(19) LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG
Ministère de l'Économie

(11) N° de publication : **LU101629**

(12) **BREVET D'INVENTION** **B1**

(21) N° de dépôt: LU101629

(22) Date de dépôt: 30/01/2020

(51) Int. Cl.:
H01S 3/00, H01S 3/067, H01S 3/11

(30) Priorité:

(43) Date de mise à disposition du public: 30/07/2021

(47) Date de délivrance: 30/07/2021

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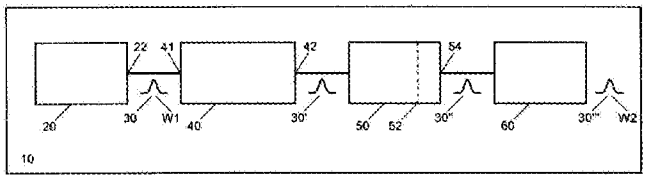
(54) **A method and system for generation of optical pulses of light.**

(57) A laser system for the generation of ultrabroadband optical pulses of light including an oscillator emitting low power and negatively chirped optical pulses with a spectral bandwidth W1, a connecting segment with positive group velocity dispersion (b2), an optical amplifier for amplifying the optical light pulses and a negative group velocity dispersion segment for compensating phase contributions of the propagation process. The negative chirp of the output pulses from the oscillator will be reduced by propagating through the connecting segment. During the propagation from the output of the oscillator to the end of the optical amplifier, the chirp of the light pulses will change once from negative to positive chirp. Depending on the fiber length and peak power within the amplifier the optical bandwidth will increase due to self-phase modulation to a bandwidth W2 > W1. By using the correct lengths of the individual segments, the amplified light pulses can be temporally compressed close to the Fourier limit by the negative dispersion segment behind the optical amplifier.



Title: A method and system for generation of optical pulses of light. LU101629

Cross-Reference to Related Application

[0001] None

Field of the invention

[0002] The invention relates to a method and system for generating optical pulses of light with a spectral bandwidth much larger than the normal gain bandwidth of a typical rare earth doped laser medium or laser active crystal. Shorter optical pulses can be generated compared to a conventional laser system by compressing these generated ultrabroadband optical pulses.

Background to the invention

[0003] Today ultrashort optical pulses of laser light with pulse durations less than a picosecond are widely used for many applications. Examples include the use in processing of micromaterials and nanomaterials, medical applications, like ophthalmology or nanosurgery, as well as in scientific applications or biomedical applications, like multiphoton microscopy. One of the well-known limitations of using these optical pulses is the so-called heat affected zone (HAZ). The heat affected zone is due to a thermal heating of the environment about a sample or a heating of living cells in biomedical applications. This can lead to thermal damage of the sample or the living cells.

[0004] The heat affected zone or thermal damage in general can be reduced by reducing the illumination time of the sample by the optical pulse. If the duration of the optical pulse (i.e. illumination time) is shorter than a relaxation time of heat to the surrounding environment, then more precise results can be obtained. This can significantly improve the accuracy of the material processing or the excitation of individual cells, for example.

[0005] There is therefore clearly a need for shorter optical pulses.

[0006] In general, the generation of ultrashort optical light pulses is based on an interaction of optical pulses with linear effects and nonlinear effects in materials. The linear effects are due to material dispersion effects and have a temporal impact on the optical pulses. For example, the group velocity dispersion (GVD; (b_2 in $ps^2/(nm*m)$) affects the duration of the optical pulse travelling through the material and thus has an effect on the temporal profile of the optical pulse. The GVD is mathematically the derivation of the inverse group velocity with respect to the angular frequency. Normal dispersion or positive group velocity dispersion ($ß_2>0$) in the material causes the optical pulses to diverge in time. In this case, red spectral components of

the optical pulse move faster than blue spectral components of the optical pulse and lead to a temporal stretched optical pulse. If anomalous or negative group velocity dispersion ($ß_2<0$) is present, then the red spectral components move slower than the blue spectral components.

[0007] On a temporal axis, the term "chirp" describes which ones of the spectral components propagates at the front of the optical pulse. A positive chirp in this case means that the red spectral components propagate in front of the blue spectral components. Similarly, a negative chirp describes that the blue spectral components propagate in front of the red spectral components. If the chirp is zero, then all of the spectral components arrive at the same time.

[0008] The larger the spectral bandwidth of the optical pulse, the more the effects of higher order material dispersion have to be taken into account. These higher order effects are mathematically a derivation of the GVD. For example, third order dispersion (TOD) will lead to an asymmetry of the temporal shape of the optical pulses.

[0009] On the other hand, nonlinear effects in the material and therefore intensity depending effects only affecting the spectral domain of the optical pulses. For example, self-phase modulation (SPM) is an effect due to a varying refractive index in the material due to the optical Kerr effect. The SPM leads to the generation of new spectral components if the optical pulse is positively chirped, and positive group velocity dispersion is present. Conversely, the SPM can destroy spectral components if the optical pulse is negatively chirped and positive group velocity dispersion is present.

[0010] Higher order nonlinear effects can also occur in the material depending on the peak power of the optical pulses.

[0011] The most common approach to generate intense ultrashort optical pulses is based on the "Chirped pulse amplification (CPA)" method (described by D. Strickland, G. Mourou, "Compression of amplified chirped optical pulses" Opt. Commun. 56, 219, 1985). The basic idea described in the paper is to stretch the optical pulse in time generated from an oscillator by a positive dispersive segment and subsequently amplify the optical light pulse in an optical amplifier. Typical stretching factors are >> 100. Finally, the amplified optical light pulses will be recompressed in time in a negative group velocity dispersive segment. This is a so-called linear amplification, as the optical pulses are stretched in time avoiding nonlinear effects during propagation. This also means that no new spectral components can be generated by SPM. Therefore, the optical bandwidth of the optical pulses remains at the best the same after amplification. Typically, the spectral bandwidth of the optical pulse decreases due to gain narrowing effects during amplification. Thus, it is not possible to generate shorter pulse durations than would be possible with the oscillator itself.

[0012] To generate new spectral components, a nonlinear process like the afore-mentioned self-phase modulation is necessary. Therefore, a new approach must be chosen compared to the prior art CPA method.

[0013] There are different approaches to generate very short pulse durations in the range of a few femtoseconds to a few ten femtoseconds. For example, after optical amplification it is possible to use nonlinear effects for propagation through a segment with positive group velocity dispersion. This is described, for example, as the multi pass concept in Optics Lett., **43**, pp. 5877-5880 (2018) or are gas filled hollow core fibers (for example Opt. Lett. **40**, 1238-1241 (2015)). For this purpose, however, a very high pulse peak power must already be available in order to generate a significant spectral broadening. Furthermore, the additional phase of the broadened optical pulses must be compressed again in a further segment of negative group velocity dispersion.

[0014] Another approach is described for example in US Patent Nr. 9,362,702 B2 (Delague et al, assigned to Amplitude Systèmes). A segment with negative group velocity dispersion is used after an oscillator prior to amplification of the optical pulses. Typically grating compressors, prism compressors or other segments with negative group velocity dispersion are suitable for this compression. In this '702 patent, the positive chirp of the optical pulses from the oscillator will be reduced within the segment of negative group velocity dispersion. Furthermore, a negative chirp can be achieved by this method set out in US'702. This leads to a change in the sign of the chirp during the propagation within the segment of negative group velocity dispersion. By amplifying and due to nonlinear effects within the positive group velocity dispersion amplifier, the negative chirped optical pulses from the segment of negative group velocity dispersion will change the chirp sign again to a positive value. This two times change of the chirp sign makes it necessary to time-compress the amplified optical light pulses after amplification with a further negative group velocity dispersion segment.

[0015] In another US Patent No 5,513,194 A (Tamura et al, assigned to MIT), negatively chirped optical pulses from a so-called Stretched Pulse Oscillator are disclosed. Due to the evolution of the optical light pulse inside a "stretched pulse laser" the chirp changes its sign twice during one roundtrip.

[0016] Using the laser system of this document, the stretched pulse oscillator can be connected directly to the amplifier via the optical fiber with positive group velocity dispersion leading to an alignment free setup. This eliminates the need for a segment with negative group velocity dispersion before amplification, which is typically a free space and bulky grating, prism or GRISM compressor.

[0017] This leads to a cost effective, robust, and very simple setup. In this case the sign of the chirp changes only once between the output of the oscillator and the end of the amplifier. LU101629

Summary of the Invention

[0018] This document describes a laser system which comprises an oscillator producing a negatively chirped optical pulse having a first spectral width W1, an amplifier for receiving the optical pulse and amplifying the optical pulse of light to produce an optical light pulse having a second spectral width W2, the second spectral width being greater than the first spectral width, and a connecting segment connected directly between the oscillator and the amplifier, wherein the connecting segment has a positive group velocity dispersion.

[0019] In one aspect, the laser system further comprises a second segment of positive group velocity dispersion after the optical amplifier.

[0020] In another aspect, the laser system further comprises a negative group velocity dispersion segment connected to an output of the amplifier and which is adapted to compensate thephase of the optical pulse.

[0021] The laser system can be implemented as a solid-state system (i.e. integrated on a chip) or as a fiber-based system. In the latter case, the amplifier is a fiber amplifier. It is also possible to use a combination of a solid-state system and a fiber-based system.

[0022] The spectral width of the optical pulse decreases from an input of the connecting segment within the amplifier to a minimum in the amplifier and then increases to a larger amount at an output of the amplifier.

[0023] The connecting segment in the laser system can be a waveguide and this can be implemented on a chip in a solid-state system, as a length of fiber in a fiber-based system or as a positive group velocity dispersion material.

[0024] The laser system may further comprise at least one optical isolator or a component which suppresses an optical signal propagating towards the oscillator, could be one of a free space or fiber coupled. This one optical isolator or a component can be located in the laser system after the oscillator or within the connecting segment. At least a pre-amplifier or an attenuator can also be incorporated within the connecting segment.

[0025] The laser system creates in effect a virtual nonlinear optical bandpass filter through the interaction of the chirp of the pulses, the dispersive effects and nonlinear effects occurred within the amplifier

[0026] The laser system includes optionally at least one optical pulse picker to reduce the repetition rate of the optical pulses or adding a pulse on demand functionality to the laser system.

[0027] The oscillator comprises a negative group velocity dispersion segment and a positive group velocity dispersion segment arranged in a way that the overall net dispersion of the cavity is less than $0.1ps^2$ ($b_2<0.1\ ps^2$).

[0028] The oscillator and the amplifier comprise a laser active medium. The laser active medium is selected from, for example, but not limited to the group of rare earth dopants comprising Yb, Nd, Tm, or Er. It should be noted that the materials need not be identical in both the oscillator and the amplifier.

[0029] In one aspect of the laser system, the oscillator comprises a linear cavity with an absorber at one end and a grating compressor at the other end.

[0030] The amplifier can be pumped by at least a single mode diode laser or a multi-mode diode laser.

[0031] The fiber sections of the oscillator and the amplifier comprise, but not limited to, single clad fibers, double clad fibers or photonic crystal fibers, also including rod-type fibers.

Brief description of the drawings

[0032] Fig. 1 shows a schematic general diagram of a first aspect of the invention

[0033] Fig. 2 shows a schematic diagram a further aspect of the invention including a second segment with positive group velocity dispersion after the amplifier.

[0034] Fig. 3 shows a third aspect of the invention containing at least an optical isolator.

[0035] Fig. 4 shows a fourth aspect of the invention including at least an optical isolator and an attenuator.

[0036] Fig. 5 shows a fifth aspect of the invention including at least an optical isolator, an attenuator or an optical preamplifier.

[0037] Fig. 6 shows a sixth aspect of the invention including at least an optical isolator, an attenuator or an optical preamplifier and a pulse picker.

[0038] Fig. 7 shows schematic diagram of the pulse evolution inside a Stretched Pulse Laser system.

[0039] Fig. 8 shows a schematic embodiment of the Stretched Pulse oscillator configured in a linear cavity.

[0040] Fig. 9 shows a schematic embodiment of the Stretched Pulse oscillator configured in a ring cavity.

[0041] Fig. 10 shows a schematic embodiment of the Stretched Pulse oscillator configured in a sigma arm cavity.

[0042] Fig. 11 shows a schematic embodiment of the Stretched Pulse oscillator configured in a linear cavity with a dispersion compensation by using a chirped fiber Bragg grating.

[0043] Fig. 12 shows a schematic embodiment of the Stretched Pulse oscillator configured in a linear cavity with a fiber-based dispersion compensation by using photonic crystal fibers or hollow core fibers.

[0044] Fig. 13 shows a time compressed optical pulse after the compressor of the system having a pulse duration below 50 fs.

[0045] Fig. 14 shows the corresponding optical spectrum of the optical pulses at the output of the laser system having a spectral bandwidth W2.

[0046] Fig. 15 shows a typical optical spectrum of the optical pulses at the output of an oscillator having a spectral bandwidth W1.

Detailed description of the invention

[0047] Fig. 1 shows an aspect of a laser system 10 for generating ultrabroadband optical pulses of light is based on a stretched pulse oscillator 20 emitting a plurality of optical pulses 30. An input 41 of a positive group velocity dispersion connecting segment 40 is connected to the output 22 of the stretched pulse oscillator 20. An optical amplifier 50 having positive group velocity dispersion is connected to an output 42 of the connecting segment 40 and amplifies the optical pulses 30′ and is followed by a negative group velocity dispersion segment 60 (also called compressor). The negative group velocity dispersion segment 60 is used to compensate the phase contributions of linear and nonlinear effects that have occurred during propagation through the connecting segment 40 and the optical amplifier 50 including the phase of output pulses 30 of the oscillator 20. In some aspects of the invention, the laser system 10 does not include the negative dispersion segment 60. In another aspect, the negative group velocity dispersion segment 60 could be replaced or complemented by an optical filter to reduce the width of the output spectrum and thus decrease the amount of amplitude noise in the output spectrum by removing light from the edges of the spectrum.

[0048] In a first aspect of the invention, the stretched pulse oscillator 20 emits negatively chirped optical pulses as the plurality of optical pulses 30. The connecting segment 40 has a positive group velocity dispersion, unlike the connecting segments 40 known in the art. The

input 41 of the connecting segment 40 is connected to the output 22 of the stretched pulse oscillator 20 by a splice of optical fibers or a free space coupling.

[0049] At the input 41 of the connecting segment 40, the optical pulses 30 have a larger negative chirp compared to the optical pulses 30' at the output 42 of the connecting segment 40. In other words, the negative chirp of the optical pulses 30' and therefore the pulse duration of the optical pulses 30' at the output 42 is reduced during propagating in a positive group velocity dispersion fiber which forms the connecting segment 40. Depending on the optical power of the optical pulses 30, nonlinear effects can occur in the connecting segment 40, which lead to a reduced spectral bandwidth of the optical pulses 30' at the output of the connecting segment 40.

[0050] It will be appreciated that it may be necessary to implement a short connecting segment 40′ with positive group velocity dispersion after the amplifier 50, shown in Fig. 2. For example, there is a need to remove the pump light (from the optical pump) from the amplifier 50 and this is done by using a cladding light stripper to remove residual pump light from the amplifier. In this case the positive chirp of the optical pulse 30'' slightly increases at the output of the short connecting segment 40'.

[0051] At least one optical isolator 43 or 43′ can be implemented in the connecting segment(s) 40 or 40' after the stretched pulse oscillator 20 and is shown schematically in Fig. 3. The position of the optical isolator 43 (43′) could be at the input 41 (41′) of the connecting segment 40 (40′), within the connecting segment 40 (40′), or at the output 42 (42′) of the connecting segment 40 (40′).

[0052] After the connecting segment 40, the negative chirped optical pulses 30' propagate into the optical amplifier 50 which is used to increase the power level of the optical pulses 30'. Due to the nonlinear effects of the afore-mentioned SPM inside the optical amplifier 50 the chirp of the optical pulses 30′ is substantially reduced to zero at a "chirp-free" point 52 within the optical amplifier 50, as shown in Figs. 1-6, as the optical amplifier 50 has a positive group velocity dispersion. At the output 54 of the optical amplifier 50, the optical pulses 30′′ are positively chirped and the chirp can be compensated by a negative group velocity dispersion segment 60 connected to the output 54 of the optical amplifier 50 to a nearly Fourier limited pulse duration 30′′′′. In Fig. 13 an example of a measured FROG trace of the compressed optical light pulse is displayed. The corresponding optical spectrum is show in Fig. 14. The negative group velocity dispersion segment 60 can be, but are not limited to, a grating compressor, a prism compressor, a GRISM compressor, chirped mirrors, or a hollow core fiber segment. For an ideal compression, a pulse shaper can also be integrated.

[0053] The dispersion of the negative group velocity dispersion segment 60 is estimated to be smaller than three times the sum of the group velocity dispersion of the connecting segment 40 and the amplifier 50, i.e. $(3*(|b_{40}+b_{50}|)>|b_{60}|)$ in which b_{40} represents the group velocity dispersion of the connecting segment, b_{50} represents the group velocity dispersion of the optical amplifier 50 and b_{60} represents the group velocity dispersion of the negative group velocity dispersion segment 60. The value of the dispersion is not, however limiting of the invention.

[0054] In a further aspect of the laser pulse system 10, the power level inside the connecting segment 40 or 40' can be adjusted by at least an attenuator 44 (or 44′) (shown in Figs. 4-6) or a preamplifier 45 (shown in Figs. 5 and 6), or a combination of both (as in Figs. 5 and 6) for controlling the non-linear effects in the connecting segment 40 and the amplifier 50. The position of the attenuators 44 or 44' or the preamplifier 45 could be at the input 41/41' of the connecting segments 40 and 40', within the connecting segments 40 and 40', or at the output 42 or 42′ of the connecting segments 40 or 40'. A higher power output can be achieved by increasing the diameter of the mode field in the optical fiber.

[0055] The preamplifier could be one of a fiber-based preamplifier, a (fiber-coupled) semiconductor optical amplifier or a solid state amplifier

[0056] An optical isolator 43 can be used after the preamplifier 45 (as shown in Fig. 5 and 6).

[0057] By combining a negative chirp of the optical pulses 30 and a positive group velocity dispersion in the connecting segment 40, the spectral bandwidth of the optical pulses 30' at the output 42 can be reduced, thus creating a "nonlinear band pass filter" at a "chirp free point" 52 inside the optical amplifier 50, as shown in Figs. 1-6. It would be possible to couple the optical pulse 30 out near to this point to provide an optical pulse 30 with a very narrow spectrum.

[0058] A sixth aspect of the laser system 10 is shown in Fig. 6 and enables the integration of an optical pulse picker 46 to reduce the repetition rate of the stretched pulse oscillator 20 to increase the pulse energy after the optical amplifier 50. A second pulse picker 46′ can be added in front of the compressor 60 within the connecting segment 40' to generate a pulse on demand functionality.

[0059] The stretched pulse oscillator 20, the connecting segment 40 and the optical amplifier 50 are connected with fiber splices. Nevertheless, transitions between any of the stretched pulse oscillator 20, the connecting segment(s) 40 and 40' and the optical amplifier 50 can also be implemented by free space coupling. Therefore, free space isolators 43 and 43' pulse pickers 46 and 46', attenuators 44 and 44' or preamplifiers 45 can also be used.

[0060] The ultrabroadband generation of the optical pulses is based on the interaction of linear effects and nonlinear effects within the amplifier and so the maximum energy, or the spectral

bandwidth, can be controlled by choosing different mode field diameters during the propagation.

[0061] The optical amplifier 50 can be made in a non-limiting example of a fiber amplifier doped with Ytterbium. It is thought that the optical amplifier 50 can be adapted to all lasing materials, such as but not limited to, Nd, Tm, Er, Er-Yb.

[0062] The principle is not limited to fiber laser technology and in different aspects, the principle can also be adapted to solid state amplifiers, including for example thin disk amplifiers, slab amplifiers, crystal-based amplifiers, rod amplifiers or other types. For a more general approach the negative chirped optical pulses 30 from the stretched pulse oscillator 20 or a soliton oscillator have to propagate through a medium of positive group velocity dispersion segment, which is not limited to optical fibers, but can also be waveguides (included those implemented as micro optics on a wafer) or materials with positive group velocity dispersion.

[0063] The use of a positive group velocity dispersion for the connecting segment 40 requires the production of the negatively chirped optical pulses 30 in the stretched pulse oscillator 20. This is illustrated in Fig. 8 and can be achieved by using two different dispersion segments inside an oscillator cavity. The oscillator cavity comprises a positive group velocity dispersion segment 21 and a negative group velocity dispersion segment 23. The overall net group velocity dispersion (GVD) has to be less than 0.1 ps^2 (b_{2net} <0.1 ps^2). In this case the optical pulses 30 undergo a change of the chirp sign within the two dispersion segments, i.e. a negative dispersion segment 21 and a positive dispersion segment 23. Fig. 7 shows the evolution of the chirp (normalized y-axis in arbitrary units (arb.unit)) of an optical light pulse inside a stretched pulse cavity during propagation (x-axis in meter). Furthermore, the corresponding group velocity dispersion segments (normalized y-axis in arbitrary unit (arb. unit)) are displayed. During the propagation, the pulse has to be free of chirp twice per round trip, as can be seen in Fig. 7. According to Fig. 7 the chirp free points are located at the ends of the linear cavity. Depending in the overall net dispersion, the position of the chirp free pulses can be changed.

[0064] Starting from a chirp free point 31 within the positive group velocity dispersion segment 21 a positive chirp is generated by propagating through the positive dispersion segment 21 forming one part of the stretched pulse oscillator 20. This positive chirp will be reduced within the negative group velocity dispersion segment 23 forming a second part of the oscillator cavity 20, leading to a chirp free optical pulse at a position 31´ within the segment 23, and changing the sign of the chirp afterwards. This negative chirp increases up to the end of the negative group velocity dispersion segment 23. Finally, the negative chirp will be reduced by entering the positive group velocity dispersion segment 21 and after one roundtrip will reach the chirp

free starting point 31 again. For the apparatus of this document the optical output pulses of the oscillator 30 have to have a negative chirp at the output coupler 27 of the oscillator 20.

[0065] One example of the stretched pulse oscillator 20 is shown in Fig. 8. The stretched pulse oscillator 20 comprises an optical pump 28 for generating the pump light for the laser active fiber segment 20'. The optical pump 28 is coupled to the cavity by using a pump coupler 29. The negative dispersion segment 23 is implemented by a grating compressor at one end of a linear cavity.

[0066] The optical fiber part forms the positive dispersion segment 21. The stretched pulse oscillator 20 is mode-locked by using a saturable absorber mirror 24 at the other end of the linear optical cavity. An output coupler 27 is placed behind the negative dispersion segment 23 (in propagation direction).

[0067] Other different aspects of the laser optical cavity of the stretched pulse oscillator 20 are shown in Figs. 9 and 10. The optical cavity can also be implemented as a ring cavity when using an optical isolator 25 and a saturable absorber 24' or as a sigma cavity when using a circulator 26 to implement a saturable absorber mirror 24 in the optical cavity.

[0068] To further reduce free space parts inside the linear cavity oscillator the negative dispersion segment 23 can be implemented using a chirped fiber Bragg grating 23' (Fig. 11) or a negative dispersion photonic crystal fiber combined with a fiber based mirror (23'') can be used (Fig.12) instead of a grating compressor.

[0069] In one aspect all of the optical fibers used are polarization maintaining fibers to achieve an environmental stable system. In general, however, the laser pulse system of this disclosure is not limited to polarization maintaining fibers. Non-polarization maintaining fibers could also be used. Furthermore, the laser pulse system 10 is not limited to single clad fibers. In addition, other types of fibers as double clad fibers can be used. Depending on the type of fibers single or multimode laser diodes can be used for pumping. Mode-locking can also be achieved by using any kind of saturable absorber (24') or virtual saturable absorber as for example nonlinear pulse evolution.

[0070] As already noted above, the laser pulse system 10 of this document can be implemented in a bulk solid, as long as there is a provision for management of the dispersion of the optical pulse. This will require at least one positive dispersion element and one negative dispersion segment.

Reference Numerals

10	Laser system
20	Stretched pulse oscillator
20'	Laser active fiber segment
21	Positive dispersion segment
22	Output
23	Negative dispersion segment
24	Absorber mirror
25	Optical isolator
26	Circulator
27	Output coupler
28	Optical pump
29	Pump coupler
30	Optical pulse
31	Chirp-free point
40	Connecting segment
41	Input
42	Output
43	Isolator
44	Attenuator
45	Preamplifier
46	Optical pulse picker
50	Optical amplifier
52	Chirp-free point
54	Output
60	Negative dispersion segment

Claims

1. A laser system (10) comprising:
   - an oscillator (20) producing a plurality of negatively chirped optical pulses (30) having a first spectral width W1;
   - an amplifier (50) for receiving the plurality of optical pulses (30) and amplifying the optical pulse of light to produce an optical light pulse having a second spectral width W2, the second spectral width being greater than the first spectral width W1; and
   - a connecting segment (40) connected directly between the oscillator (20) and the amplifier (50), wherein the connecting segment has a positive group velocity dispersion (b_2).

2. The laser system (10) of claim 1, further comprising a second segment of positive group velocity dispersion segment (b_2) (40′) connected to an output of the amplifier (50).

3. The laser system (10) of claim 1 or 2, further comprising a negative group velocity dispersion segment (b_2) (60) connected to an output of the amplifier (50) and being adapted to compensate the phase of the optical pulse (30).

4. The laser system (10) of any of the above claims, wherein the amplifier (50) is one of a fiber amplifier, a rod-type amplifier, a slab amplifier, thin disk amplifier or a solid-state amplifier.

5. The laser system (10) of any of the above claims, wherein the spectral width of the optical pulse (30) decreases from an input (42) of the connecting segment (40) through the amplifier (50) to a minimum in the amplifier (50) and then increases to a larger amount at an output (54) of the amplifier (50).

6. The laser system (10) of any of the above claims, further comprising at least one optical isolator located after the oscillator (20).

7. The laser system (10) of claim 6, wherein the optical isolator is one of a free space or fiber coupled.

8. The laser system (10) of any of the above claims, further including at least one of a pre-amplifier or an attenuator within the connecting segment.

9. The laser system (10) of claim 8, wherein the preamplifier is one of a fiber-based amplifier, a semiconductor optical amplifier or a solid-state amplifier.

10. The laser system (10) of any of the above claims, further including at least an optical pulse picker to adjust the temporal separation between the optical pulses.

11. The laser system (10) of any of the above claims creates a virtual nonlinear optical bandpass filter through the interaction of dispersive effects and nonlinear effects during the propagation of the optical pulses.

12. The laser system (10) of any of the above claims, wherein the oscillator (20) comprises at least a segment (23) of positive group velocity dispersion (b_2) and a segment (21) of negative group velocity dispersion (b_2).

13. The laser system (10) of any of the above claims, wherein the laser active medium of at least one of the oscillator (20) or the amplifier (50) is selected from the group of dopants comprising Yb, Nd, Tm, or Er.

14. The laser system (10) of any of the above claims, wherein the oscillator (20) comprises a linear cavity with a saturable absorber at one end and a grating compressor at the other end.

15. The laser system (10) of any of the above claims, wherein the amplifier (50) is pumped by at least one of a single mode diode laser or multi-mode laser .

16. The laser system (10) of any of the above claims, wherein the oscillator 20 and amplifier (50) is one of a single clad fiber or a double clad fiber or a combination of these.

Revendications

1. Système laser (10) comprenant :

- un oscillateur (20) produisant une pluralité d'impulsions optiques à modulation de fréquence négative (30) ayant une première largeur spectrale W1 ;
- un amplificateur (50) pour recevoir la pluralité d'impulsions optiques (30) et amplifier l'impulsion optique de lumière pour produire une impulsion optique de lumière ayant une deuxième largeur spectrale W2, la deuxième largeur spectrale étant supérieure à la première largeur spectrale W1 ; et
- un segment de connexion (40) connecté directement entre l'oscillateur (20) et l'amplificateur (50), dans lequel le segment de connexion a une dispersion de vitesse de groupe positive (b2).

2. Système laser (10) selon la revendication 1, comprenant en outre un deuxième segment de dispersion de vitesse de groupe positive (b2) (40') connecté à une sortie de l'amplificateur (50).

3. Système laser (10) selon la revendication 1 ou 2, comprenant en outre un segment de dispersion de vitesse de groupe négatif (b2) (60) connecté à une sortie de l'amplificateur (50) et étant adapté pour compenser la phase de l'impulsion optique (30).

4. Système laser (10) selon l'une quelconque des revendications précédentes, dans lequel l'amplificateur (50) est un amplificateur à fibre, un amplificateur à tige, un amplificateur à plaque, un amplificateur à disque mince ou un amplificateur à semi-conducteurs.

5. Système laser (10) selon l'une quelconque des revendications précédentes, dans lequel la largeur spectrale de l'impulsion optique (30) diminue à partir d'une entrée (42) du segment de connexion (40) à travers l'amplificateur (50) jusqu'à un minimum dans l'amplificateur (50) et augmente ensuite jusqu'à une quantité plus importante à une sortie (54) de l'amplificateur (50).

6. Système laser (10) selon l'une quelconque des revendications précédentes, comprenant en outre au moins un isolateur optique situé après l'oscillateur (20).

7. Système laser (10) selon la revendication 6, dans lequel l'isolateur optique est un isolateur à couplage par espace libre ou par fibre.

8. Système laser (10) selon l'une quelconque des revendications précédentes, comprenant en outre au moins un parmi un préamplificateur ou un atténuateur dans le segment de connexion.

9. Système laser (10) selon la revendication 8, dans lequel le préamplificateur est un amplificateur à base de fibre, un amplificateur optique à semi-conducteur ou un amplificateur à semi-conducteur.

10. Système laser (10) selon l'une quelconque des revendications précédentes, comprenant en outre au moins un capteur d'impulsions optiques pour ajuster la séparation temporelle entre les impulsions optiques.

11. Système laser (10) selon l'une quelconque des revendications précédentes, qui crée un filtre passe-bande optique non linéaire virtuel par l'interaction d'effets dispersifs et d'effets non linéaires pendant la propagation des impulsions optiques.

12. Système laser (10) selon l'une quelconque des revendications précédentes, dans lequel l'oscillateur (20) comprend au moins un segment (23) de dispersion de vitesse de groupe positive (b2) et un segment (21) de dispersion de vitesse de groupe négative (b2).

13. Système laser (10) selon l'une quelconque des revendications précédentes, dans lequel le milieu actif de laser d'au moins l'un de l'oscillateur (20) ou de l'amplificateur (50) est choisi dans le groupe des dopants comprenant Yb, Nd, Tm ou Er.

14. Système laser (10) selon l'une quelconque des revendications précédentes, dans lequel l'oscillateur (20) comprend une cavité linéaire avec un absorbeur saturable à une extrémité et un compresseur à réseau à l'autre extrémité.

15. Système laser (10) selon l'une quelconque des revendications précédentes, dans lequel l'amplificateur (50) est pompé par au moins un laser à diode monomode ou un laser multi-mode.

16. Système laser (10) selon l'une quelconque des revendications précédentes, dans lequel l'oscillateur (20) et l'amplificateur (50) sont constitués d'une fibre à simple gaine ou d'une fibre à double gaine ou d'une combinaison de celles-ci.

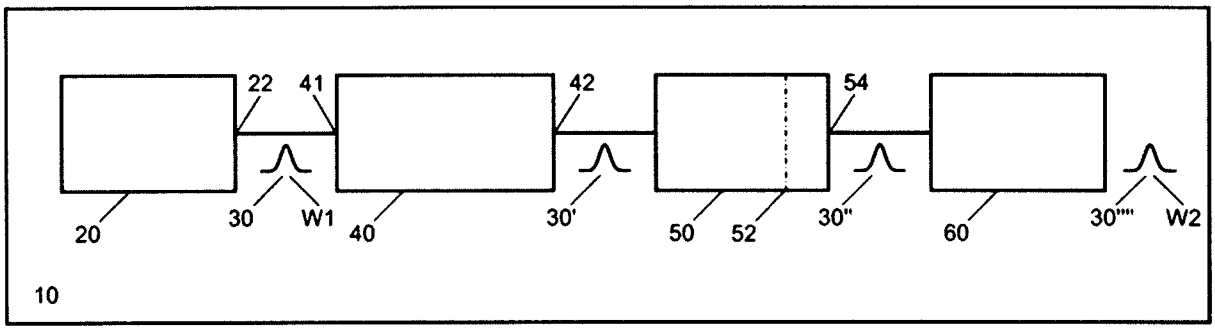


Fig. 1

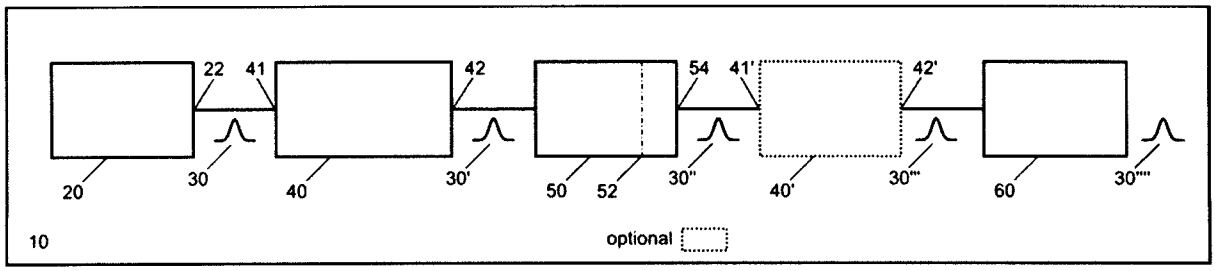


Fig. 2

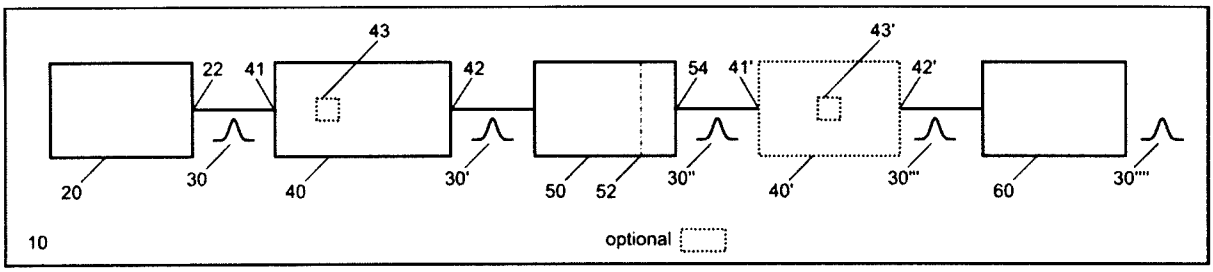


Fig. 3

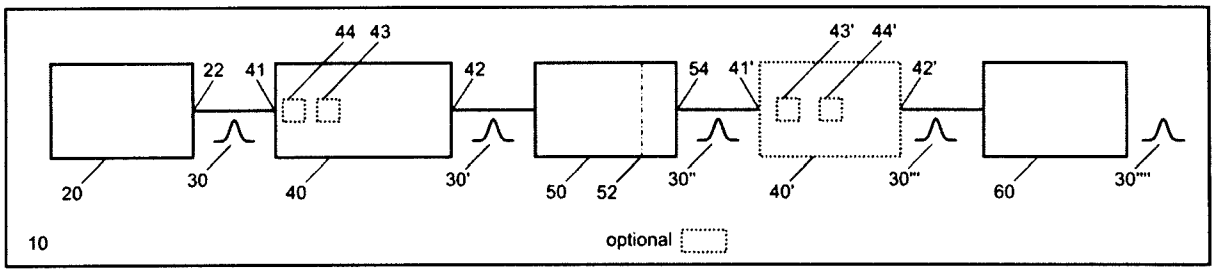


Fig. 4

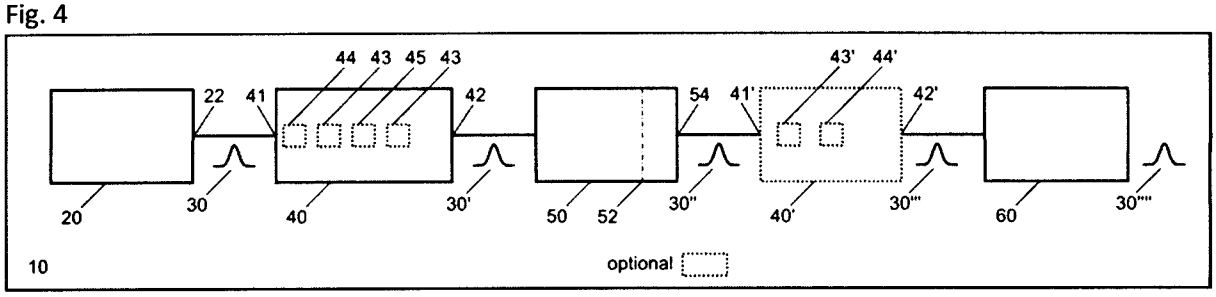


Fig.5

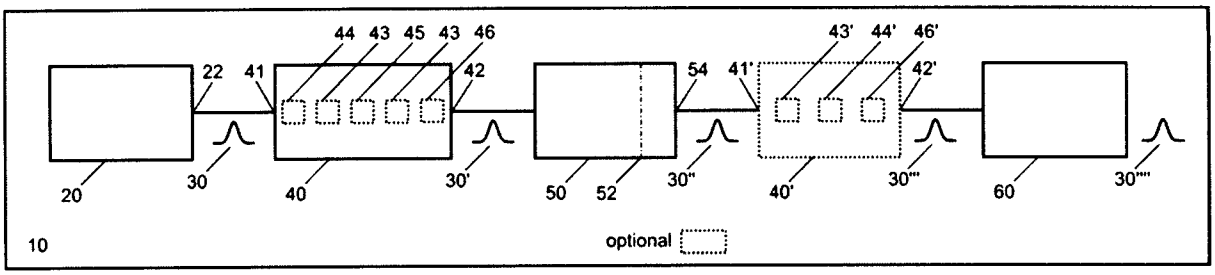


Fig. 6

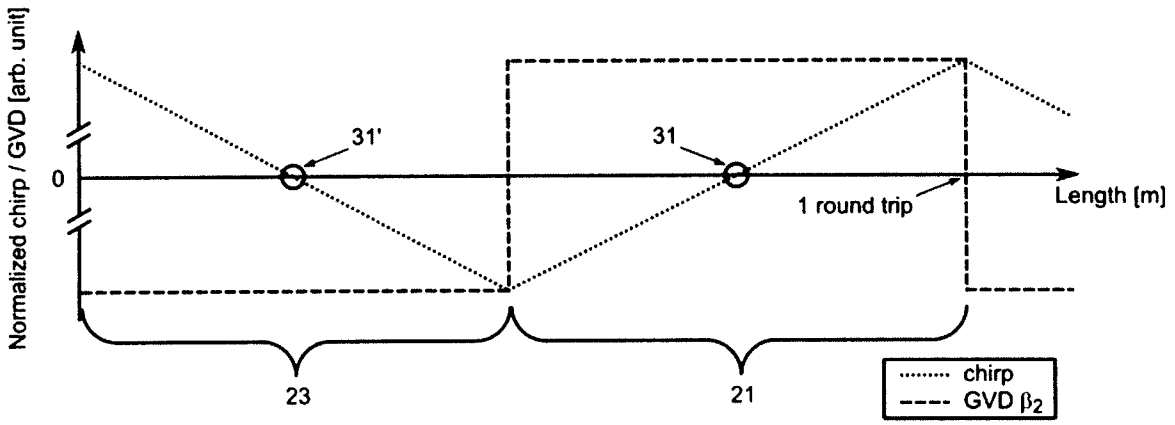


Fig. 7

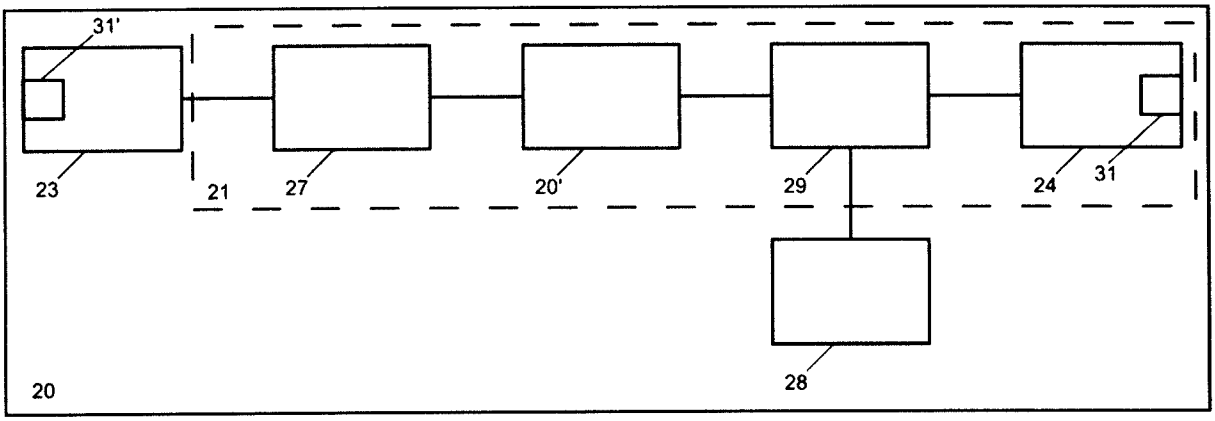


Fig.8

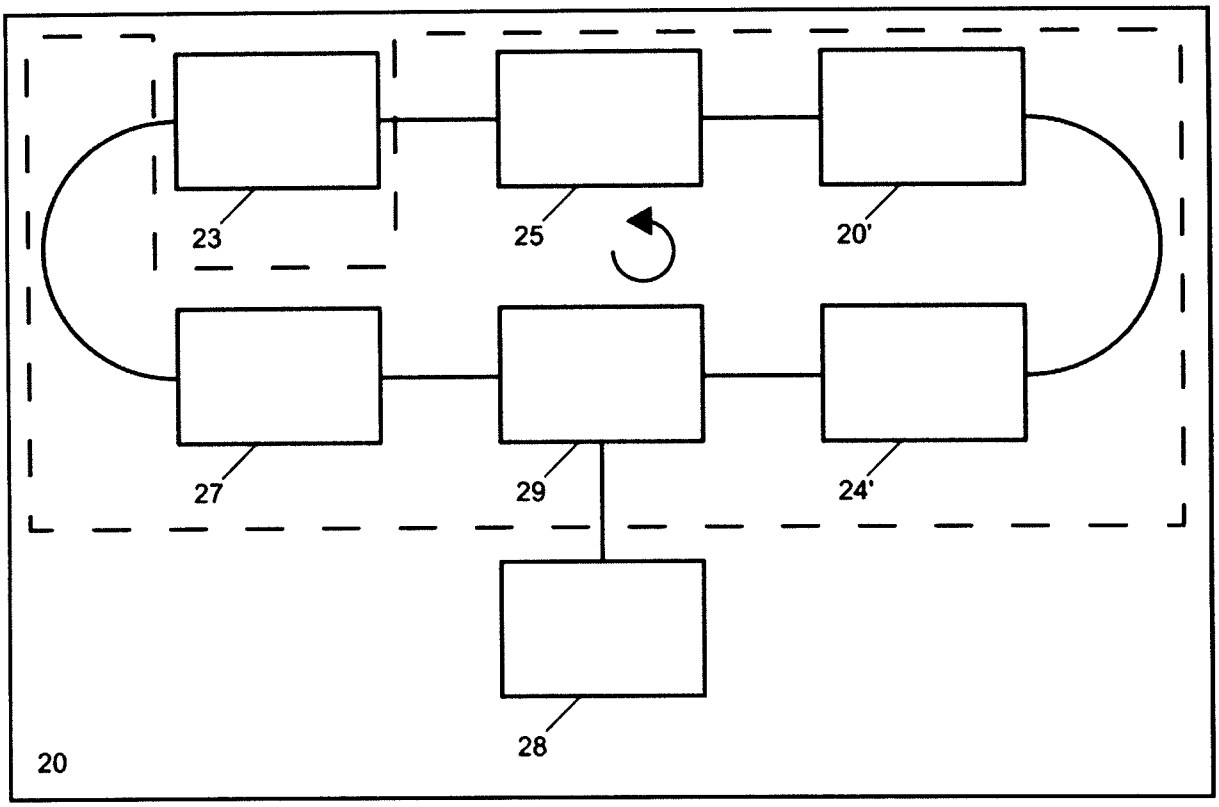


Fig. 9

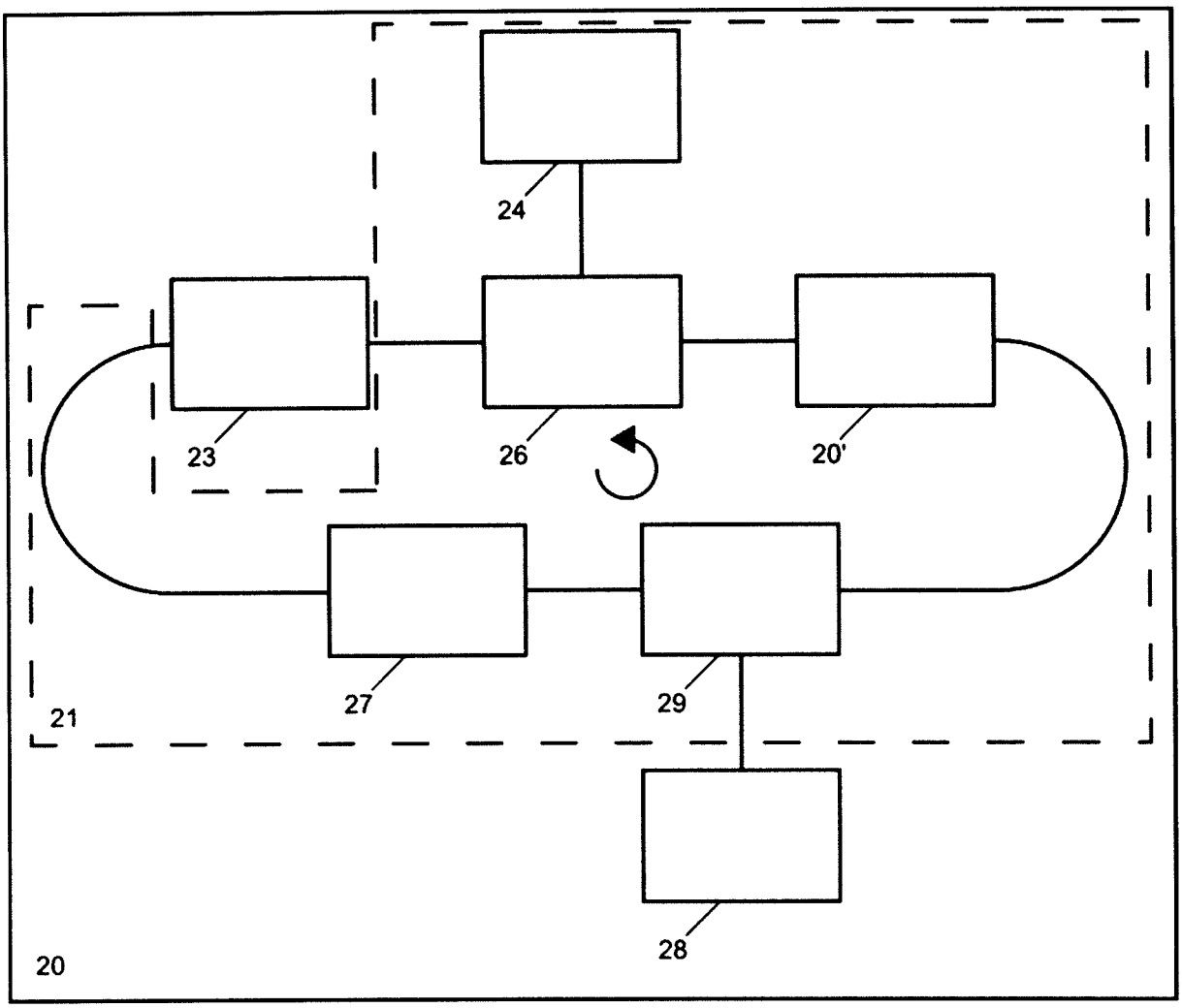


Fig. 10

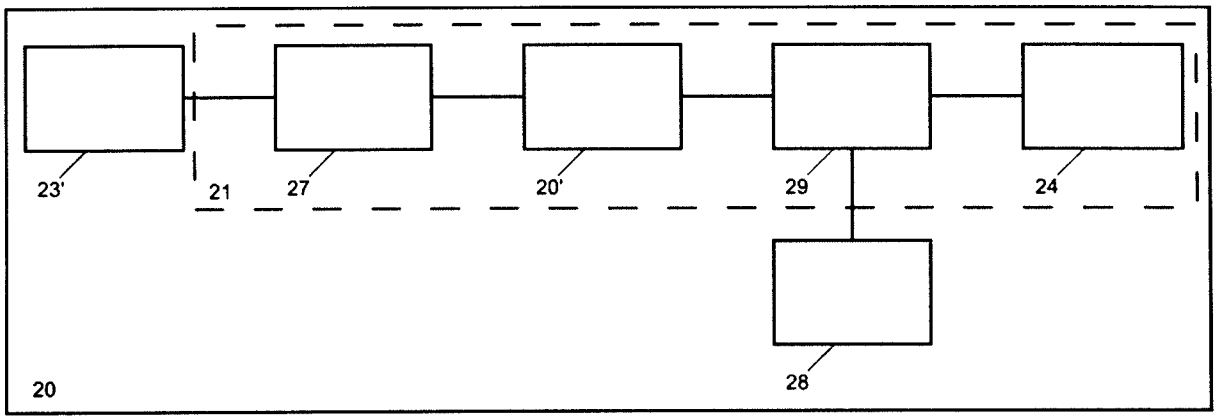


Fig. 11

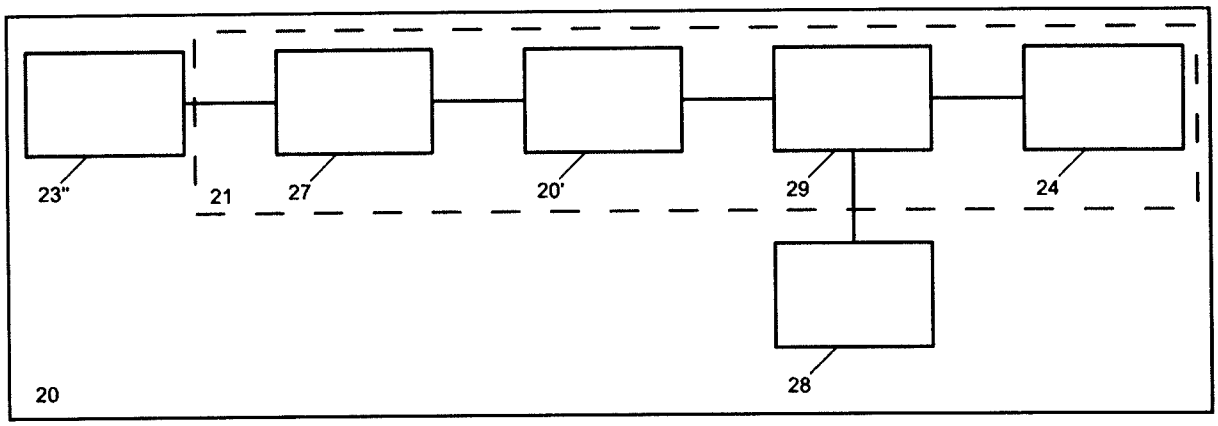
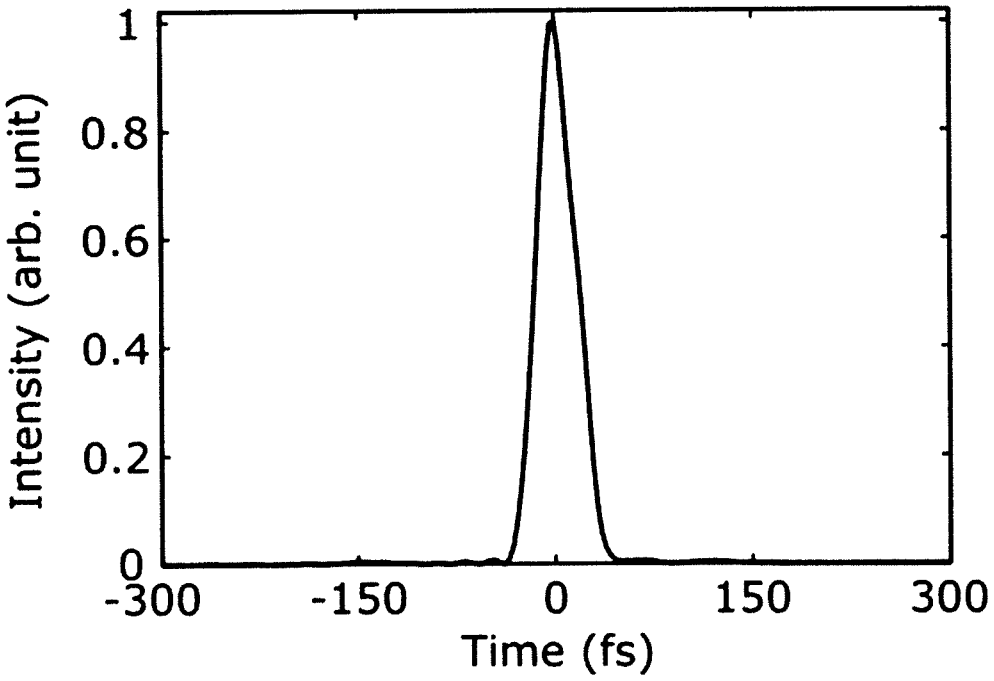

23"
21
27
20'
29
24
28
20

Fig. 12


Intensity (arb. unit)
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0.8
0.6
0.4
0.2
0
-300
-150
0
150
300
Time (fs)

Fig. 13

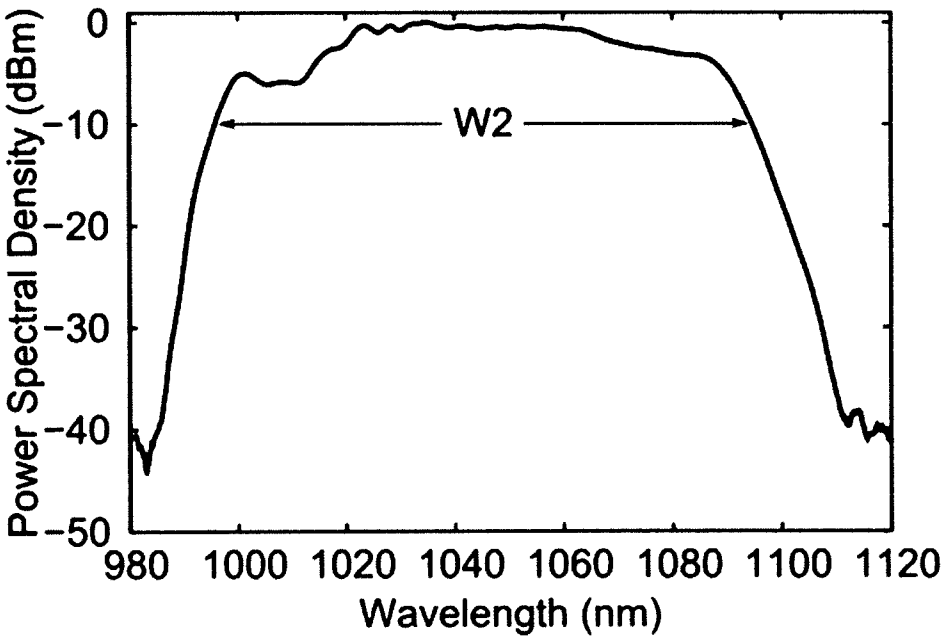
Power Spectral Density (dBm)
0
−10
−20
−30
−40
−50
W2
980
1000
1020
1040
1060
1080
1100
1120
Wavelength (nm)

Fig. 14

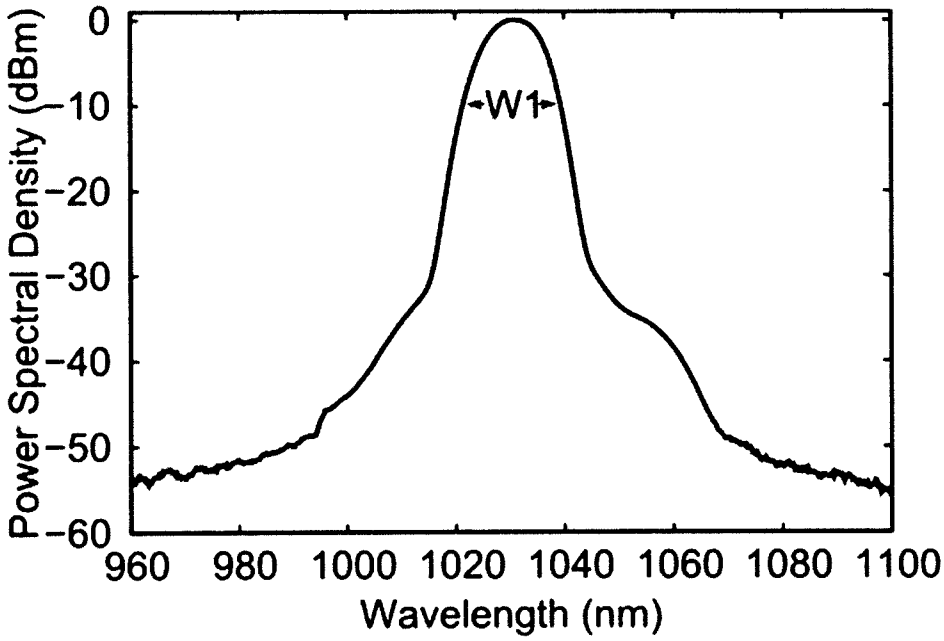
Power Spectral Density (dBm)
0
−10
−20
−30
−40
−50
−60
W1
960
980
1000
1020
1040
1060
1080
1100
Wavelength (nm)

Fig. 15