Figure 6
as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(H))
— of inventorship (Rule 4.17(iv))
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HOMOGENIZATION OF SPECTRA OF SHORT LASER PULSES BY PASSIVE NON-LINEAR ATTENUATION

FIELD OF INVENTION

This invention relates to the field of laser technology. More specifically it relates to optical pulse shaping and bandwidth extension in pulsed laser systems.

BACKGROUND OF INVENTION

Modern laser technologies allow generation of short (less than a millisecond) and ultrashort (less than a picosecond) laser pulses. Commonly, ultrafast pulses are produced by using ultrafast mode-locked laser oscillators and temporal pulse compressors. Ultra-fast lasers include Ti:sapphire Kerr lens mode-locked lasers or rare earth metal doped lasers, often passively mode-locked with a SESAM (Semiconductor Saturable Absorber Mirror). Pulse compressors can help modify a temporal shapes of a pulse by relatively delaying some wavelength components in time, which is also understood as artificially introducing negative refraction. Although this has been shown to be an effective method for compressing pulses, it does not modify spectrum of pulses, for example of Gaussian profile, in such a way that the spectral width of the pulse may be expanded. This is important because according to Fourier optics the duration of Gaussian pulse is inversely proportional to the spectral width. Increasing the spectral width would allow a pulse to be temporally compressed beyond the extent of using a standard pulse compressor alone.

Methods and devices that propose solutions for temporal pulse shaping, particularly, for increasing a bandwidth of lasing medium-specific generation spectra and could be used as solution for bandwidth expansion are named hereafter.

The US patent US5682262 published on 28-10-1997 discloses a method and a device for shaping both the temporal and spatial profiles of an input optical pulse to generate an output optical waveform. The method includes the step of dispersing the spectral frequencies of the input pulse. These frequencies are then focused with a cylindrical lens to form a two-dimensional optical field. The field is imaged on a mask featuring a two-dimensional array of pixels. The amplitudes, phases, or phases and amplitudes of the two-dimensional optical field are then filtered with the mask. The
filtered spectral frequencies are then recombined to form the collective temporal profile of the output waveform. The two-dimensional optical field is then imaged in a sample plane to form the spatially coherent regions.

The US patent US4655547 published on 07-04-1987 discloses a method for controlling, manipulating and tailoring the shape of input optical pulses to produce substantially transform-limited output pulses which can be shorter than the input pulses. In embodiments of a first aspect of this invention an input optical pulse is chirped, the chirped pulse is then passed through an optical component that spatially disperses the frequency components of the chirped pulse and partially compensates the chirp, the spatially dispersed frequency components are then passed through spatial amplitude and/or phase masks that control and/or adjust the amplitude and/or phase of the frequency components, and, finally, the masked components are passed through the first or a second optical component that returns the masked, spatially dispersed frequency components substantially to the spatial distribution of the input pulse while substantially completing the compensation of the chirp to form an output pulse.

The US patent US5132824 published on 21-07-1992 discloses a liquid-crystal phase modulator array, comprising a planar electrode on one glass support and an array of finger electrodes on the other glass support with a nematic liquid filling the gap between the two supports. The alignment layer between the finger electrodes and the liquid crystal is rubbed to have an alignment direction extending along the finger electrodes and perpendicular to the gap between them. The alignment layer between the planar electrode and the liquid crystal is rubbed in the anti-parallel direction. Voltages are selectively applied to different ones of the finger electrodes to provide a phase modulator array for light passing through the assembly. The alignment direction of the invention eliminates ragged edges adjacent the edges of the finger electrodes arising from an instability. Thereby, the finger electrodes can be made much narrower, and more pixels can be included in the array. The phase modulator of the invention can be advantageously used in a Fourier optical pulse shaper.

The disclosed prior art solutions are based on the spatial separation of the pulse frequency components on spatially separate optical paths and introducing predetermined optical losses (or phase shifts) on those individual paths. It is sought to introduce optical losses to the peak components of generated spectra, such that the sidebands of such spectra would experience higher amplification, thus the overall bandwidth would be expanded. Prior art solutions feature a common drawback, since
the exact optical paths, representing spectral modes, which have to be suppressed must be known prior to distributing optical loses in space. In practice, no laser systems can be considered as mechanically stable and misalignments of the optical components always appears over time and especially on change of temperature of mechanical and optical components. Mechanical instabilities will offset the optical paths for individual pulse frequency components, decreasing the amount of control over the process of pulse shaping.

Moreover, the suggested use of pixel arrays is also disadvantageous because of losses and distortions that can be introduced during propagation through the array, since individual frequency components are distorted by the finite edges of the individual pixels, i.e. the spectra becomes less homogenous.

In addition, the use of materials such as liquid crystals imposes limitations on fluence, since liquid crystals possess a relatively low optical damage threshold compared to many other optical materials.

SUMMARY

In order to eliminate the drawbacks indicated above, this invention provides a simple and effective method for broadening the spectral width of an input optical pulse or a pulse circulating in an optical cavity. The method is based on suppression of highest intensity spectral components.

The effect of spectra broadening is achieved by spatial decomposition of an electromagnetic pulse into spatially separated frequency components and the introduction of intensity dependent losses after which the spatially displaced frequency components are reassembled on the same optical path or reflected back into an optical cavity. As a result, sidebands of the emission spectra are amplified more evenly comparing to the peaks and, in overall, the spectra becomes broader and more homogenous. The intensity dependent losses are introduced by means of one or more optical elements featuring non-linear attenuation, which is dependent on intensity of said spectral components, i.e. absorbing elements selectively absorb spectral components having highest intensity.

This solution can be used to prevent gain saturation for a single wavelength or a narrow interval of wavelengths in rare-earth metal doped lasers, and allows for the amplification of other spectral components that correspond to the lower parts of the gain profile of a gain medium used. The method could be applied to broad emission
or radiation spectra as well, such as those radiated by Tksapphire or CrLiCaF laser sources or supercontinuum light sources.

DESCRIPTION OF DRAWINGS

In order to understand the invention better, and appreciate its practical applications, the following pictures are provided and referenced hereafter. Figures are given as examples only and in no way shall limit the scope of the invention.

Figure 1. illustrates absorption and emission spectra of lasing media (Yb:CaF2, Tksapphire) commonly used in ultra-short pulse laser generation; sidebands are indicated on both sides of the emission spectra (b);

Figure 2. illustrates implementation of the invention in Q-switched lasers (a), cavity dumped lasers (b) and passively mode-locked oscillators (c); all diagrams are provided of a block-type;

Figure 3. illustrates implementation of the invention in regenerative amplifier layout;

Figure 4. illustrates implementation of the invention in single-pass optical layouts, such as spectral homogenization of an oscillator output or an output of a supercontinuum source;

Figure 5. illustrates four different examples of optical layouts of the spectral homogenization unit in a configuration, where an input pulse is not dispersed and the output beam is dispersed both spatially and temporally;

Figure 6. illustrates two different examples of optical layouts of the spectral homogenization unit in a configuration, where an input pulse is not dispersed and the output beam is dispersed temporally, but not dispersed spatially;

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

This invention provides a method and an apparatus, where spatial decomposition of laser pulses and introduction of attenuation means is used to
homogenize the effective gain profile of a laser oscillator that is used to generate laser pulses of a high spectral bandwidth. The method comprises the following steps:

I. spatial decomposition of a pulse into spatially separated independent spectral components by means of dispersive components, such as prisms or gratings;

II. optionally, focusing the spatially displaced spectral components using a cylindrical lens (14) or similar optics, whereas a line focus is created on a selectively attenuating optical medium (4);

III. intensity dependent attenuation of the individual spectral components in a passive optical medium (4) having non-linear (multi-photon) absorption;

IV. reassembly of the separated spectral components onto a single optical path by means of another configuration of dispersive components;

V. optionally, compensating a chirp induced by the dispersive optical components, used to make the decomposition and reassembly of spectral components.

The homogenizer unit (2 or 3), comprising dispersive optical components and at least a passive optical component, which is transparent in the whole or great majority of emission bandwidth, but features non-linear attenuation, can be used in various optical assemblies, where broadening of the spectral bandwidth is desired. Such optical assemblies may range from Q-switched lasers to femtosecond oscillators or regenerative amplifiers. Other applications include homogenization of spectra for supercontinuum sources, spectral filtering or similar.

A material used for selective attenuation of spatially decomposed spectral components shall feature non-linear (multi-photon) absorption or in other embodiments it may utilize other non-linear effects, including but not limited to Kerr-effect, second harmonic generation, parametric generation, multi-photon absorption, self-phase modulation. For the sake of simplicity, herein and further we will refer to this material as a selective attenuator (4).

The attenuator can be used in multiple different optical layouts including optical cavity-based or single-pass configurations. The common feature of all optical
configurations is that the selective attenuator (4) is arranged in the path of a spatially displaced spectral components so that it could induce losses for spectral components having highest gain and largest amplification. Spatial decomposition of spectral components of a pulse is achieved by placing dispersive means in the optical path, such as prisms (18), reflection gratings (19), transmission gratings (20), etc. Dispersive means can be combined with other beam shaping means, such as spherical lenses (17), cylindrical lenses (14), roof-mirrors (11) and other conventional optical components used for beam shaping and guiding. It should be apparent to a person skilled in the art that dispersive means can be selected and arranged to compensate normal or anomalous dispersion, introduce or remove a chirp. Just few examples of optical layouts used for spatial decomposition of spectral components are illustrated in Fig. 5 and Fig. 6.

In the most preferred embodiment, at the point of incidence into the selective absorber (4), spatially displaced spectral components are parallel to each other and strike the surface of the selective attenuator (4) essentially perpendicularly. Radiation experiences losses only in those areas of the selective attenuator (4), where intensity of particular spectral components is highest. The higher the intensity is, the more losses are caused by the selective attenuator (4). As a result, the spectra is homogenized and sidebands and recesses in emission bandwidth are amplified more than the emission peaks (in case of intra-cavity optical layout) or sidebands and recesses in the emission bandwidth are transmitted without significant losses as opposed to the peaks (in case of single-pass optical layout).

In the most preferred embodiment, the homogenizer unit (2 or 3) is arranged inside an optical cavity of an ultra-short pulse laser. The cavity is determined by the end mirrors (6, 7). Herein the increased bandwidth of generated radiation directly links with the duration of pulses achieved. The broader the bandwidth, the shorter pulses can be generated, even possibly leading to generation of pulses having just few optical cycles. In this embodiment the optical cavity can be arranged either as a mode-locked oscillator (Fig. 2c) using a SESAM (12) or as a regenerative amplifier (Fig. 3). In case of passive mode-locking with SESAM (12), the beam must be converted back into a beam without spatial displacement of spectral components, therefore optical layouts depicted in Fig. 6 are more suitable. However these layouts are provided as an example only and a person skilled in the art could vary these layouts or create new layouts delivering the same or similar result.

Yet in another embodiment, the homogenizer unit (2 or 3) is arranged in the cavity of a Q-switched laser (Fig. 2a) in order to increase the radiation bandwidth of
such laser. Such feature is potentially useful in applications of optical coherence tomography (white light interferometry), absorption spectroscopy or similar. In this embodiment one of the end mirrors (7) is preferably made partially transparent for pulse outcoupling.

Yet in another embodiment, the homogenizer unit (2 or 3) is arranged in the resonator of a cavity dumped lasers, including actively mode-locked lasers (Fig. 2b). In such arrangement generated pulses are outcoupled from the optical cavity by means of an electrooptical or acoustooptical switch (9). In such cavity pulses can be formed using active Q-switching (unit (8)), active or passive mode-locking or other techniques for generation of optical pulses inside a cavity.

Yet in another embodiment, the homogenizer unit (2) is arranged as a stretcher of a chirped pulse amplification (CPA) system. Fig. 4b depicts a typical block diagram of a stretcher system, where ultra-short laser pulses are emitted from a primary laser source (10), preferably a mode-locked oscillator. Further the pulses propagate below a tilted mirror (13) and enter the homogenizer unit (2). After passing the homogenizer unit (2), spatially displaced spectral components are reflected using a roof-mirror and shifted to a parallel plane. Further the pulses propagate the same optical path but opposite direction through the homogenizer unit (2), then are reflected by the tilted mirror (13) and directed towards the output of such stretcher assembly. At the output of such optical system, the pulses are chirped and suitable for amplification in a regenerative amplifier or other amplification stages.

Yet in another embodiment, the homogenizer unit (3) is arranged at the output of a supercontinuum source, as depicted in Fig. 4b.

The lasing medium used in optical cavities discussed above is preferably a medium having large sidebands or several neighboring peaks, separated by deep recesses in the spectral gain. For smooth generation of ultra-short pulses, the spectra has to be as even in gain as possible. Therefore, without using special means for homogenization of spectral bandwidth, neighboring spectral peaks of gain provide almost no advantage, for example spectral lines of Nd:YVO4 at 1064 nm and around 1080 nm. Another example - Yb:CaF2 gain medium, which has a strong peak at around 980 nm and very broad weaker emission spectra from 1000 nm to 1080 nm. By employing the technique provided by this invention, the usable spectral width could be of almost 120 nm broad instead of -20 nm, as depicted in Fig. 1a.

In the most preferred embodiment, the selective attenuator (4) is comprised of a material capable of attenuating the spectral components during a process of multi-photon, preferably two-photon absorption. This is a nonlinear process, occurring
with significant rates only at high optical intensities, because the absorption coefficient is proportional to the optical intensity. Therefore the lowest intensity spectral components would not be attenuated, whereas the high intensity spectral components would be attenuated to a great extent. The two-photon absorber can be a semiconductor material that has a larger band-gap than the energies of photons of the spatially decomposed spectral components, including but not limited to materials such as GaN and its composites. It is preferable that materials used for multi-photon absorption have a low threshold for two-photon absorption. On the other hand, non-linear absorbing material can be selected based on the intensity of radiation, which strikes the selective attenuator (4).

Yet in another embodiment, the selective attenuator (4) is a non-linear optical crystal cut in an angle as to feature phase-matching for complete or great majority of the bandwidth. More particularly it could be a crystal designed for the generation of second harmonic. The dependency of wavelength conversion efficiency on the intensity of the incident radiation is nonlinear and spectral components of the lowest intensity are attenuated the least, i.e. they are not converted to the second harmonic. The radiation converted in the said crystal can be of wavelengths that do not overlap with the spectral amplification profile of the gain medium, thus it is not reflected by the resonator mirrors (6, 7), or absorbed by an additional filter.

Yet in another embodiment, the attenuation of individual spectral components is achieved by employing the use of thermal effects, such as Kerr effect. The change of the refractive index of a material in response to an applied electric field allows to diverge the high intensity spectral components from the optical path by inducing diffraction losses.

Yet in another embodiment, the gain medium (1) is composed of several different gain media, whereas the homogenization of spectra provided by this invention would be readily used for homogenization of radiation intensity for all of the gain media used.
CLAIMS

1. Apparatus for homogenization of emission spectra of a gain medium in laser systems, comprising at least an optical arrangement for spatially dispersing spectral components, a passive selective attenuator, which is arranged in the path of a spatially displaced spectral components so that it could induce selective attenuation for spectral components having highest intensity, characterized in that said passive selective attenuator comprises material featuring non-linear optical attenuation, whereas said selective attenuator selectively attenuates those spatially displaced spectral components, having highest gain in the emission spectra of a gain medium.

2. Apparatus according to claim 1, characterized in that the selective attenuator comprises material featuring multi-photon absorption.

3. Apparatus according to claim 1, characterized in that the selective attenuator comprises material featuring Kerr-effect.

4. Apparatus according to claim 1, characterized in that the selective attenuator comprises material featuring non-linear optical frequency conversion.

5. Apparatus according to claim 1, characterized in that the selective attenuator comprises material featuring non-linear self-phase modulation.

6. Apparatus according to one of the claims 1 to 5, characterized in that the complete homogenizer unit, comprising dispersive means for spatial displacement of spectral components and the selective attenuator, is arranged for single pass configuration.

7. Apparatus according to one of the claims 1 to 5, characterized in that the complete homogenizer unit, comprising dispersive means for spatial displacement of spectral components and the selective attenuator, is arranged in an optical cavity defined by the end mirrors.
8. Apparatus according to claim 6, characterized in that the homogenizer unit is arranged at the output of a short pulse or an ultra-short pulse laser in order to homogenize the spectra thereof.

9. Apparatus according to claim 6, characterized in that the homogenizer unit is arranged at the output of a supercontinuum source in order to homogenize the spectra thereof.

10. Apparatus according to claim 7, characterized in that the homogenizer unit is arranged in the cavity of a Q-switched laser.

11. Apparatus according to claim 7, characterized in that the homogenizer unit is arranged in the cavity of a cavity dumped laser.

12. Apparatus according to claim 7, characterized in that the homogenizer unit is arranged in the cavity of a passively mode-locked laser.

13. Apparatus according to claim 7, characterized in that the homogenizer unit is arranged in the cavity of an actively mode-locked laser.

14. Apparatus according to claim 7, characterized in that the homogenizer unit is arranged in the cavity of a regenerative amplifier.

15. Apparatus according to claims 2, characterized in that the material of the selective attenuator is selected from GaN or its composites.

16. Apparatus according to claims 4, characterized in that the material of the selective attenuator is selected from non-linear crystals for second harmonic generation, whereas the effective phase-matching is at least for those spectral components, representing peaks of the gain bandwidth.

17. Apparatus according to one of the claims 1 to 16, characterized in that two or more different gain media are used in an optical cavity.
## A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S3/00
ADD. H01S3/106

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

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

HOIS

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

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

EPO-Internal, COMPENDEX, INSPEC, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

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

**X** See patent family annex.

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Date of the actual completion of the international search

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