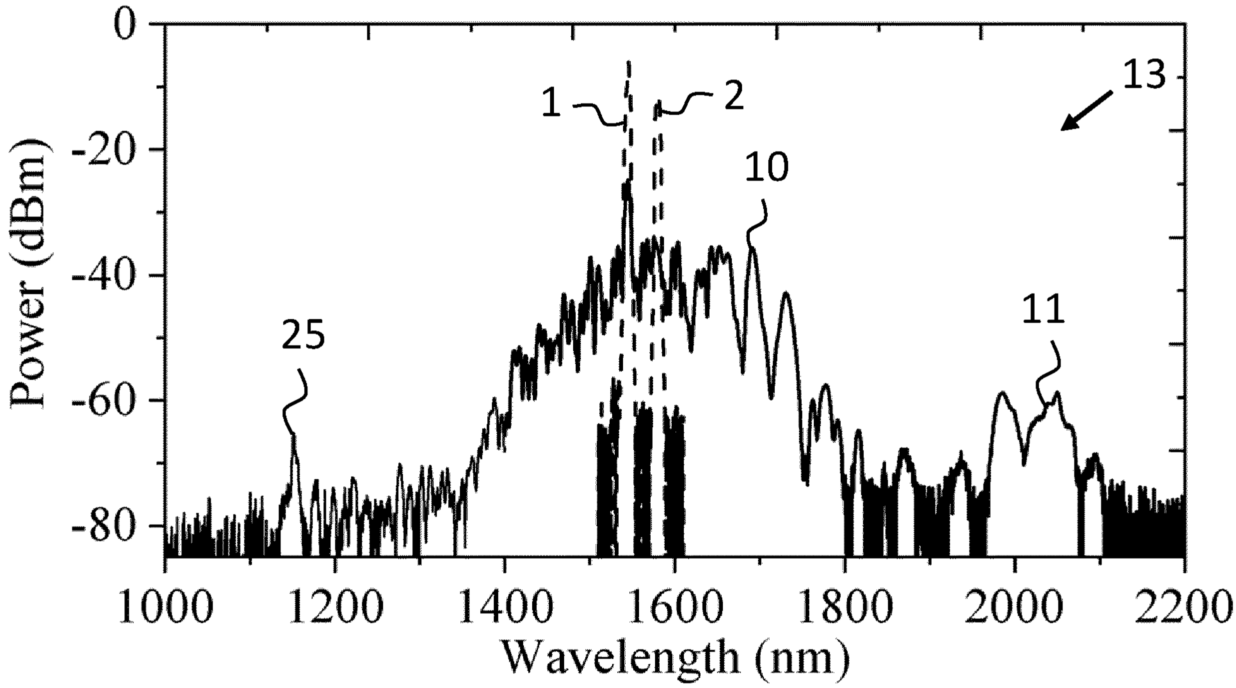
Power (dBm)
Wavelength (nm)
0
-20
-40
-60
-80
1000
1200
1400
1600
1800
2000
2200
1
2
13
10
25
11

Fig. 7

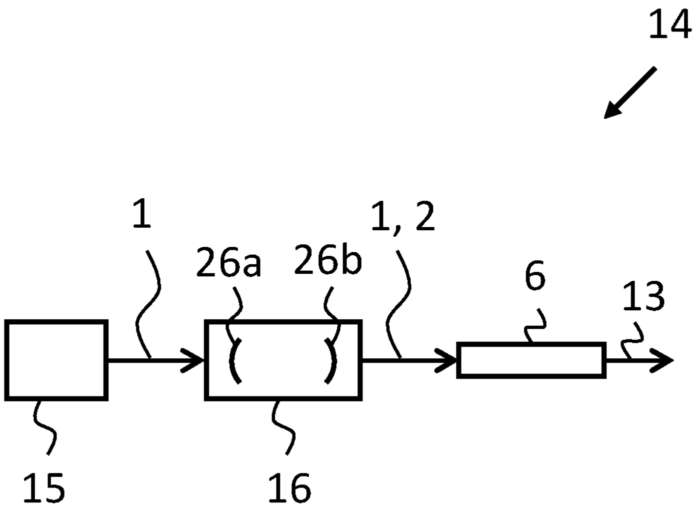

Fig. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/069084

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02F1/35
ADD. G02F1/39

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)
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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GREGORY MOILLE ET AL: "Ultra-Broadband Kerr Microcomb Through Soliton Spectral Translation", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 7 September 2021 (2021-09-07), XP091044286, the whole document -----	1-17
X	GREGORY MOILLE ET AL: "Ultra-Broadband Soliton Microcomb Through Synthetic Dispersion", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 30 January 2021 (2021-01-30), XP081871214, the whole document -----	1,12

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

* Special categories of cited documents :

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"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
12 September 2024	20/09/2024

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
Topak, Eray

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