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(54) LASER SYSTEM USING ULTRASHORT LASER PULSES

LASERSYSTEM MIT ULTRAKURZEN LASERIMPULSEN

SYSTEME LASER METTANT EN OEUVRE DES IMPULSIONS LASER ULTRACOURTES

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(56) References cited:

- **Z. ZHENG, A.M. WEINER: "Coherent control of second harmonic generation using spectrally phase coded femtosecond waveforms", CEHMICAL PHYSICS, vol. 267, no. 1-3, 1 June 2001 (2001-06-01), pages 161-171, XP002539909,**
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Description

BACKGROUND AND SUMMARY OF THE INVENTION

5 **[0001]** The present invention generally relates to a laser system and more particularly to a laser system using ultrashort laser pulses with phase modulation.

[0002] Commercially practical femtosecond lasers have been unavailable until recently. For example, lasers which can generate 10 femtosecond or less laser pulse durations have traditionally been extremely expensive, required unrealistically high electrical energy consumption (for extensive cooling, by way of example) and depended on laser dyes that had to be replenished every month thereby leading to commercial impracticality. The efficiency of sub-10 femtosecond lasers was not practical until the year 2000 because of the prior need for dyes and flash lamps instead of YAG and Ti:Sapphire crystals pumped by light or laser emitting diodes.

10 **[0003]** Ultrashort pulses are prone to suffer phase distortions as they propagate through or reflect from optics because of their broad bandwidth. There have been recent experimental attempts to shape the phase of ultrashort pulses since shaped pulses have been shown to increase the yield of certain chemical reactions and multiphoton excitation.

15 **[0004]** Conventional pulse characterization is typically done by one of the following methods. Autocorrelation is a simple traditional method that yields only the pulse duration. Furthermore, frequency resolved optical gating (hereinafter "FROG") is a known method which yields phase and amplitude following iterative analysis of the time-frequency data. Interferometric methods such as DOSPM and spectral phase interferometry (hereinafter "SPIDER") yield phase and amplitude from frequency resolved Interferometric data; these are very complex and expensive but reliably provide the required information. Both FROG and SPIDER methods require some type of synchronous autocorrelation setup. In the case of the FROG method, autocorrelation is used to provide a time axis while a spectrometer provides the frequency domain information. In the case of the SPIDER method, the ultrashort pulse is split into three beams during autocorrelation; the pulse in one of the beams is stretched to provide the shear reference, while the other two pulses are cross-correlated with the stretched pulse at different times. The output is sent to a spectrometer where the interference in the signal is used to reconstruct the electric field. This extra synchronous autocorrelation step adds time and cost in addition to necessitating highly skilled operators. Limitations with prior devices and methods are discussed in R. Trebino et al., "Measuring Ultrashort Laser Pulses," *Optics & Photonics News* 23 (June 2001). Moreover, the Grenouille method requires a setup consisting of a Fresnel biprism, a doubling crystal and lenses that need to be specifically chosen for a particular pulse duration and wavelength, making this method less flexible.

20 **[0005]** The present invention proposes the use of multiphoton intrapulse interference phase scan for laser pulse characterization. In another aspect, the invention proposes a laser system using ultrashort laser pulses is provided. In another aspect of the present invention, the system includes a laser, pulse shaper and detection device. A further aspect of the present invention employs a femtosecond laser and a spectrometer. Still another aspect of the present invention uses a laser beam pulse, a pulse shaper and a SHG crystal. In yet another aspect of the present invention, a multiphoton intrapulse interference phase scan (hereinafter "MIIPS") system and method characterize the spectral phase of femtosecond laser pulses. In another aspect of the present invention, a system employs electromagnetic pulse shaping design to take advantage of multiphoton intrapulse interference. Fiber optic communication systems, photodynamic therapy and pulse characterization tests use the laser system with additional aspects of the present invention.

25 **[0006]** The laser system of the present invention is advantageous over conventional constructions since the MIIPS aspect of the present invention employs a single beam which is capable of retrieving the magnitude and sign of second and third order phase modulation directly, without iteration or inversion procedures. Thus, the MIIPS system is much easier to set up and use, thereby creating a much less expensive system which is more accurate than conventional systems and methods. Furthermore, the MIIPS system of the present invention avoids the inaccuracies of the prior FROG, SPIDER and DOSPM methods due to environmental effects such as wind, humidity and the like. The present invention MIIPS system utilizes the full bandwidth which works best with shorter laser beam pulses, such as femtosecond pulses; this is in contrast to the mere single frequency optimization of some conventional devices. The present invention MIIPS system overcomes the traditional need for slower picosecond pulses for space-time correlation corrections due to inherent time delays created with prior synchronous use of multiple matched pulses, a first pump or fundamental pulse and another reference second harmonic pulse, caused by the pulse passage through a pulse shaping crystal. Additionally, the present invention advantageously uses one or more pre-stored comparison values for pulse signal decoding at a communications receiver such that the second reference pulse (and corresponding time delay correlation) are not necessary. The present invention also improves the encoding-decoding functionality of pulses by adding considerably more information to each pulse by obtaining the entire phase function directly from a phase scan. Intrapulse interferences of the present invention causes self separation (for example, inherent communication signal routing address differentiation) thereby allowing use of inexpensive receivers in an asynchronous manner, in other words, without the need for synchronous detection such as by traditional autocorrelation or interferometers. Additional advantages and features of the present invention will become apparent from the following description and appended claims, taken in conjunction

with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

5 **[0007]**

Figure 1 is a diagrammatic view showing a first preferred embodiment of a laser system of the present invention; Figures 2A-2C are schematic and graphical representations of two photon and three photon induced fluorescence employed with the system, wherein Figure 2B is a schematic representation of the pulse spectrum (dashed line) and the phase (solid line);

10 Figures 3A-3D are sets of two and three photon absorption probability simulations and the laser beam pulse shapes employed, while Figures 3E-3H are experimental results;

Figures 4A-4G are experimental results obtained with the system for two and three photon induced fluorescence;

15 Figures 5A-5F are sets of pie charts and laser beam pulse shape graphs showing contrast ratios obtained with the system;

Figure 6 is a diagrammatic view showing second and third preferred embodiments of the present invention system applied to optical coherence tomography and photodynamic therapy;

Figures 7A-7C are graphs showing the laser beam pulse spectrum, phase, and chirp employed with the system;

20 Figures 8A and 8B are graphs showing the calculated two and three photon absorption probability obtained with the system;

Figures 9A-9C are graphs showing the calculated two and three photon absorption probability employed with the system;

Figure 10 is a diagrammatic view showing an alternate embodiment of the present invention system applied to fiber optic communications;

25 Figure 11 is a diagrammatic view showing a fourth preferred embodiment of the present invention system applied to fiber optic communications;

Figures 12A and 12B are diagrammatic views showing components employed in the fourth preferred embodiment system;

30 Figure 13 is a diagrammatic view showing a fifth preferred embodiment of the system of the present invention for use with pulse characterization or communications;

Figure 14 is a diagrammatic view showing the fifth preferred embodiment system;

Figure 15 is a diagrammatic view showing a sixth preferred embodiment of the system of the present invention for use with pulse characterization;

35 Figure 16 is a graph showing phase scans created by use of the fifth and sixth preferred embodiment system;

Figures 17A-17C are graphs showing phase scans created by use of the sixth preferred embodiment system;

Figures 18 and 19 are flowcharts of computer software employed in the sixth preferred embodiment system; and

Figure 20 is a perspective view showing a preferred embodiment of a fixed, two-dimensional shaper employed in the present invention system.

Figures 2-14 are given as examples but are not in claimed invention.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

System with Transmissive and Active Pulse Shaper

45 **[0008]** The first preferred embodiment of a laser system 21 using ultrashort laser pulses of the present invention is generally shown in Figure 1. System 21 includes a femtosecond laser 23, an upstream grating 25, an upstream convex mirror 27, a laser beam pulse shaper 29, a downstream concave mirror 31, a downstream grating 33, a detection device 35, and a personal computer 37. Personal computer 37 has a microprocessor based electrical control system, memory, an output screen, a data storage device, an input keyboard, and a removable disk. More specifically, the detection device

50 is a spectrometer 35. Bursts or pulses of a laser beam 43 are emitted from laser 23, through the optics 25, 27, 31 and 33, as well as through pulse shaper 29 for detection and sensing by spectrometer 35 for further evaluation, analysis, comparison and subsequent control by personal computer 37.

[0009] The laser is preferably an ultra-short femtosecond laser that can deliver high peak intensity (with a typical peak greater than 10^{10} watts/cm²) which preferably emits laser beam pulses of less than 100 femtosecond duration, and more preferably at or less than 50 femtoseconds, and for certain applications even more preferably emits laser beam pulses of less than 100 femtosecond duration, and more preferably at or less than 50 femtoseconds, and for certain applications even more preferably at or less than 10 femtosecond duration, for each pulse burst or shot. The intense optical pulses that are required to modify material are formed in a Kerr-Lens modelocked titanium sapphire oscillator. Such lasers are

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capable of producing hundreds of nanometers of coherent bandwidth, although only about 50 nm are typically used. The output may be amplified in a 1 kHz regenerative chirped pulsed amplifier. The output pulse is typically 100 fs long with a central wavelength of 800 nm and total pulse energy of 0.1 to 1 mJ. Preferred lasers include: the Kapteyn and Murnane femtosecond laser oscillator, which can produce less than 15 fs pulses at 100 MHz; the Hurricane model from Spectra Physics Inc., which is diode pumped and gives 0.8 mJ per pulse with sub-50 fs pulses at 1 kHz; and the CPA-2001+ model from Clark-MXR Inc., which gives 1.3 mJ per pulse with sub-150 fs pulses at 1 kHz, pumping a Clark-MXR Inc. non-collinear parametric amplifier (hereinafter "NOPA") which produces 0.2 mJ per pulse, and is capable of generating sub-20 fs pulses. This NOPA system can even produce pulses between 10 fs and 4.5 fs.

[0010] A Fourier plane pulse shaper is preferably used with the present invention for the transmissive construction illustrated with this embodiment. Ultra-fast laser pulses contain from one to fifty optical cycles, and last only a few femtoseconds. This is much faster than most current electronics and therefore shaping with fast time gates is very difficult. On the other hand, as a consequence of the uncertainty principle, the optical spectrum spans tens to hundreds of nanometers. Such a large bandwidth is relatively easy to measure and to filter, and there are several techniques to shape the spectrum in the frequency domain, and thereby shape the temporal pulse upon recompression.

[0011] In order to access the frequency domain and the individual frequency components that comprise the pulse, a geometric arrangement is employed, using two back-to-back spectrometers. The spectrometers are especially designed to introduce no net temporal dispersion: that is, all colors pass through the spectrometers within the same amount of time. The first spectrometer (including grating 25 and mirror 27) spreads the unshaped pulse spectrum along a line according to its dispersion function $y(\alpha)$. The light intercepts spatial amplitude and phase mask pulse shaper 29 at this point. The mask output then forms the entrance to a second spectrometer (including grating 33 and mirror 31) which recombines the colors into a single shaped pulse.

[0012] The heart of pulse shaper 29 is the programmable 256 pixel liquid-crystal mask (consisting of two overlapping 128 pixel liquid crystal arrays) that is placed at the Fourier plane. For the applications envisioned herein, the mask must be capable of shifting the phase of individual frequencies. For alternate embodiment pulse shapers, a different electronically programmable mask that is capable of controlling phase has been demonstrated: a liquid crystal display (hereinafter "LCD"), an acousto-optic modulator (hereinafter "AOM"), a deformable mirror, and a permanently deformed mirror. A LCD pulse shaper can be obtained from CRI Co, and has a modulator electronic driver.

[0013] The AOM consists of an anti-reflection coated Tellurium Dioxide (TeO₂) crystal with a piezo electric transducer glued onto one end. The central frequency of the acoustic wave is $ac/2\pi = 200$ MHz. The acoustic velocity v_s in the crystal is 4.2 km/s and the light pulse spends less than 10ps in the crystal, so the acoustic wave moves less than 0.002λ acoustic during the transit of the light field through the crystal. Since the acoustic wave is essentially frozen as the optical pulse travels through the crystal, the complex amplitude of the acoustic wave traveling through the crystal in the y direction, $A(t)\cos\alpha ct = A(y/v_s)\cos\alpha ct$, is mapped onto the optical field $E(\alpha)$ as it passes through the AOM. If some of the dispersed optical field encounters a weak acoustic wave, that frequency is attenuated; if the acoustic wave carrier is shifted by phase angle ϕ , that phase shift is imposed on the optical field. This pulse shaper has a total efficiency of about 20% including the diffraction efficiency of the AOM and the diffraction efficiency of the gratings. The diffracted light is used and the undiffracted "zero order" beam is blocked, to allow full modulation of both amplitude and phase in the shaped beam. The shaped beam then has the form

$$[1] \quad E_{shaped}(\omega) = E_{input}(\omega) \alpha(\omega) x e^{i\phi(\omega)t}$$

where $\alpha(\omega)e^{i\phi(\omega)} = A[y(\omega)/v_s]$; α is the frequency, and e is a constant. Fixed pulse shaping optics, such as chirped mirrors, can also be employed as will be discussed further hereinafter with regard to Figure 20.

[0014] The transform limited pulses (hereinafter "TL"), having all their frequencies in phase, are fed into the pulse shaper where curved mirror 27 focuses the spectrum onto Fourier plane 29. Changes in the phase ϕ and amplitude A of the spectral components indicated by the computer are used to tailor the laser pulse before reconstruction with second curved mirror 31 and grating 33. Once compressed, the shaped pulse is directed to spectrometer 35 for evaluation. The Fourier transform relationship between the time and the frequency domain allows us to calculate the necessary mask to create a certain shaped pulse. These calculations are based on

$$[2] \quad f(v) = \frac{1}{2\pi} \int_0^p f(t) e^{i2\pi vct} dt$$

and

$$[3] \quad f(t) = \int_0^{\infty} f(\nu) e^{-i2\pi\nu ct} d\nu$$

where ν is the frequency in wave numbers, t is the time, and c is the speed of light.

[0015] In this embodiment, the phase and amplitude masks of the pulse shaper are controlled by the computer wherein the laser pulse shape takes a dynamic role. The microprocessor within personal computer 37 will then control laser 23, receive an essentially real time feedback input signal from spectrometer 39, and then perform calculations, comparisons and evaluations, and possibly automatic variation of subsequent pulse shapes. These automated steps can be substituted with manual user calculations and decisions if desired based on personal computer outputs.

System With Reflective Pulse Shaper

[0016] A reflective pulse shaping system 121, employed with a sixth preferred embodiment of the present invention is shown in Figure 15, and includes a femtosecond laser 123, an upstream prism 125, a partially cylindrical or partially spherical mirror 133, a pulse shaping mirror 129 at the Fourier plane, and an offset or pickoff mirror 131. Upstream prism 125 initially acts to disperse the colors of the emitted laser beam pulse while mirror 133 serves to focus, collimate and redirect this dispersed laser beam pulse toward pulse shaping mirror 129. Pulse shaping mirror 129 has either a predetermined or fixed pulse shaping surface or a computer controlled deformable mirror.

[0017] For the fixed pulse shaper, as shown in Figure 20, the patterned shaping surface has, for example, a sinusoidal profile along the direction of frequency dispersion. If the profile is slanted then the vertical axis provides different phase modulation that can be used for a single shot pulse characterization or decoding in a communications application. The surface modulation wave forms are schematically shown as 701. Inexpensive replicas can be achieved by injection molding with polymers such as pmma substrate 703 and reflection coated or anti-reflection coated depending if it is used in reflection or transmission mode respectively. The physical characteristic or shape of the actual pulse shaping surface is predetermined through optimization experimentation for the intended use and intended laser beam input; each row (or column) of the shaped wave is displaced or offset in phase from the immediately adjacent rows or shaped wave form patterns. Cosine, stepped or other wave form patterns can also be used. A silver coating 705 is applied to the front side of substrate 703 if used as a reflective pulse shaper as preferred with this embodiment. Alternately, anti-reflective coatings are applied to substrate 703 if fixed pulse shaper 129 is used as a transmissive optic. Substrate 703 can be removably snapped into a receptacle 707 and replaced by differently configured wave form patterns for different pulse phases and uses. After the desired mirror surface shape is known for the intended use, the less expensive, fixed shape mirror can be employed to reduce equipment costs for actual production systems. Also, the computer and optimization program are not required for these types of known set up and known applications after the initial determination is conducted. Pulse shaping with a permanently shaped optic to achieve specific tailoring of the phase of a fs laser pulse. The optic can be reflective or transmissive. Motion of the optic can be used to cause the phase function to scan from odd to even. This setup can be used to encode and decode the phase of fs laser pulse.

[0018] Pulse shaper 129 thereby reshapes the laser beam pulse to now include one or more certain characteristic, reflects it back through the same prism and mirror in reverse order, and in an offset or time-delayed manner. Offset mirror 131 subsequently reflects the shaped laser beam toward the receiver, which can be a spectrometer, fiber optic sensor/switch, or a targeted tissue specimen, as will be discussed in greater detail hereinafter. It is further envisioned that an in-line optical system can be used, such as that disclosed with the first preferred embodiment, however, the pulse shaper at the Fourier plane would be replaced by a phase mask shaper having a transmissive optic with a predetermined coefficient of refraction, or a polarizing-type sine mask on a transparent substrate. Also, a polymer-doped glass or blend of polymer sheets that are capable of retarding the phase of the laser beam pulse wave or otherwise varying a wavelength, timing or shaping characteristic of same can be employed.

[0019] Alternately, certain optics can be used such as a backside coated, chirped mirror having multiple dichroic layers, which would be satisfactory for pulse shaping without dispersive optics and without the need for a Fourier plane. An acceptable chirped mirror is disclosed in Matuschek, et al, "Back-side-coated Chirped Mirrors with Ultra-smooth Broad-band Dispersion Characteristics," Applied Physics B, pp. 509-522 (2000). A negative dispersion mirror from CVI Laser Corp., part no. TNM2-735-835-1037 is another suitable example. A rotatable wheel having multiple different liquid carbon disulphide. The construction of system 221 as illustrated supposes transmission imaging; the same end result can alternately be accomplished with back scattered imaging. Image 253 could be viewed like an x-ray-type image of the internal organs of the human or animal specimen but without harmful three photon exposure. The use of the shaped pulse in OCT provides for an increase in laser intensity for better imaging while preventing the damaging effects caused by multiphoton excitation of healthy tissue. The MIIPS process discussed hereinafter can be advantageously used to activate different dyes and other compounds within a human or animal tissue, to achieve compound specific or functional

OCT or microscopy.

Photodynamic Therapy

5 **[0020]** A third preferred embodiment of the present invention uses a system also shown as 221 for laser excitation or ionization with photodynamic therapy ("PDT"). In general, Figure 6 also illustrates the PDT application of system 221, but optical gate 251 and image 253 are not required. Shaper 229 allows two photon excitation but essentially prevents three photon excitation. Shaper 229 enhances the laser induced activity of a therapeutic agent which prevents damage of healthy tissue. Use of laser beam pulse shaping of the present invention should provide superior control and results for PDT applications as compared to those practically possible with conventional methods as disclosed, for example, in 10 U.S. Patent No. 6,042,603 entitled "Method for Improved Selectivity in Photo-Activation of Molecular Agents" which issued to Fisher et al. on March 28, 2000. Alternately, the pulse shaper can be tuned to target cancerous cells for multiphoton gene therapy or destruction, with or without the presence of a therapeutic agent, without damaging healthy tissue. The MIIPS process discussed hereinafter can be advantageously used to activate only certain pharmaceuticals or chemicals, or used to allow the laser pulse to enter human or animal tissue to a known depth, based on the phase 15 tuning and associated nonlinear spectrum tuning of the laser beam pulse.

Control of Nonlinear Optical Processes

20 **[0021]** As applied to all of the applications herein, selective control of one and multiphoton processes in large molecules, including proteins, is possible using a simple pulse shaping method that is based on taking maximum advantage of the multiphoton intrapulse interference caused in short pulses with large bandwidths. The results show an extraordinary level of control that is robust and sample independent, with contrast ratios near two orders of magnitude (clearly visible with the naked eye). Such large contrast ratios allow for more precise cancellation control of undesired photons and 25 other laser beam characteristics, such that nonlinear transitions induced by each pulse are controlled. Because simple phase functions can be incorporated into a passive optical component such as mirror 129 (see Figure 15), these applications do not require the shaper can be tuned to target cancerous cells for multiphoton gene therapy or destruction, with or without the presence of a therapeutic agent, without damaging healthy tissue. The MIIPS process discussed hereinafter can be advantageously used to activate only certain pharmaceuticals or chemicals, or used to allow the laser 30 pulse to enter human or animal tissue to a known depth, based on the phase tuning and associated nonlinear spectrum tuning of the laser beam pulse.

Control of Nonlinear Optical Processes

35 **[0022]** As applied to all of the applications herein, selective control of one and multiphoton processes in large molecules, including proteins, is possible using a simple pulse shaping method that is based on taking maximum advantage of the multiphoton intrapulse interference caused in short pulses with large bandwidths. The results show an extraordinary level of control that is robust and sample independent, with contrast ratios near two orders of magnitude (clearly visible with the naked eye). Such large contrast ratios allow for more precise cancellation control of undesired photons and 40 other laser beam characteristics, such that nonlinear transitions induced by each pulse are controlled. Because simple phase functions can be incorporated into a passive optical component such as mirror 129 (see Figure 15), these applications do not require the complexity and expense of computer controlled pulse shapers after initial set up, although systems can still be employed.

45 **[0023]** The underlying concept of the system and associated method are shown in Figures 2A-2C. Multiphoton transitions are optimized when the central bandwidth of the laser pulse ω_0 , is some fraction (half for two-photons, a third for three-photons, etc.) of the total energy of the transition as illustrated in Figures 2A and 2C. For ultrafast pulses, when the bandwidth is large, different frequency components ($\omega_0 \pm \Omega$) of the pulse can interfere, thereby reducing the probability for multiphoton excitation. Referring to Figure 2B, the spectrum of the ultrafast laser pulse with amplitude $A(\Omega)$ is plotted as a function of detuning from the central frequency. A phase mask $\varphi(\Omega)$ can be imprinted on the pulse such that the 50 phase of each frequency component Ω acquires a specific value. The effect of pulse shaping on the probability for two-photon absorption (hereinafter "2PA") can be calculated as follows:

$$55 \quad [4] \quad P_{2PA} \propto \left| \int_{-\infty}^{\infty} A(\Omega) A(-\Omega) \exp[i\{\varphi(\Omega) + \varphi(-\Omega)\}] d\Omega \right|^2$$

and for three-photon absorption ("3PA"), a similar formula can be derived as follows:

$$P_{3PA} \propto \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(\Omega_1) A(\Omega_2) A(-\Omega_1 - \Omega_2) \exp[i\{\varphi(\Omega_1) + \varphi(\Omega_2) + \varphi(-\Omega_1 - \Omega_2)\}] d\Omega_1 d\Omega_2 \right|^2 \quad [5]$$

where amplitudes and phases are introduced for two different detuning values Ω_1 and Ω_2 , as shown in Figure 2C. One photon transitions are not affected by the phase of the pulses, however, exclusive one photon excitation is difficult to achieve at high photon flux due to the onset of multiphoton processes.

[0024] A schematic representation of two photon and three photon induced fluorescence is illustrated in Figures 2A and 2B, respectively. The vertical arrows represent ultrafast pulses that induce the two and three photon transitions. Because of their broad bandwidth, ultrafast pulses contain photons that are detuned from the central wavelength ω_0 by an amount Ω . Referring again to Figure 2C, ultrafast laser pulses are shaped using a sine function phase mask across the pulse spectrum underlying the dashed curve while the structures of the chromophores are also shown.

Example 1

[0025] The experiments in all of the following examples were carried out using an amplified titanium sapphire laser producing 50 fs pulses. The pulses were shaped using a spatial light modulator (hereinafter "SLM") at the Fourier plane of a zero-dispersion two grating arrangement. The two independent modulator plates, based on liquid crystal technology in the SLM (128 pixels each), were calibrated so that only phase delays were introduced without changes to the output spectrum, intensity, and polarization. The shaped pulses centered at 809 nm were characterized by second harmonic generation frequency resolved optical gating. When all phases were set to zero, laser pulses were near transform limited. Unless indicated otherwise, measurements were made with pulse energies of 0.4 μ J/pulse at the sample. Experiments were carried out by setting the phase function equal to a sinusoid, as shown in Figure 2B, in the 779-839 nm spectral range. Emission from one photon or multiphoton induced processes from various samples was measured as a function of δ , the phase shift of the mask across the spectrum. The maximum phase advancement or retardation was 1.5π .

[0026] Equations 4 and 5 can be used to calculate the expected signal for two and three photon processes as a function of δ . These calculations are graphed in Figures 3A - 3H for sinusoidal phase functions having a half (Figures 3A and 3B) or a full (Figures 3C and 3D) period across the entire phase mask. The calculated probability for two photon and three photon transitions peaks at half integer values of π in Figures 3A and 3B, while the calculated probability for two photon and three photon transitions peaks at integer values of π in Figures 3C and 3D. The shape of the phase function, where maxima and minima in the probability are achieved, is indicated as inserts.

[0027] Experimental data were obtained with the phase functions used for the calculations in Figures 3A - 3D. In these experiments, the two and three photon emission from large organic molecules is detected as a function of δ . Although the model described by equations 4 and 5 assumes two level systems, Figures 3E - 3H experimentally demonstrate that this principle can be applied to complex systems having a manifold of vibrational states broadened by the presence of a solvent. It is noteworthy that the peaks and valleys predicted by equations 4 and 5 are observed in the experimental data; essentially, the intensity maxima are found when the phase function is antisymmetric with respect to the central wavelength of the pulse and minima when it is symmetric.

[0028] More specifically, theoretical and experimental phase-mask control of two and three photon induced fluorescence is shown in Figures 3A - 3H. Equations 4 and 5 predict that as the phase mask is translated by an amount δ , the probability of two (hereinafter " P_{2PA} ") and three photon transitions (hereinafter " P_{3PA} ") is modulated, as illustrated in Figures 3A - 3D, for a half period sine mask (Figures 3A and 3B) and a full period sine mask (Figures 3C and 3D). Transform limited pulses yield a maximum value of 1. The small inserts in Figures 3A and 3C display the phase function at specific positions where maximum and minimum values of fluorescence take place (Figures 3E - 3H) wherein experimental two and three photon laser induced fluorescence measured for Coumarin and Stilbene, respectively, as a function of phase mask position δ are shown. The phase masks used for these experiments were the same as those used in the calculations. Thus, the pulse shaping masks can be predetermined or fixed in shape based on calculations, experiments or learning program values for known equipment and known specimens.

Example 2

[0029] Experimental results for various samples obtained with a full-period sinusoidal phase mask are shown in Figures 4A - 4G. Figure 4A shows one photon laser induced fluorescence (hereinafter "1PLIF") of IR144 observed at 842 nm as a function of phase mask position. This measurement was made with 0.3 nJ/pulse to avoid nonlinear processes at

the specimen. It is noteworthy that one photon process in the weak field regime show no dependence on phase shaping. Figure 4B shows results for the two photon laser induced fluorescence (hereinafter "2PLIF") from Coumarin collected at 500 nm. The data in Figure 4C shows the dependence of 2PLIF in recombinant green fluorescent protein (hereinafter "rGFP") detected at 505 nm. The data in Figure 4D corresponds to the intensity of the second harmonic generation (hereinafter "SHG") signal at 405 nm from a 0.3mm β -barium borate crystal. The maximum and minimum signal for SHG coincides with that observed for 2PLIF but is not identical.

[0030] With reference to Figure 4E, the dependence of three photon laser induced fluorescence (hereinafter "3PLIF") from Trans-Stilbene is illustrated. The signal was collected at 350 nm as a function of δ . In this case, the maximum contrast (max:min) is measured to be 60:1. The data in Figure 4F corresponds to the 3PLIF from Tryptophan residues in Con A, collected at 350 nm. In 3PLIF the maximum fluorescence signal is less than that obtained for transform limited pulses (when all the phases in the mask are set equal to zero), but the overall contrast ratio over the three-photon excitation is excellent, approaching two orders of magnitude. The data in Figure 4G corresponds to the continuum generation response (a nonlinear self-frequency modulation process yielding white light pulses) from a 3 mm slab of quartz detected at 600 nm.

[0031] More specifically, Figures 4A - 4G demonstrate the experimental measurements of one and multi-photon emission obtained as a function of phase mask position δ . In all cases, the phase mask is a full period sine function. The signal measured with transform limited pulses is unity. The contrast ratio (max:min) is given in the upper right corner of each of the experimental plots. Here we find that the higher the order of the optical nonlinearity, the greater the contrast that we observe, therefore discrimination among different order processes is possible. In other words, the higher the order, the greater the photons, which makes it easier for photon cancellation. Also, the greater the contrast ratio, the more the background noise is filtered out.

Example 3

[0032] Figure 5A presents the maximum discrimination between linear and nonlinear response observed for intense pulses (0.5 μ J/pulse). Separate detectors simultaneously collected the 1PDF from IR144 solution and a portion of the continuum output. Maximum and minimum contrast ratios of $>10^3:1$ and 1:0.6 were obtained for one photon process versus continuum, respectively, as shown in Figures 5A and 5B. This control is extremely valuable when one is interested in linear processes under high-flux conditions, like in laser microscopy or in optical fiber communications. Using the simple phase function discussed earlier, particular windows of opportunity to control second versus higher order processes can be employed as demonstrated in Figures 5C and 5D. For certain values of δ , continuum generation even for relatively high intensity laser pulses ($\sim 1 \mu$ J/pulse) can be completely suppressed. Figures 5C and 5D show that maximum and minimum contrast ratios of $>10^3:1$ and 1:4 were obtained for 2PLIF versus continuum, respectively.

[0033] Two photon transitions can be achieved while suppressing three photon processes for use in two photon microscopy or in two photon PDT. This type of control is much more difficult because once multiphoton transitions take place it is very difficult to stop at a particular order. A mixture of Coumarin and Fluoranthene were prepared to explore control of 2PLIF versus 3PLIF. Because fluorescence from these two molecules overlaps the same spectral region, the separation between the two signals was achieved by temporal gating. Coumarin fluorescence was detected at 495 nm during the first 20 ns, while fluoranthene fluorescence was detected at 460 nm with a gate that opened 40 ns after the initial rise and extended for 120 ns. Maximum and minimum contrast ratios of 1.4:1 and 1:2.2 were obtained for 2PLIF versus 3PLIF, respectively, as presented in Figures 5E and 5F. The contrast data presented in Figures 5A - 5F were obtained when transform limited pulses yielded equal intensities for the processes. Better contrast can be obtained using additional pulse shaping as described in the following section, especially as the multiphoton processes are detuned from resonance.

[0034] A fs-pulse shaper arrangement can be used to achieve background free functional imaging (pH, Na or Ca concentration gradients, electric fields, charge, fluorescent probes, nanoclusters, or quantum dots, chemical composition) by taking advantage of multiphoton intrapulse interference. For example, A. H. Buist, M. Muller, R. I. Ghauharali, G. J. Brakenhoff, J. A. Squire, C. J. Bardeen, V. V. Yakovlev, and K. R. Wilson, "Probing microscopic chemical environments with high-intensity chirped pulses," Optics Letters 24, 244-246 (1999). Buist et al, showed that linear chirp can be used to crudely distinguish the pH environment of a pH-sensitive dye. With phase modulation, and specifically taking advantage of multiphoton intrapulse interference, the present invention can achieve much more sensitive pH sensitivity with a greater number of pH-sensitive dyes. Using the same principle, dyes that are sensitive to sodium, calcium or other chemical gradients including also charge and can also be probed selectively. Alternatively, multiple probes such as dyes, nanoclusters or quantum dots can be selectively excited through two- or three-photon excitaiton.

Predetermined Pulse Shaping and Phase Control of Multiphoton Processes

[0035] The present invention takes maximum advantage of the phenomenon described as "Multiphoton Intrapulse

Interference" as optimized for large molecules, proteins, and other condensed phase materials, through a combination of: (a) a chirped mask pulse shaper; and (b) a smooth function of phase versus frequency for the mask pulse shaper. The following formulas provide a predictive advantage for finding appropriate phase masks. The probability of two photon transitions can be calculated as follows for any given pulse shape:

For an electric field with a carrier frequency ω_0 and a slow amplitude $E_0(t)$,

$$[6] \quad E(t) = E_0(t)e^{-i\omega_0 t} \quad \text{and} \quad E_0(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F_0(\Omega)e^{-i\Omega t} d\Omega$$

where the Fourier image $F_0(\Omega)$ around carrier frequency $\Omega = \omega - \omega_0$ can be written as:

$$[7] \quad F_0(\Omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E_0(t)e^{i\Omega t} dt,$$

the amplitude of two photon transition at resonance frequency ω is:

$$[8] \quad A_2(\omega) \propto \int_{-\infty}^{\infty} E(t)^2 e^{i\omega t} dt = \int_{-\infty}^{\infty} E_0(t)^2 e^{i(\omega - 2\omega_0)t} dt = \int_{-\infty}^{\infty} E_0(t)^2 e^{i\Delta t} dt,$$

where detuning $\Delta = \omega - 2\omega_0$, the probability of two photon transition is:

$$[9] \quad P_2(\omega) = |A_2(\omega)|^2 .$$

[0036] Furthermore, the Fourier image of convolution is the product between Fourier images

$$[10] \quad T(f * g) = (Tf)(Tg)$$

where convolution (*, function from Δ) of two functions (f) and (g) is:

$$[11] \quad f * g = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(\Omega)g(\Delta - \Omega) d\Omega.$$

Direct (T, function from Ω) and inverse (T^{-1} , function from t) Fourier images are

$$[12] \quad T(f) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t)e^{i\Omega t} dt \quad \text{and} \quad T^{-1}(f) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(\Omega)e^{-i\Omega t} d\Omega.$$

Additionally, the relation between direct and reverse transforms is:

$$[13] \quad T^{-1}T(f) = TT^{-1}(f) = f.$$

5

Thus, using the inverse transform, the formula can be written as:

10

$$[14] \quad f * g = T^{-1}T(f * g) = T^{-1}[(Tf)(Tg)] \text{ or}$$

formula [14] in integral form is as follows:

15

$$[15] \quad \int_{-\infty}^{\infty} f(\Omega)g(\Delta-\Omega)d\Omega = \int_{-\infty}^{\infty} e^{i\Delta t} \left[\left(\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(\Omega)e^{-i\Omega t} d\Omega \right) \left(\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} g(\Omega)e^{-i\Omega t} d\Omega \right) \right] dt.$$

20

[0037] The time-frequency transformation can be calculated. Using the spectral presentation of formula [7] and convolution theorem of formula [15], formula [8] can be rewritten to obtain the formula for two photon transitions as follows:

25

$$[16] \quad A_2(\Delta) \propto \int_{-\infty}^{\infty} E_0(t)^2 e^{i\Delta t} dt \propto \int_{-\infty}^{\infty} F_0(\Omega)F_0(\Delta-\Omega)d\Omega$$

30

This expression provides the two photon absorption amplitude given the spectrum of the laser pulse $F_0(\Omega)$ and the detuned spectrum of the $F_0(\Delta-\Omega)$ that depends on the absorption spectrum of the sample.

[0038] The probability of three photon transitions can be subsequently calculated. The complex amplitude of transition is:

35

$$[17] \quad A_3(\omega) \propto \int_{-\infty}^{\infty} E(t)^3 e^{i\omega t} dt = \int_{-\infty}^{\infty} E_0(t)^3 e^{i\Delta t} dt,$$

40

where detuning $\Delta = \omega - 3\omega_0$. Using the reverse Fourier presentation for the fields of formula [6], formula [17] can be rewritten as:

45

$$[18] \quad A_3(\omega) \propto \int_{-\infty}^{\infty} e^{i\Delta t} \left[\int_{-\infty}^{\infty} F_0(\Omega)e^{-i\Omega t} d\Omega \int_{-\infty}^{\infty} F_0(\Omega)e^{-i\Omega t} d\Omega \int_{-\infty}^{\infty} F_0(\Omega)e^{-i\Omega t} d\Omega \right] dt$$

50

Next, equation [18] can be rewritten using a new function $G(\Omega)$

55

$$[19] \quad A_3(\omega) \propto \int_{-\infty}^{\infty} e^{i\Delta t} \left[\int_{-\infty}^{\infty} F_0(\Omega_1)e^{-i\Omega_1 t} d\Omega_1 \int_{-\infty}^{\infty} G(\Omega_1)e^{-i\Omega_1 t} d\Omega_1 \right] dt,$$

where $G(\Omega_1)$ is defined as the kernel of the integral

$$[20] \quad \int_{-\infty}^{\infty} G(\Omega_1) e^{-i\Omega_1 t} d\Omega_1 = \int_{-\infty}^{\infty} F_0(\Omega_1) e^{-i\Omega_1 t} d\Omega_1 \int_{-\infty}^{\infty} F_0(\Omega_1) e^{-i\Omega_1 t} d\Omega_1,$$

and
using the convolution formula [15], the following formula is obtained:

$$[21] \quad A_3(\omega) \propto \int_{-\infty}^{\infty} F_0(\Omega_1) G(\Delta - \Omega_1) d\Omega_1.$$

[0039] The Fourier image of the Reverse Fourier image of equation [20] defines the intermediate function using relationship of equation [13] and the integral form of the convolution theorem expressed in formula [15] as:

$$[22] \quad G(\Delta - \Omega_1) \propto \int_{-\infty}^{\infty} e^{i(\Delta - \Omega_1)t} \left[\int_{-\infty}^{\infty} F_0(\Omega_2) e^{-i\Omega_2 t} d\Omega_2 \int_{-\infty}^{\infty} F_0(\Omega_2) e^{-i\Omega_2 t} d\Omega_2 \right] dt = \int_{-\infty}^{\infty} F_0(\Omega_2) F_0(\Delta - \Omega_1 - \Omega_2) d\Omega_2$$

[0040] The final formula for the detuned $\Delta = \omega - 3\omega_0$ three photon transition is obtained by using equations [21] and [22] after changing the order of integration:

$$[23] \quad A_3(\Delta) \propto \int_{-\infty}^{\infty} E_0(t)^3 e^{i\Delta t} dt = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} F_0(\Omega_1) F_0(\Omega_2) F_0(\Delta - \Omega_1 - \Omega_2) d\Omega_1 d\Omega_2$$

such that the probability is:

$$[24] \quad P_3(\omega) = |A_3(\omega)|^2.$$

The method described above gave the formula for the n-photon transition by recurrence:==

$$[25] \quad A_n(\Delta) \propto \int_{-\infty}^{\infty} E_0(t)^n e^{i\Delta t} dt \propto \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} F_0(\Omega_1) \dots F_0(\Omega_{n-1}) F_0(\Delta - \Omega_1 - \dots - \Omega_{n-1}) d\Omega_1 \dots d\Omega_{n-1}$$

where detuning is $\Delta = \omega - n\omega_0$. Thus,

$$[26] \quad P_n(\omega) \propto |A_n(\omega)|^2.$$

[0041] It is also desirable to take into account inhomogeneous broadening (as encountered in solutions and condensed phase materials). The integrated probability for the n-photon transition in molecules with a spectral density $g_n(\omega)$ with

amplitude defined by formula [25] is proportional to the weighed average

$$[27] \quad P_n = \int_{-\infty}^{\infty} g_n(\omega) |A_n(\omega)|^2 d\omega.$$

Normalization for the case of transform limited laser pulse is N_n and

$$[28] \quad N_n = \int_{-\infty}^{\infty} g_n(\omega) |A_{TLn}(\omega)|^2 d\omega,$$

where

$$[29] \quad A_{TLn}(\omega) = \int_{-\infty}^{\infty} |F_0(\Omega_1)| \dots |F_0(\Omega_{n-1})| |F_0(\Delta - \Omega_1 \dots - \Omega_{n-1})| d\Omega_1 \dots d\Omega_{n-1}.$$

[0042] The preceding formulas [6] - [29] give the general result. The following parameters must be defined, however, for a user to define a phase mask that would minimize or maximize a particular multiphoton process. First, the laser pulse spectrum of Figure 7A must be defined. The shorter the pulses (broader spectrum), the better the control. 45 fs pulses have been satisfactorily used but 20 or 10 fs would lead to even better results. The carrier frequency (or center wavelength) must also be defined by availability. Tuning the wavelength of the pulse could enhance certain processes but is not typically required. Secondly, the phase modulator (or alternately, the SLM, deformable mirror, chirped mirror, etc.) should cover the entire pulse spectrum and must be defined. Thirdly, a phase mask definition should be introduced. The simple sine function of Figure 7B works remarkably well, yet other functions that can become symmetric and antisymmetric as a function of their position are also suitable. Fourthly, the addition of positive or negative linear chirp ϕ further enhances the observed control, as expressed in Figure 7C, and should be defined. The phase mask used in the examples presented herein is defined by

$$[30] \quad \phi_m(\lambda, \delta) = \phi_a \sin\left(\frac{\lambda - \lambda_{\min}}{\lambda_{\max} - \lambda_{\min}} \cdot 2\pi N - \delta\right)$$

where δ is the position of the sine function (centering) across the spectrum, ϕ_a is the maximum phase delay, and N_{pixel} is the number of pixels in the SLM, as illustrated in Figure 7B.

[0043] When chirp is added, it can be defined by

$$[31] \quad \phi_c(\Omega) = \frac{1}{2} \phi'' \Omega^2$$

where β is the amount of linear chirp expressed in Figure 7C. Thus, the complete phase mask with chirp is:

$$[32] \quad \phi(\lambda) = \phi_m(\lambda, \delta) + \phi_c(\lambda).$$

[0044] Figures 8A and 8B show the calculated two and three photon absorption probability using the equation presented and the absorption spectra as calculated by the dotted lines in Figures 9A - 9C. Figure 9C shows the calculated ration two:three photon absorption for the two different combinations of absorption spectra given in Figures 9A and 9B. Ac-

cordingly, robust control of multiphoton processes in molecules, proteins and nonlinear optical materials can be achieved through either adaptive, active and self optimizing learning programs and control systems, or through calculated, predetermined or fixed, passive laser beam pulse shaping devices. Therefore, inexpensive fixed phase masks can be designed before the experiment, and even without computer controlled shapers and learning programs, to control the order of multiphoton processes for large, complex molecules, proteins in photodynamic therapy, optical tomography, surgery (such as laser cutting by five or greater photon wave conveyance to maximize nonlinear energy), and photochemistry control of, for example: (a) photopolymerization (by photon pair switching to seed the process), (b) charge transfer, (c) radical reaction, (d) nucleophilic attack and (e) electrophilic attack.

Communications

[0045] With reference to Figure 10, an alternate embodiment of a laser excitation system 421 of the present invention employs a femtosecond laser 423, an optical fiber 451, a laser beam pulse shaper device 429, a laser beam pulse unshaper device 453, and a receiver 441 which includes an optical switch or sensor and the related circuitry and electrical control unit. Laser 423 emits a series of laser beam pulses, each shorter than 1 ps, into the connected fiber 451. Pulse shaper device 429 is of a predetermined mask type with a fixed pulse characteristic varying shape (such as with calculated sine wave surface shapes) and has three elements connected to fiber 451: a dispersive element 455 such as a fiber that incorporates a diffraction grating; a phase mask element 457 that can be made using a doped glass or polymer sheet; and a dispersive element 459, like element 455 but reversed, for accepting spectrally dispersed light and coupling it back to fiber 451.

[0046] The shaped laser beam pulse is capable of traveling long distances through fiber 451 without suffering nonlinear distortion because of the unique phase function imprinted or formed on shaper device 429. For example, the red color spectrum may be advanced in front of the blue color spectrum in a precise sine manner. Un-shaper device 453 subsequently reverses the phase changes introduced by shaper device 429. It is constructed the same as the shaper device but with a different phase mask element 461 that compensates for the pulse characteristic changes made by mask element 457. Alternately, an acousto-optic modulator or transient grating can be used for optical switching through constructive or destructive reference of waves. Shaping and unshaping can also be accomplished by means of a chirped mirror or spectral masks.

[0047] Thus, the present invention's ability to precisely control the laser beam pulse shape or other characteristic, especially for nonlinear or multiphoton emissions, significantly improves the quality of the communication transmission while minimizing self-focusing, self phase modulation and possible destruction of the fiber. The pulse characteristic control of ultrafast laser beam pulses, as described in all of the embodiments herein, should minimize, if not prevent, multiplicative noise effect disruption of nonlinear propagation channels in fiber optic lines, as discussed in Mitra, et al., "Nonlinear Limits to the Information Capacity of Optical Fibre Communications," Nature, vol. 411, pp. 1027-1030 (June 28, 2001). It is further envisioned that this type of pulse shaping system can be employed within salt water oceans for submarine-to-submarine communications using short laser pulses of 1 ps or less. This type of pulse shaping can be used to induce soliton formation to achieve minimally distorting pulses for communications. Moreover, MIIPS can be used to measure the distance of a fs laser emitter by determining the magnitude of the acquired second order phase modulation as the laser pulse transmits through air or water. This method does not require echo or reflection. In water longer pulses (1 ps) are desired because of the much greater dispersion. Depending on the transmission medium, air or water, and the distances expected different pulses are required. For air, short pulses with durations between 10-20 fs will be preferred. For water, pulses with much longer durations will be preferred, for example for 100 m distance 100 ps pulses would be preferred.

[0048] Referring to Figures 11, 12A and 12B, a fourth preferred embodiment of the system of the present invention is used for fiber optic communications. Multiple transmission users who are each sending a communications message or signal are using a communications device such as a telephone 491, personal computer, facsimile machine or the like, at remote locations from each other. These remote transmitters are connected to a "smart" main transmitter assembly which includes a computerized, central processing unit 493 through electric wires, fiber optic cables, microwave signals or the like. A phase modulated pulse shaper 505 is actively controlled by CPU 493. Laser 509 and shaper 505 are also contained as part of the main transmitter assembly. Laser 509 emits an ultrashort laser pulse which is carried within a fiber optic cable 497 after shaping. The ultrashort laser beam pulses have a duration of about 100 femtoseconds based on currently available fiber optic cable limitations but pulse durations of less than 50 femtoseconds would be preferred and those of 10 or less femtoseconds would be the most desired if fiber optics allow for such in the future. For example, photonic band gap materials such as optical fibers with holes therein may allow for use of approximately 10 femtosecond pulses.

[0049] Pulse shaper/phase mask 505 causes each laser beam pulse phase to tune the second and third order harmonics of each peak and to cause multiple peaks, by way of example, but not limitation, in each pulse frequency. This allows encoding of routing addresses and the associated communications information to be encoded within each laser

beam pulse based on CPU control of the laser beam emissions in combination with actively varied shaping of each emitted pulse.

5 [0050] A "dumb" central receiver 501, one that does not require an additional laser or complex computational capabilities, is connected to the downstream end of fiber optic cable 497. Receiver 501 includes a focusing lens 515, a thick SHG crystal 507' and a detector 511. Each laser beam pulse transmitted through fiber optic cable 497 is dispersed onto lens 515 which serves to focus and direct each pulse, in a converging angular manner, onto crystal 507'. A thick optical crystal 507' is defined herein as one having a transmissive path thickness of greater than about 0.5 millimeters while a thin optical crystal 507 (see Figure 15) is defined herein as having a transmissive path thickness less than about 0.5 millimeters. The preferred thickness for the thick crystal is approximately 3.0 millimeters for 50 femtosecond or less pulse duration and 5.0 millimeters for a 50 to 200 femtosecond pulse duration. Thick crystal 507' creates a second order harmonic and second order spectrum within each pulse as previously shaped by the pulse shaper. In other words, the thick crystal disperses essentially the entire color spectrum without use of a separate spectrometer because of the phase matching angle requirement.

10 [0051] Each separated color frequency angularly dispersed from the thick crystal is encoded by the pulse shaper to contain individual communication routing addresses and the actual communications information, which is then detected by a multiplexer-type of detector 511 such as a CCD camera employing a linear array. Alternately, detector 511 is a two-dimensional array that can be used to achieve higher data densities by adding one more dimension. It is also alternately envisioned that detector 511 is an array of optical fibers that are connected to remote controllers/subdetectors. The data can be read asynchronously using only the transmission pulse containing the information and not additional reference pulse. A single detector 511 is operable to digitize the detected signals carried in each pulse as separated through the spectrum and transmit them through wires, fiberoptics, microwaves or the like to individual decoding micro-processor controllers 503 within or external to receiver 501. A set of prestored variables or decryption information or key is located within memory of each controller 503 in order to decode each corresponding digitized communication signal received by detector 511 without requiring synchronous communication transmissions (in other words, a second laser pulse that provides a complimentary phase) from transmitter 495. The decoded communications are then sent to the end users who receive such by telephones 505, personal computers, facsimile machines or the like at the identified routing addresses desired. Alternately, controllers 503 can be replaced by simple light detection devices such as photodiodes which can be employed in a digitized on/off self-switching mode based on the signal detected by detector 511 to control or send information to remote destinations. It is significant that interferometry and synchronous laser pulses are not required for decoding the transmitted information with the presently preferred communications embodiment of the present invention. It is also noteworthy that pulse shaper 505 can encode each pulse by use of second harmonic generation or any other non-linear mixing method including, but not being limited to, frequency mixing, difference frequency mixing, and four wave mixing.

20 [0052] The present invention should be contrasted to a prior experiment which employed a difficult and a synchronous reference pulse at the decoder for supplying a complimentary phase to control the emission of a single specific wavelength. This is disclosed in Z. Zheng and A. Weiner, "Coherent Control of Second Harmonic Generation Using Spectrally Phase Coded Femtosecond Waveforms," *Chemical Physics* 267, p. 161 (2001); this prior approach, however, required pulses which overlap in time and space, which is difficult to control, and only for a single pulse frequency.

40 Multiphoton Intrapulse Interference Phase Scan

[0053] A multiphoton intrapulse interference phase scan (hereinafter "MIIPS") system and method of the present invention characterize the spectral phase of femtosecond laser pulses. This single beam method is capable of retrieving the magnitude and sign of second and third order phase modulation (in other words, linear and quadratic chirp) directly, without iteration or inversion procedures. MIIPS achieves accurate phase retrieval from chirped ultrashort pulses. For MIIPS, no synchronous autocorrelation, beam splitting, or time delays are required because the second harmonic spectrum depends on the relative phases of all frequencies within the pulse. The amplitude of the pulse is obtained directly from a spectrometer in a communications receiver. In order to precisely determine of the phase of all frequency components in a pulse from a fs laser 123 (see Figure 15), a pulse shaper, such as the one described in A. M. Weiner, "Femtosecond pulse shaping using spatial light modulators," *Rev. Sci. Instrum.* 71, pp. 1929-1960 (2000), is employed to introduce a reference phase function designed to yield this information directly, as further described hereinafter. The shaped pulses are frequency doubled by a thin SHG crystal 507 (see Figure 15) and the output is directed to spectrometer 503.

50 [0054] The system and method of the present invention are aimed primarily at decoding the phase as a function of frequency of an ultrafast laser pulse. The measurement requires determination of the intensity of the second order electric field of the laser pulse. This property can be measured by measuring the spectrum of the laser after it has been frequency doubled. A comparison of the spectrum of the pulse and the spectrum of its second harmonic is enough to decode phase distortions. This simple approach works well in all asymmetric phase functions. For symmetric phase

functions there are potential ambiguities. For example, quadratic chirp only leads to attenuation of the second harmonic spectrum; from this attenuation alone, it would be impossible to determine the sign of the chirp. A setup that compares the SHG spectrum from a pulse that has been additionally shaped by a known phase function would solve those ambiguities. The resulting data then contains enough information to determine the spectral phase of the ultrafast pulse, including sign.

[0055] As a communications device, the above system can use the phase introduced in ultra-short pulses, taking advantage of multiphoton intrapulse interference to tune the nonlinear optical conversion, for example second harmonic generation spectrum, to decode phase encoded data transmissions. The encoder can be used to encode information that upon nonlinear optical conversion, for example second harmonic generation, yields a specific set of peak heights at specific wavelengths. This encoder can use sine or cosine functions to create a peak in the second order spectrum. Conversely, the encoder can create a number of peaks on the second order spectrum thereby achieving a greater number of communication bits. Fast encoding and almost instantaneous decoding of shaped pulse phases using phase functions as discussed herein can be achieved with the present invention.

[0056] When thin doubling crystals are used, a dispersive spectrometer 503 (see Figure 15), such as a grating, prism or similar device, is required to detect the resulting wavelength tuning caused by the phase modulation. Different wavelengths will travel to different locations, however, if the signal beam is focused tightly on a thick second harmonic generation crystal 507' (see Figure 12B). Tight focusing, for example $f/1$, ensures that the incident light samples a number of phase matching angles instead of only one. As the phase-matched beam enters the crystal 507' one direction will be preferred based on the phase that was imprinted on the message. The phase imprinted on the pulse can therefore be used for the message to "route itself." These applications are related but different than others in which a long SHG crystal is used with minimal or no focusing, therefore having a narrow frequency conversion range limited by the phase matching angle. In those cases only two outputs are possible emission or no emission. In the present invention emission at multiple wavelengths is possible thereby providing great multiplicity.

[0057] It is noteworthy that when the present invention is used for pulse characterization a reference or known phase function is superimposed to the unknown phase using a pulse shaper 129 (see Figure 15) or alternately, 505 (see Figure 14). A two-dimensional preset, fixed pulse shaping mask (such as that shown in Figure 20) can be employed to allow a one shot method for phase determination and characterization or even for encoding and decoding in communications. With this one shot approach, the phase mask pulse shaper generates pulses that contain a complex two-dimensional phase. Such pulse after nonlinear optical conversion yields hundreds of spectra from one pulse rather than the many pulses otherwise required with more conventional pulse shapers. A two-dimensional CCD camera is used to collect and detect the nonlinear optical signal and retrieve all the information. This single shot system and method factor out instabilities between multiple pulses and are considerably faster than conventional approaches. Furthermore, the two dimensional CCD detector 511 does not require a movable or deformable pulse shaping mask and does not require the conventional need for considerable calculations within computer 531 in order to convert the single dimensional measurements to the more desirable two-dimensional measurements as shown in the phase scanned graphs. In addition to laboratory testing and specimen optic distortion analysis, the MIIPS system and method employing this single shot construction can also be applied to some communication situations in order to add considerably more encoded information into each pulse phase to supply additional encoding variables.

[0058] The MIIPS method is based on the principle that second harmonic generation, as well as other nonlinear optical processes, depend on the phase function $\phi(\omega)$ across the spectrum of the laser pulse. The phase function can be expanded in a Taylor series around carrier frequency $\Omega = \omega - \omega_0$ as follows:

$$\phi(\omega) = \phi(\omega_0) + \phi'(\omega_0)\Omega + \frac{1}{2}\phi''(\omega_0)\Omega^2 + \frac{1}{6}\phi'''(\omega_0)\Omega^3 + \dots,$$

[33]

where the first two terms provide only the relative (common) phase and a time delay, respectively. Only the third and higher terms are responsible for phase distortion. These higher terms are retrieved in MIIPS by superimposing a reference phase function on the pulse to obtain,

$$\phi(\Omega) = \alpha \cos(\gamma\Omega - \delta) + \phi(\Omega)$$

[34]

where the first term is the reference phase function introduced by the shaper with maximum phase amplitude α , period γ and the absolute position in the spectral window δ . $\phi(\Omega)$ is given by Equation 33.

[0059] The maximum SHG signal as a function of Ω is obtained when $d^2\phi(\Omega)/d\Omega^2=0$. A parameter in the reference phase function can be varied to obtain a plot from which the phase distortions (ϕ'' , ϕ''' , ...) can be obtained in the laser pulse. The maximum signal in a (wavelength, δ) MIIPS trace describes a series of lines given by

$$\delta_{\max} = \delta_0 + (\lambda_{\max} - \pi c/\omega_0)\omega_0^2/(\pi c) \{\gamma - \phi'''/(\alpha\gamma^2 \sin \delta_0)\},$$

[35]

10 where δ_{\max} is the position where maximum SHG signal is obtained, $\delta_0 = \arccos[\phi''/(\alpha\gamma^2)]$, and λ_{\max} is the position of the maximum SHG signal.

[0060] A complete data set, from which a phase function can be retrieved, consists of a series of spectra obtained as a function of the parameter δ . The resulting experimental MIIPS trace shown in Figure 16, contains the required information to extract ϕ'' , ϕ''' and higher order terms as follows. First the data is fit to a series of lines which follow $\lambda_{\max}(\delta_{\max})$ as expected from Equation 35. The quadratic phase modulation (responsible for linear chirp) is determined directly from the distances x_1 and x_2 between the SHG maxima (see Figure 16), according to

$$\phi'' = \alpha\gamma^2 \arcsin[(x_1-x_2)/4].$$

[36]

Note that the magnitude and sign of ϕ'' are obtained directly from the MIIPS trace. Furthermore, the accuracy of the measurement can be improved for small phase distortion by decreasing the reference phase function parameters $\alpha\gamma^2$.

25 [0061] The cubic phase modulation (quadratic chirp) is determined by the slope $\Delta\delta/\Delta\lambda$ that the maximum SHG features make in the λ δ plane. Analytically, cubic phase modulation is given by

$$\phi''' = 0.5 \alpha\gamma^2 \pi c/\omega_0^2 \cos[(x_1-x_2)/4] \{(\Delta\delta/\Delta\lambda)_1 - (\Delta\delta/\Delta\lambda)_2\},$$

[37]

where the slopes are measured in nm^{-1} (see Figure 16). Higher order phase distortions, such as self-phase modulation and quadratic phase components can be obtained from the curvature of the line defined by the maximum SHG response.

35 These higher order terms are not always essential and are left for a more elaborate presentation of the theory behind MIIPS. The fit to the experimental data shown in Figure 16 - 17C is given by Equation 35, and the phase parameters are extracted with Equations 36 and 37.

[0062] The version of MIIPS illustrated in Figure 15 uses a thin SHG crystal 507, spectrometer 503, pulse shaper 129 and a femtosecond laser 123. A fs laser pulse is preferred but, for test data disclosed herein, 50 fs pulses from a regeneratively amplified Ti:Sapphire laser were employed wherein the pulse energy was attenuated down to $\sim 5 \mu\text{J}$. For the test data herein, A 0.3 mm βBSO type I crystal was used for SHG 507 and the output was attenuated and directed to spectrometer 503 with a cooled CCD detector 511. System 121 further has a redirecting mirror 513, two quartz cylindrical lenses 515 (200 mm focal length, the upstream one for focusing and the downstream one for collimating). For the tests, a spatial light modulator was used for pulse shaper 129 consisting of two 128 LCD elements (which can be obtained from CRI Inc. as model number SLM-256). For the test, the pulse shaper was carefully calibrated to provide accurate phase delays (better than one degree) with no changes to polarization or amplitude. The phase distortions used to obtain the data were generated at the pulse compressor after regenerative amplification.

[0063] The experimental results in Figure 16 correspond to laser pulses that are close to transform limited. Analysis of the data indicates a residual phase distortion with quadratic and cubic components. The SHG intensity as a function of phase mask position δ is given by the contours. The diagonal lines are fits to the experimental data using Equation 35 and 36, using the spacing between the features and the angles that these make. Figures 17A and 17B present data obtained for positive and negative linear chirp. Changes in the spacing of the SHG signals are shown. In both cases there is some quadratic chirp. In contrast, Figure 17C shows data obtained for heavy quadratic chirp. In this case, the angles of the SHG features are visibly different. This data has a relatively small amount of linear chirp. In other word, in Figures 17A - 17C experimental data is for pulses with greater phase distortion. The MIIPS data of Figures 17A and 17B show positive and negative quadratic phase distortion in addition to a substantial cubic component. The difference in the distance between the features can be used to obtain the sign and magnitude of ϕ'' using Equation 36. The ability to determine quadratic phase modulation by inspection is very valuable given that it results from normal dispersion,

when ultrashort pulses propagate through any optical medium.

[0064] The MIIPS trace obtained for pulses with significant cubic phase modulation is illustrated in Figure 17C. The difference in the angle between the features indicates the presence of cubic phase modulation, which is determined quantitatively using Equation 37. A number of additional measurements have been made using the MIIPS method with the following advantages. The setup is as simple as adding an SHG crystal and sending the output to a spectrometer.

[0065] Because the resolution and range of the MIIPS method are directly proportional to the reference function parameters, it is simple to adjust them as needed. The range is given by $|\phi| < \alpha\gamma^2$ and $|\phi'''| < \alpha\gamma^3$. The resolution is determined by the shaper resolution and, here, was found to be less than one percent of the full range for both ϕ'' and ϕ''' . For example, ϕ'' values can be determined in the range of 10 to 10^5 fs² for 10-100 fs pulses. The simplicity and accuracy of this method make it practical for the evaluation laser pulses close to transform limit and for the evaluation of phase distortion from optical elements.

[0066] Referring now to Figures 13 and 14, self-ultrafast switching is based on pulse phase modulation in pulse shaper 505, a thin SHG crystal 507 causing multiphoton intrapulse interference, dispersive optics 523, and CCD camera detector 511.

[0067] Figure 18 illustrates the software logic flow used in the microprocessor control unit of the personal computer 531, shown in Figure 15. This software is stored on a medium, such as a memory chip of the computer, and determines nonlinear phase distortion for an analysis of optics. This method is based on the use of pulse determination by the phase scan and the measurements can be done for different laser pulse intensities. The software logic flowchart for the automated pulse chirp determination is shown in Figure 19. This software is also stored in the computer's memory and can adjust parameters in the pulse compressor to obtain distortion and to optionally adjust the laser components for chirp. This method is based on the use of a pulse shaper and obtaining a phase scan, which is the spectrum of the SHG as a function of phase parameter δ using the reference phase function:

$$[38] \quad \phi(\omega) = \alpha \cos(\gamma\omega + \delta)$$

This method is non-iterative and directly obtains the desired values without learning algorithms. Therefore, this method is very stable and does not depend on overlap between two pulses in space and time. The pulse in the single laser beam analyzes itself in a thin SHG crystal.

[0068] In summary, the present invention provides a system and method to characterize the spectral phase of femtosecond pulses. This single beam method is capable of retrieving the magnitude and sign of linear and quadratic chirp with high resolution. Pulse retrieval is based on analytical expressions that yield the phase distortion, without iteration or inversion procedures. Linear and quadratic chirp values, and to some extent cubic chirp values, are important because there are knobs on the laser that can be used to correct for this distortion by mechanically adjusting the grating spacing in the laser beam amplifier compressor. The method can be used with very short pulses. This adjustment can be automatically controlled with the computer controlled software as disclosed in Figure 19. The method is very versatile, and can be used with high or very low intensity pulses for any wavelength for which low cost, off-the-shelf SHG crystals exist. MIIPS can also be used by obtaining third or higher order harmonics in gases. The maximum signal will also agree with Equation 35, making the method useful for the characterization of pulses in wavelength regions for which SHG crystals are not available. In summary, uses of MII and MIIPS are as follows:

MII can be used to make self-switching pulses as long as they undergo one non-linear optical process, such as SHG, sum frequency generation, difference frequency generation or four-wave mixing;

MIIPS can be used to allow automated laser optimization, specifically quadratic and cubic phase distortions;

MIIPS can be used for pulse characterization;

MIIPS can be used to measure the phase modulation induced by optical elements and similarly it can be used to measure the thickness of a substrate;

MIIPS can be used for decoding information (address and/or message) stored in the phase;

Shapers operating to optimize the MII phenomenon can encode self-decoding messages;

MII can be used to prevent three photon damage of DNA from fs pulses; and

MII can be used to optimize the activation of PDT agents specifically at a particular depth.

[0069] The following references disclose two-photon photopolymer initiators:

(1) "New Photopolymers based on Two-Photon Absorbing Chromophores and Application to Three-Dimensional Microfabrication and Optical Storage," B. H. Cumpston, J. E. Ehrlich, L. L. Erskine, A. A. Heikal, Z.-Y. Hu, I.-Y. S.

Lee, M. D. Levin, S. R. Marder, D. J. McCord, J. W. Perry, H. Röckel, and X.-L. Wu, Mat. Res. Soc. Symp. Proc., Vol. 488, "Electrical, Optical, and Magnetic Properties of Organic Solid-State Materials IV," (MRS, Warrendale, 1998) p. 217; and

(2) "Two-Photon Polymerisation Initiators for Three-Dimensional Optical Data Storage and Microfabrication," B. H. Cumpston, S. Ananthavel, S. Barlow, D. L. Dyer, J. E. Ehrlich, L. L. Erskine, A. A. Heikal, S. M. Kuebler, I.-Y. Sandy Lee, D. McCord-Maughon, J. Qin, H. Röckel, M. Rumi, X.-L. Wu, S. R. Marder and J. W. Perry, Nature, in press. It is envisioned that multiphoton intrapulse interference can be advantageously used to enhance this non-linear photopolymerization.

[0070] While the preferred embodiment of the control system and system of the present invention have been disclosed, it should be appreciated that various modifications can be made. For example, other laser beam pulse characteristics can be varied and employed with the present invention beyond the pulse shaping, wavelength and duration characteristics preferably described. Furthermore, additional software subroutines and statistical analyses can be employed. Moreover, other optical and pulse shaping components can be used in place of those described. Finally, analog, solid state and fiber optic electrical control circuits can be substituted for or used in addition to a microprocessor and other computer circuitry. Various optics, including lenses and mirrors, can be used to achieve reflecting, collimation or focusing. Additionally, dispersive optics, such as gratings and prisms, can be interchanged. Detection of the laser induced processes may use various spectroscopic methods including laser induced fluorescence, Raman spectroscopy, nuclear magnetic resonance, gas chromatography, mass spectrometry and absorption spectroscopy. While various materials, specimens and components have been disclosed, it should be appreciated that various other materials, specimens and components can be employed.

The invention also proposes the followings items.

Item 1. A system comprising:

- a laser operable to emit a laser beam pulse;
- a pulse shaper operable to shape the laser beam pulse with encoded characteristics;
- a crystal operable to separate multiple frequencies of the pulse;
- a detection device operable to detect the characteristics of the shaped laser beam pulse as separated by the crystal; and
- a unit connected to the device operably decoding the characteristics.

Item 2. The system of Item 1 wherein the laser beam pulse is encoded with a routing address.

Item 3. The system of Item 2 wherein the laser beam pulse is encoded with multiple routing addresses and a second, subsequent laser beam pulse is emitted from the laser and is also encoded by the pulse shaper with multiple routing addresses.

Item 4. The system of Item 3 wherein each routing address contained in the laser beam pulse is encoded by the pulse shaper and corresponds to separate frequencies after second harmonic generation.

Item 5. The system of Item 2 wherein the laser beam pulse is encoded with communications message data.

Item 6. The system of Item 1 further comprising:

- a main transmitting controller; and
- multiple remote initial-transmitting sources connected to the transmitting controller;
- the main transmitting controller operably causing the pulse shaper to encode multiple successive laser beam pulses differently in an active manner.

Item 7. The system of Item 6 wherein the main transmitting controller, laser and pulse shaper act as a main communications transmitter to send encoded optical signals to the to a receiver, including the crystal and detection device, in order to decode the characteristic in an asynchronous manner without autocorrelation and without interferometry.

Item 8. The system of Item 1 wherein the crystal is a second harmonic generation crystal located in a path between the pulse shaper and the detection device.

Item 9. The system of Item 1 wherein the crystal is a thick crystal.

Item 10. The system of Item 1 wherein the unit operably determines quadratic phase modulation.

Item 11. The system of Item 1 further comprising a fiber optic cable carrying the laser beam pulse from the pulse shaper.

Item 12. The system of Item 1 wherein the pulse shaper has a fixed wave form molded on a substrate.

Item 13. The system of Item 1 wherein the laser is a femtosecond laser operable to emit a single laser beam pulse

of less than about 50 femtosecond pulse duration.

Item 14. The system of Item 1 wherein the laser operably transmits a laser beam pulse of less than 11 femtosecond duration.

5 Item 15. The system of Item 1 wherein the pulse shaper is operable to control amplitude and phase of the laser beam pulse.

Item 16. The system of Item 1 wherein the pulse shaper includes a deformable mirror.

Item 17. The system of Item 1 further comprising a lens located between the pulse shaper and the crystal, the lens causing the spectrum of the pulse to converge upon the crystal in a phase matching angle manner for subsequent dispersion and separation by the crystal across substantially the entire spectrum of the pulse.

10 Item 18. The system of Item 1 wherein the detecting device is a CCD camera.

Item 19. The system of Item 1 wherein the detecting device includes an array of optical fibers with multiples of the unit being connected downstream of the corresponding fibers.

Item 20. A system comprising:

15 a laser beam pulse;
a pulse shaper operably varying the pulse;
an optic component operably receiving the pulse as shaped by the pulse shaper in a converging phase matching angle manner and then causing the pulse to diverge into separate color frequencies.

20 Item 21. The system of Item 20 further comprising a single detection device operable to simultaneously detect characteristics for a plurality of the frequencies of the shaped laser beam pulse as separated by the optic component, and the detection device subsequently sending a separate output signal corresponding to each separate frequency detected. Item 22. The system of Item 20 wherein the single laser beam pulse is encoded with the multiple communications routing addresses.

25 Item 23. The system of Item 22 wherein each routing address contained in the laser beam pulse is encoded by the pulse shaper in a separate frequency region.

Item 24. The system of Item 20 wherein the laser beam pulse is encoded by the pulse shaper with communications message data.

30 Item 25. The system of Item 20 further comprising a transmitting control unit and multiple communications sources connected to and sending input signals to the transmitting control unit, the transmitting control unit operably changing an aspect of the pulse shaper to encode multiple successive laser beam pulses in accordance with the input signals received from the communications sources.

Item 26. The system of Item 20 wherein the optic component is a crystal.

35 Item 27. The system of Item 26 wherein the crystal is a second harmonic generation crystal located in a path between the pulse shaper and the detection device.

Item 28. The system of Item 26 wherein the crystal is a thick crystal.

Item 29. The system of Item 26 further comprising a lens located between the pulse shaper and the crystal, the lens causing the spectrum of the pulse to converge upon the crystal in a phase matching angle manner for subsequent dispersion and separation by the crystal across substantially the entire spectrum of the pulse.

40 Item 30. The system of Item 20 further comprising:

a communications transmitter assembly including a laser and the pulse shaper, the laser operably emitting the laser beam pulse; and
45 a communications receiver assembly including the optic component and a detector;
the transmitter assembly operably sending encoded laser signals to the receiver assembly which operably decodes the laser signals in an asynchronous manner based on a predetermined decryption code.

Item 31. The system of Item 20 further comprising a fiber optic cable carrying the laser beam pulse from the pulse shaper.

50 Item 32 A communication system comprising:

a laser operably emitting a laser beam pulse;
an encryptor operably varying at least one characteristic of the pulse to include encoded communications data;
and
55 a remotely located unencryptor operable to decode the varied pulse characteristic in an asynchronous manner.

Item 33. The system of Item 32 wherein the pulse is encoded to carry address routing information and the associated communications information.

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Item 34. The system of Item 32 further comprising at least one passive optic component associated with the unencryptor operably causing self-separation of the encoded pulse. Item 35. The system of Item 34 wherein intrapulse interference causes the self-routing process and the separated frequencies of the pulse corresponding to encoded individual address routing data.

Item 36. The system of Item 32 wherein the encryptor is a pulse shaper located in a communications transmitter.

Item 37. A system comprising:

a laser operably emitting a laser beam pulse;

an optic operably causing phase modulation of the laser beam pulse; and

a unit operably receiving the phase modulated pulse and determining at least one of: (a) the magnitude and (b) sign, of the phase modulation in the frequency domain.

Item 38. The system of Item 37 further comprising a controller calculating a distance from a component associated with the laser to the receiving unit being targeted, by determining the magnitude of the acquired second order phase modulation as the laser beam pulse travels through a fluid.

Item 39. The system of Item 38 wherein the fluid is water.

Item 40. The system of Item 38 wherein the controller makes the distance calculation without a reflected signal from the receiving unit being targeted.

Item 41. The system of Item 37 wherein the unit independently measures quadratic phase modulation from the shaped pulse independent of higher order phase modulations. Item 42. The system of Item 37 wherein the optic is a pulse shaper which introduces a known reference phase to the pulse so the unit can analyze an unknown phase in the pulse.

Item 43. The system of Item 37 wherein the unit includes a spectrometer.

Item 44. The system of Item 37 wherein the unit includes a thick, second harmonic generation crystal and a measuring device.

Item 45. The system of Item 37 further comprising a controller operable to determine the quadratic phase modulation and automatically adjust a member associated with the laser to reduce quadratic chirp.

Item 46. The system of Item 37 wherein a subsequent laser beam pulse is used for photodynamic therapy upon tissue.

Item 47. The system of Item 37 wherein a subsequent laser beam pulse is used for communicating data from a transmission source to a remotely located receiving source. Item 48. The system of Item 37 wherein both the magnitude and sign of the pulse are determined by the receiving unit.

Item 49. A communications system comprising:

a laser operably emitting laser beam pulses;

a first device operable to modify the phase of the pulses emitted from the laser;

a second device operable to interpret communications data carried in the modified pulses, the second device including a crystal having at least second harmonic generation separation properties.

Item 50. The communications system of Item 49 further comprising at least one of the following transmissive media: (a) an optical fiber; (b) air; and (c) water; connecting the first and second devices.

Item 51. The communications system of Item 49 wherein the first device includes a laser beam pulse shaper.

Item 52. The communications system of Item 49 wherein the laser is a femtosecond laser and the first device includes a chirped phase mask element with a passive pulse changing characteristic and a dispersive element.

Item 53. The communications system of Item 49 further comprising a controller operably calculating the distance between a component associated with the laser and the second device being targeted, by determining the magnitude of the acquired second order phase modulation as the laser beam pulse travels through a fluid.

Item 54. The communications system of Item 49 wherein first order harmonic, background free functional imaging occurs when the pulses are received by the second device through use of multiphoton intrapulse interference.

Item 55. The communications system of Item 49 wherein the first device is a deformable mirror and the crystal is a thick crystal.

Item 56. A laser system comprising:

a laser beam pulse;

a pulse shaper operably varying a characteristic of the pulse; and

a device operable to create multiphoton intrapulse interference in the pulse.

Item 57. The system of Item 56 wherein the device causes the pulse to become self-switching when it undergoes a non-linear optical process.

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Item 58. The system of Item 57 wherein the non-linear optical process includes second harmonic generation.

Item 59. The system of Item 57 wherein the non-linear optical process includes sum frequency generation.

Item 60. The system of Item 57 wherein the non-linear optical process includes difference frequency generation.

Item 61. The system of Item 57 wherein the non-linear optical process includes four-wave mixing.

5 Item 62. The system of Item 56 wherein quadratic phase distortions are sensed and automatically minimized if present.

Item 63. The system of Item 56 wherein phase modulation induced by an optical component is measured.

Item 64. The system of Item 56 further comprising a detector operable to receive the shaped pulse.

Item 65. The system of Item 64 wherein the detector includes a CCD camera.

10 Item 66. The system of Item 64 wherein the detector includes an array of optical fibers connected to remote controllers.

Item 67. A system for use with living tissue, the system comprising:

a high peak intensity laser beam pulse; and

15 a device operable to change a characteristic of the pulse prior to emission of the pulse upon the living tissue through use of multiphoton intrapulse interference;

wherein nonlinear transitions induced by each pulse are controlled.

Item 68. The system of Item 67 wherein the device uses a pulse shaper and the desired excited substances in the tissue undergo two photon absorption.

20 Item 69. The system of Item 67 wherein the pulse has a duration of less than fifty one femtoseconds.

Item 70. The system of Item 67 further comprising generating an optical tomography image produced by the shaped pulse passing through the tissue.

Item 71. The system of Item 67 wherein the device is a pulse shaper which enhances two photon absorption by a therapeutic substance and substantially prevents three photon induced damage of adjacent healthy tissue.

25 Item 72. The system of Item 67 wherein the device includes a phase modulation mask operably modifying the beam.

Item 73. The system of Item 67 wherein the pulse is shaped to enhance targeted multiphoton damage to modify or destroy certain molecules in the living tissue.

Item 74. The system of Item 67 wherein the multiphoton intrapulse interference operably activates desired photo-dynamic therapy agents at desired tissue depths.

30 Item 75. A laser beam pulse shaper comprising a substrate and permanently fixed wave patterns located on the substrate, at least some of the wave patterns being offset from each other.

Item 76. The pulse shaper of Item 75 wherein the patterns are offset as a function of the wave phase.

Item 77. The pulse shaper of Item 75 wherein the substrate is polymeric.

Item 78. The pulse shaper of Item 75 wherein the substrate and wave patterns are created by injection molding.

35 Item 79. The pulse shaper of Item 75 wherein the wave pattern is a sine wave which repeats across the substrate with adjacent rows of the pattern being offset from each other.

Item 80. The pulse shaper of Item 75 wherein the wave patterns operably generate hundreds of spectra as output from a single laser beam pulse.

40 Item 81. The pulse shaper of Item 75 wherein the wave pattern is configured for a laser beam pulse of less than about 11 femtosecond duration.

Item 82. A method of using a laser beam, the method comprising:

(a) emitting a laser beam pulse;

(b) shaping the laser beam pulse with encoded data;

45 (c) controlling the nonlinear optical processes induced by the laser beam pulse; and

(d) decoding the data with a receiver in an asynchronous manner.

Item 83. The method of Item 82 further comprising independently measuring quadratic phase modulation from the pulse.

50 Item 84. The method of Item 82 further comprising retrieving the magnitude and sign within a non-linear pulse.

Item 85. The method of Item 82 further comprising retrieving magnitude and sign of the pulse which is of a duration less than about 50 femtoseconds.

Item 86. The method of Item 82 further comprising introducing a known reference phase to the shaped pulse in order to analyze an unknown phase of the shaped pulse.

55 Item 87. The method of Item 82 further comprising scanning the phase of the shaped pulse by use of a spectrometer.

Item 88. The method of Item 82 further comprising scanning the phase of the shaped pulse with the assistance of a thick crystal.

Item 89. A method of using a laser beam, the method comprising:

- (a) emitting a laser beam pulse;
- (b) shaping the laser beam pulse;
- (c) transmitting the shaped pulse through a crystal; and
- (d) measuring a characteristic of the shaped pulse in an asynchronous manner.

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Item 90. The method of Item 89 further comprising independently measuring quadratic phase modulation from the pulse.

Item 91. The method of Item 89 further comprising retrieving the magnitude and sign of the phase modulation in the pulse.

10 Item 92. The method of Item 89 further comprising retrieving magnitude and sign of the phase for a pulse which is of a duration less than about 50 femtoseconds.

Item 93. The method of Item 89 further comprising introducing a known reference phase to the shaped pulse in order to analyze an unknown phase of the shaped pulse.

15 Item 94. The method of Item 89 further comprising analysis of the phase of the shaped pulse by use of a non-linear optical process and a spectrometer.

Item 95. The method of Item 89 further comprising analysis of the phase of the shaped pulse with the assistance of a thick crystal.

20 **Claims**

1. A laser pulse characterization method comprising:

- (a) producing a laser beam pulse (123);
- 25 (b) introducing a known reference phase function in said laser beam pulse (123), wherein said reference phase function is a sine or cosine function comprising a varying phase parameter (δ) that defines the position of said function across the spectrum of said laser beam pulse (123);
- (c) generating harmonic frequencies of said laser beam pulse (123);
- (d) detecting the harmonic frequencies of the laser beam pulse (123);
- 30 (e) obtaining a data set of the detected harmonic frequency intensities of the laser beam pulse (123) versus said varying phase parameter (δ);
- (f) determining changes in said intensities in said data set of the detected harmonic frequency intensities;
- (g) determining a value (δ_{MAX}) corresponding to each intensity maximum in said data set of the detected harmonic frequency intensities;
- 35 (h) determining a second (Φ'') derivative of a spectral phase function of said laser beam pulse (123) from the data set of the detected harmonic frequency intensities;
- (i) automatically correcting a phase distortion in said laser beam pulse (123) on the basis of said second (Φ'') derivative of the spectral phase function by adjusting said known reference phase function by means of a computer without a learning algorithm.

40 2. A laser pulse characterization method according to claim 1, wherein the laser pulse is a femtosecond laser pulse.

3. A laser pulse characterization method according to claim 2, wherein the duration of the laser pulse is in the range of 10 fs to 100 fs.

45 4. A laser pulse characterization method according to any one of claims 1 to 3 for characterization of the spectral phase of a pulse in an automated manner.

5. A laser pulse characterization method according to any one of claims 1 to 4, comprising using a pulse shaper (129; 505) for creating multiphoton intrapulse interference into the pulse.

6. A laser pulse characterization method according to claim 5, comprising the use of a non linear optical element (507) for applying a non linear process to the laser pulse shaped by a pulse shaper (129).

55 7. Software adapted to control a laser pulse characterizing system comprising:

- (a) producing a laser beam pulse (123);
- (b) introducing a known reference phase function in said laser beam pulse (123), wherein said reference phase

function is a sine or cosine function comprising a varying phase parameter (δ) that defines the position of said function across the spectrum of said laser beam pulse (123);

(c) generating harmonic frequencies of said laser beam pulse (123);

(d) detecting the harmonic frequencies of the laser beam pulse (123);

(e) obtaining a data set of the detected harmonic frequency intensities of the laser beam pulse (123) versus said varying phase parameter (δ);

(f) determining changes in said intensities in said data set of the detected harmonic frequency intensities;

(g) determining a value (δ_{MAX}) corresponding to each intensity maximum in said data set of the detected harmonic frequency intensities;

(h) determining a second (Φ'') derivative of a spectral phase function of said laser beam pulse (123) from the data set of the detected harmonic frequency intensities;

(i) controlling a pulse shaper to correct a phase distortion in said laser beam pulse (123) on the basis of said second (Φ'') derivative of the spectral phase function by adjusting said known reference phase function by means of a computer without a learning algorithm.

8. Software according to claim 7, wherein the software is also adapted to characterize the laser pulse without learning algorithms.

9. Software according to claim 7 or 8, wherein the software is also adapted to characterize the spectral phase of the laser pulse.

10. Laser system comprising a control unit (531) using the software according to any one of claims 7 to 10 for controlling the laser system.

11. Laser system according to claim 9 or 10, comprising a non linear optical element (507) for applying a non linear process to the laser pulse after introducing a reference phase function, said non linear process being used for said generation of harmonic frequencies of said laser beam pulse.

12. Laser system according to claim 11, comprising a detector (503, 511) for receiving the shaped pulse after application of the non linear process.

Patentansprüche

1. Laserimpulscharakterisierungsverfahren, umfassend:

(a) Erzeugen eines Laserstrahlimpulses (123);

(b) Einführen einer bekannten Referenzphasenfunktion in den Laserstrahlimpuls (123), wobei die Referenzphasenfunktion eine sin- oder cosinus-Funktion ist, die einen Parameter (δ) der variierenden Phase umfasst, welcher die Position der Funktion über das Spektrum von Laserstrahlimpulsen (123) definiert;

(c) Erzeugen von harmonischen Frequenzen des Laserstrahlimpulses (123);

(d) Feststellen der harmonischen Frequenzen des Laserstrahlimpulses (123);

(e) Gewinnen eines Datensatzes der festgestellten Intensitäten der harmonischen Frequenzen des Laserstrahlimpulses (123) als Funktion des Parameters (δ) der variierenden Phase;

(f) Bestimmen von Änderungen in den Intensitäten im Datensatz der festgestellten Intensitäten der harmonischen Frequenzen;

(g) Bestimmen eines Wertes (δ_{max}), der jedem Intensitätsmaximum im Datensatz der festgestellten Intensitäten der harmonischen Frequenzen entspricht;

(h) Bestimmen einer zweiten Ableitung (Φ'') einer spektralen Phasenfunktion des Laserstrahlimpulses (123) aus dem Datensatz der festgestellten Intensitäten der harmonischen Frequenzen;

(i) automatisches Korrigieren einer Phasenverzerrung im Laserstrahlimpuls (123) auf der Basis der zweiten Ableitung (Φ'') der spektralen Phasenfunktion durch Einstellen der bekannten Referenzphasenfunktion durch einen Computer ohne Lernalgorithmus.

2. Laserimpulscharakterisierungsverfahren nach Anspruch 1, wobei der Laserimpuls ein Femtosekunden-Laserimpuls ist.

3. Laserimpulscharakterisierungsverfahren nach Anspruch 2, wobei die Dauer des Laserimpulses im Bereich von 10

fs bis 100 fs liegt.

4. Laserimpulscharakterisierungsverfahren nach einem der Ansprüche 1 bis 3 zur automatischen Charakterisierung der spektralen Phase eines Impulses.

5. Laserimpulscharakterisierungsverfahren nach einem der Ansprüche 1 bis 4, das die Verwendung eines Impulsformers (129; 505) zum Erzeugen von Multiphotonen-Intraimpulsinterferenz im Impuls umfasst.

6. Laserimpulscharakterisierungsverfahren nach Anspruch 5, welches die Verwendung eines nichtlinearen optischen Elementes (507) zum Anwenden eines nichtlinearen Prozesses auf den Laserimpuls umfasst, der von einem Impulsformer (129) geformt ist.

7. Software, die zum Steuern eines Laserimpulscharakterisierungsverfahrens ausgelegt ist, umfassend:

(a) Erzeugen eines Laserstrahlimpulses (123);

(b) Einführen einer bekannten Referenzphasenfunktion in den Laserstrahlimpuls (123), wobei die Referenzphasenfunktion eine sin- oder cosinus-Funktion ist, die einen Parameter (δ) der variierenden Phase umfasst, der die Position der Funktion über das Spektrum von Laserstrahlimpulsen (123) definiert;

(c) Erzeugen von harmonischen Frequenzen des Laserstrahlimpulses (123);

(d) Feststellen der harmonischen Frequenzen des Laserstrahlimpulses (123);

(e) Gewinnen eines Datensatzes der festgestellten Intensitäten der harmonischen Frequenzen des Laserstrahlimpulses (123) als Funktion des Parameters (δ) der variierenden Phase;

(f) Bestimmen von Änderungen in den Intensitäten im Datensatz der festgestellten Intensitäten der harmonischen Frequenzen;

(g) Bestimmen eines Wertes (δ_{max}), der jedem Intensitätsmaximum im Datensatz der festgestellten Intensitäten der harmonischen Frequenzen entspricht;

(h) Bestimmen einer zweiten Ableitung (Φ'') einer spektralen Phasenfunktion des Laserstrahlimpulses (123) aus dem Datensatz der festgestellten Intensitäten der harmonischen Frequenzen;

(i) Steuern eines Impulsformers zum Korrigieren einer Phasenverzerrung im Laserstrahlimpuls (123) auf der Basis der zweiten Ableitung (Φ'') der spektralen Phasenfunktion durch Einstellen der bekannten Referenzphasenfunktion durch einen Computer ohne Lernalgorithmus.

8. Software nach Anspruch 7, wobei die Software auch zum Charakterisieren des Laserimpulses ohne Lernalgorithmus ausgelegt ist.

9. Software nach Anspruch 7 oder 8, wobei die Software auch zum Charakterisieren der spektralen Phase des Laserimpulses ausgelegt ist.

10. Lasersystem, das eine Steuereinheit (531) umfasst, welche die Software nach einem der Ansprüche 7 bis 10 zum Steuern des Lasersystems verwendet.

11. Lasersystem nach Anspruch 9 oder 10, das ein nichtlineares optisches Element (507) zum Anwenden eines nichtlinearen Prozesses auf den Laserimpuls nach dem Einführen einer Referenzphasenfunktion umfasst, wobei der nichtlineare Prozess zur Erzeugung von harmonischen Frequenzen des Laserstrahlimpulses verwendet wird.

12. Lasersystem nach Anspruch 11, das einen Detektor (503, 511) zum Aufnehmen des geformten Impulses nach Anwendung des nichtlinearen Prozesses umfasst.

Revendications

1. Procédé de caractérisation d'impulsion laser comprenant :

(a) la production d'une impulsion de faisceau laser (123) ;

(b) l'introduction d'une fonction de phase de référence connue dans ladite impulsion de faisceau laser (123), ladite phase de référence connue étant une fonction sinus ou cosinus comprenant un paramètre de phase variable (δ) qui définit la position de ladite fonction dans le spectre de ladite impulsion de faisceau laser (123) ;

(c) la génération de fréquences harmoniques de ladite impulsion de faisceau laser (123) ;

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- (d) la détection des fréquences harmoniques de l'impulsion de faisceau laser (123) ;
(e) l'obtention d'un ensemble de données des intensités de fréquences harmoniques détectées de l'impulsion de faisceau laser (123) par rapport audit paramètre de phase variable (δ) ;
(f) la détermination de changements desdites intensités dans ledit ensemble de données des intensités de fréquences harmoniques détectées ;
(g) la détermination d'une valeur (δ_{MAX}) correspondant à chaque maximum d'intensité dans ledit ensemble de données des intensités de fréquences harmoniques détectées ;
(h) la détermination d'une dérivée seconde (Φ'') d'une fonction de phase spectrale de ladite impulsion de faisceau laser (123) à partir de l'ensemble de données des intensités de fréquences harmoniques détectées ;
(i) la correction automatique d'une distorsion de phase dans ladite impulsion de faisceau laser (123) en fonction de ladite dérivée seconde (Φ'') de la fonction de phase spectrale en réglant ladite fonction de phase de référence connue au moyen d'un ordinateur sans algorithme d'apprentissage.
2. Procédé de caractérisation d'impulsion laser selon la revendication 1, dans lequel l'impulsion laser est une impulsion laser de femtosecondes.
3. Procédé de caractérisation d'impulsion laser selon la revendication 2, dans lequel la durée de l'impulsion laser est comprise dans la gamme de 10 fs à 100 fs.
4. Procédé de caractérisation d'impulsion laser selon l'une quelconque des revendications 1 à 3 pour la caractérisation de la phase spectrale d'une impulsion de manière automatisée.
5. Procédé de caractérisation d'impulsion laser selon l'une quelconque des revendications 1 à 4, comprenant l'utilisation d'un conformateur d'impulsion (129 ; 505) pour créer une interférence intra-impulsion multiphotonique dans l'impulsion.
6. Procédé de caractérisation d'impulsion laser selon la revendication 5, comprenant l'utilisation d'un élément optique non linéaire (507) pour appliquer un processus non linéaire à l'impulsion laser conformée par un conformateur d'impulsion (129).
7. Logiciel adapté pour commander un système de caractérisation d'impulsion laser comprenant :
- (a) la production d'une impulsion de faisceau laser (123) ;
(b) l'introduction d'une fonction de phase de référence connue dans ladite impulsion de faisceau laser (123), ladite phase de référence connue étant une fonction sinus ou cosinus comprenant un paramètre de phase variable (δ) qui définit la position de ladite fonction dans le spectre de ladite impulsion de faisceau laser (123) ;
(c) la génération de fréquences harmoniques de ladite impulsion de faisceau laser (123) ;
(d) la détection des fréquences harmoniques de l'impulsion de faisceau laser (123) ;
(e) l'obtention d'un ensemble de données des intensités de fréquences harmoniques détectées de l'impulsion de faisceau laser (123) par rapport audit paramètre de phase variable (δ) ;
(f) la détermination de changements desdites intensités dans ledit ensemble de données des intensités de fréquences harmoniques détectées ;
(g) la détermination d'une valeur (δ_{MAX}) correspondant à chaque maximum d'intensité dans ledit ensemble de données des intensités de fréquences harmoniques détectées ;
(h) la détermination d'une dérivée seconde (Φ'') d'une fonction de phase spectrale de ladite impulsion de faisceau laser (123) à partir de l'ensemble de données des intensités de fréquences harmoniques détectées ;
(i) la commande d'un conformateur d'impulsion pour corriger une distorsion de phase dans ladite impulsion de faisceau laser (123) en fonction de ladite dérivée seconde (Φ'') de la fonction de phase spectrale en réglant ladite fonction de phase de référence connue au moyen d'un ordinateur sans algorithme d'apprentissage.
8. Logiciel selon la revendication 7, le logiciel étant également adapté pour caractériser l'impulsion laser sans algorithmes d'apprentissage.
9. Logiciel selon la revendication 7 ou 8, le logiciel étant également adapté pour caractériser la phase spectrale de l'impulsion laser.
10. Système laser comprenant une unité de commande (531) utilisant le logiciel selon l'une quelconque des revendications 7 à 10 pour commander le système laser.

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11. Système laser selon la revendication 9 ou 10, comprenant un élément optique non linéaire (507) pour appliquer un processus non linéaire à l'impulsion laser après l'introduction d'une fonction de phase de référence, ledit processus non linéaire étant utilisé pour ladite génération de fréquences harmoniques de ladite impulsion de faisceau laser.

5 12. Système laser selon la revendication 11, comprenant un détecteur (503, 511) pour recevoir l'impulsion conformée après l'application du processus non linéaire.

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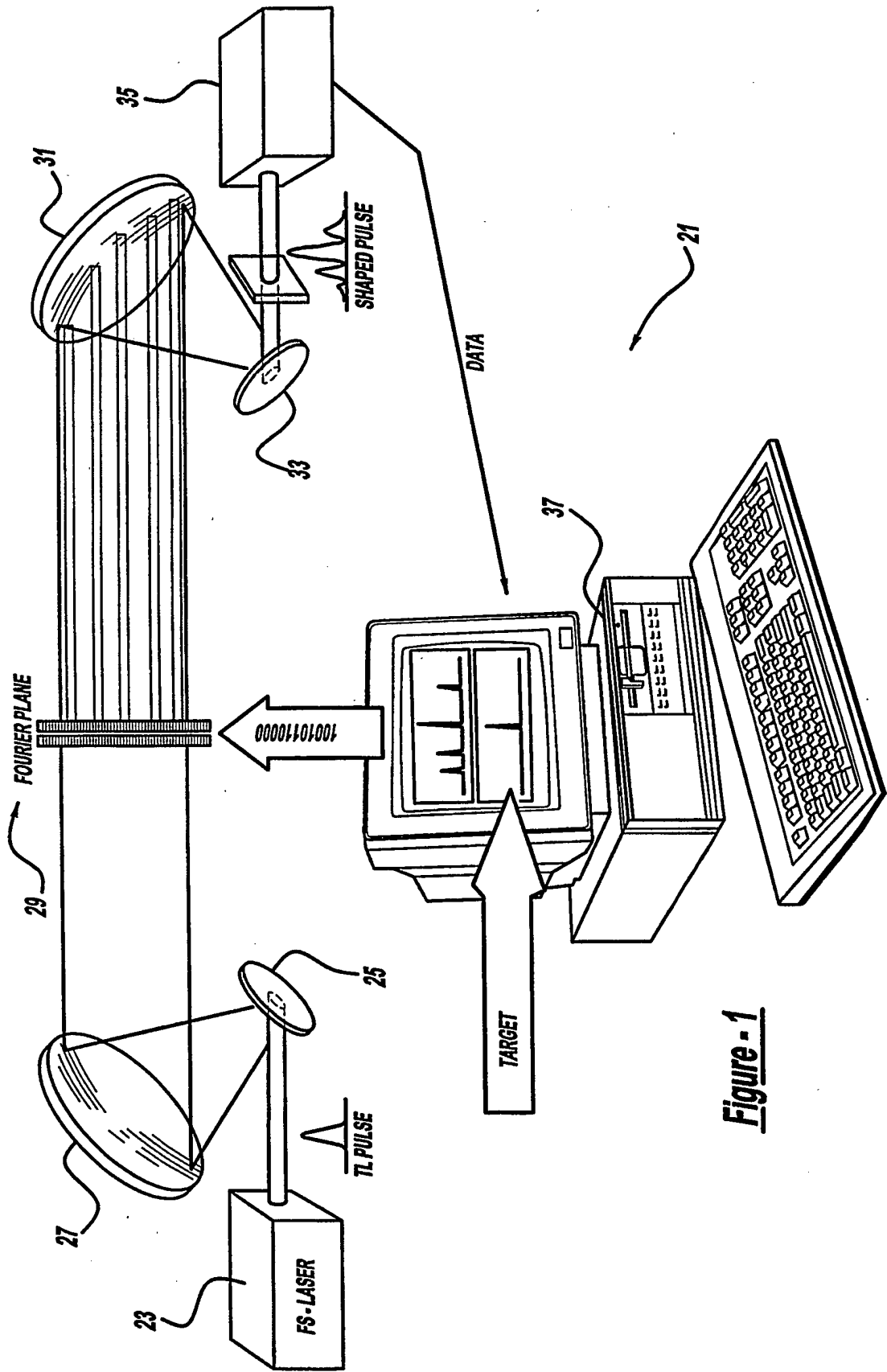


Figure - 1

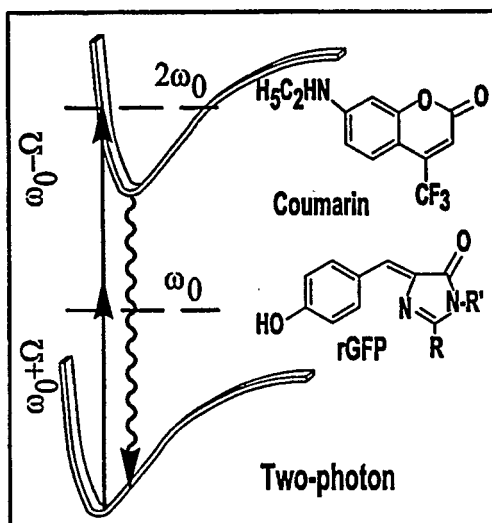


Figure - 2A

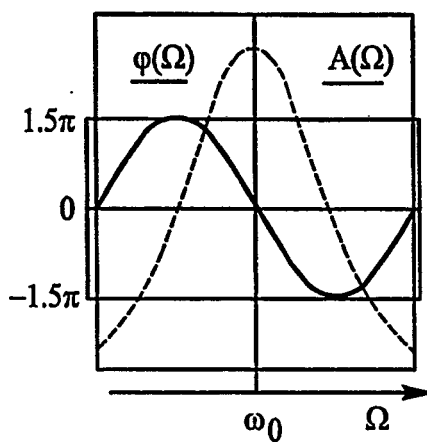


Figure - 2B

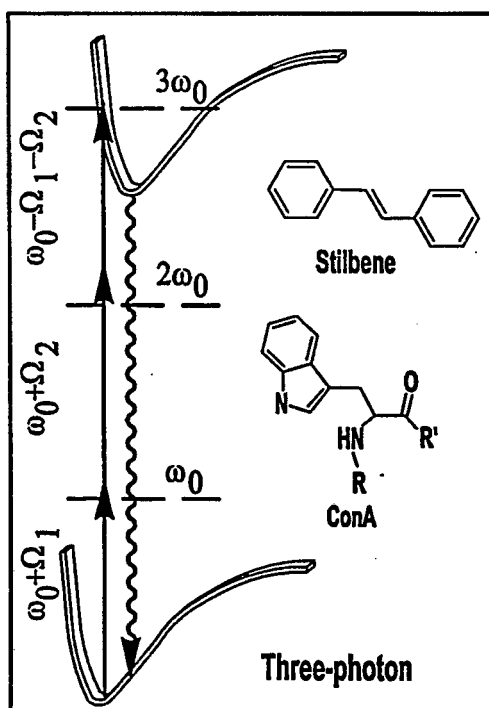


Figure - 2C

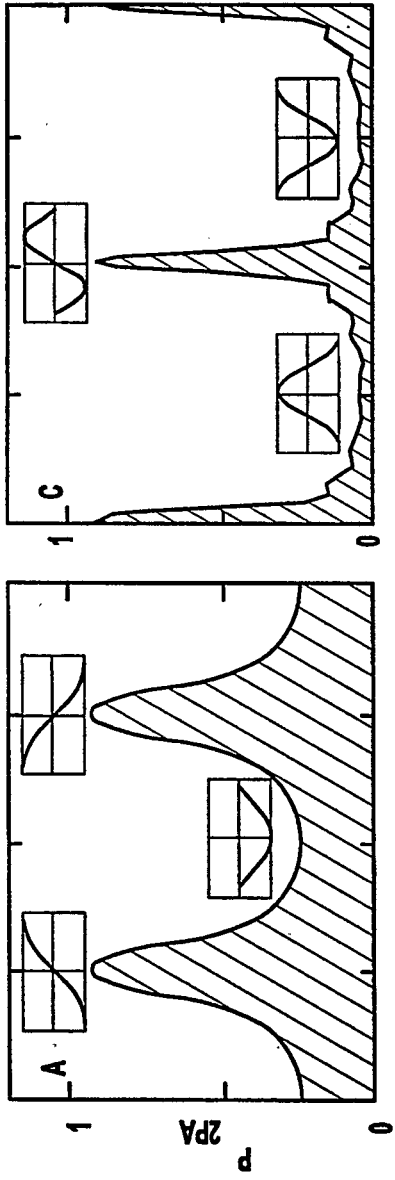


Figure - 3A

Figure - 3C

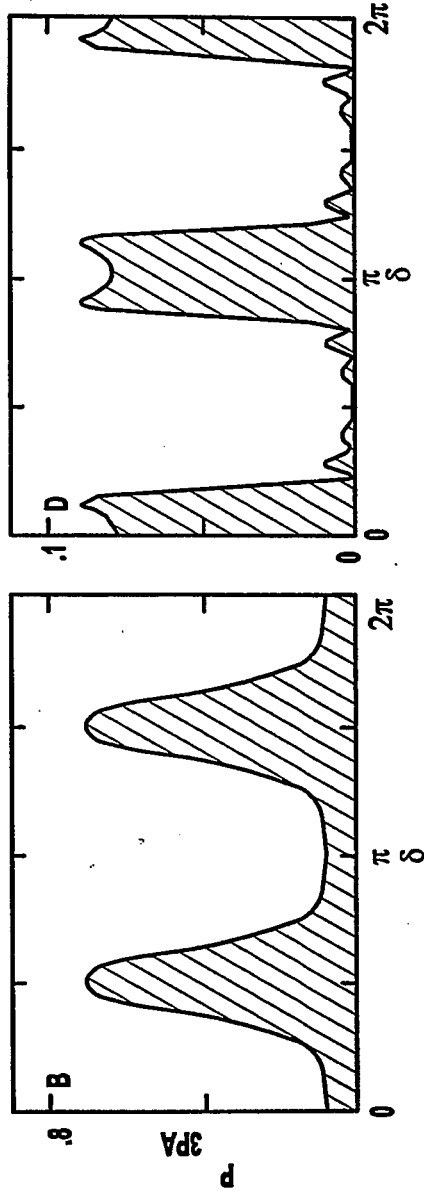


Figure - 3B

Figure - 3D

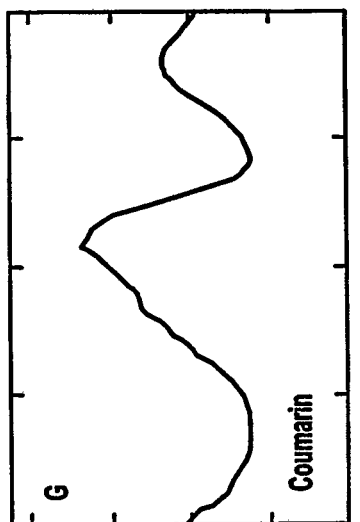


Figure - 3E

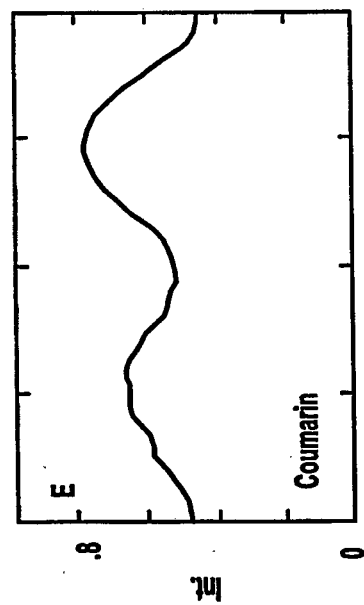


Figure - 3G

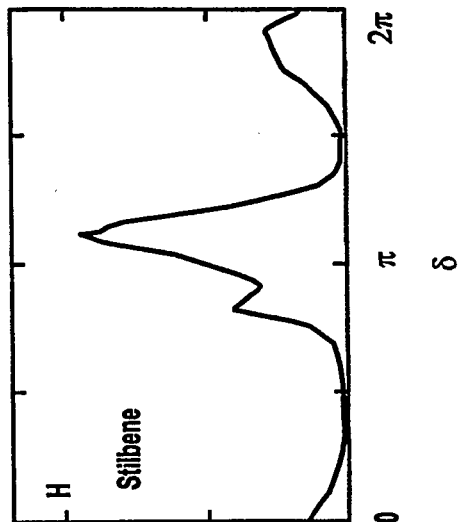


Figure - 3F

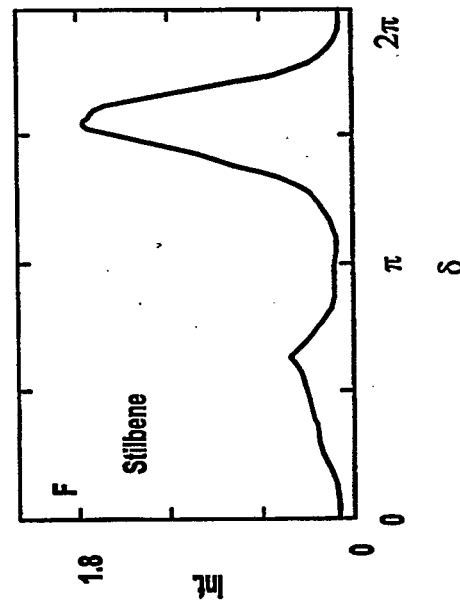


Figure - 3H

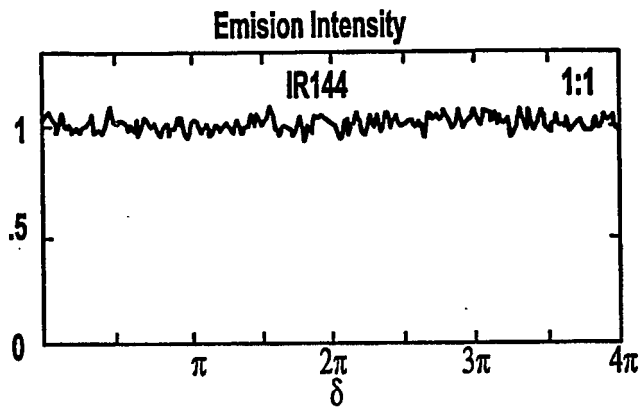


Figure - 4A

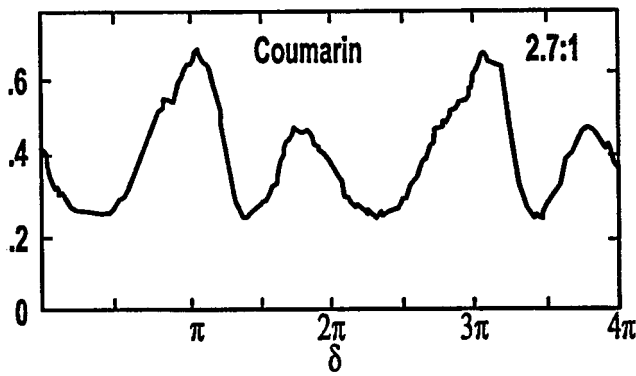


Figure - 4B

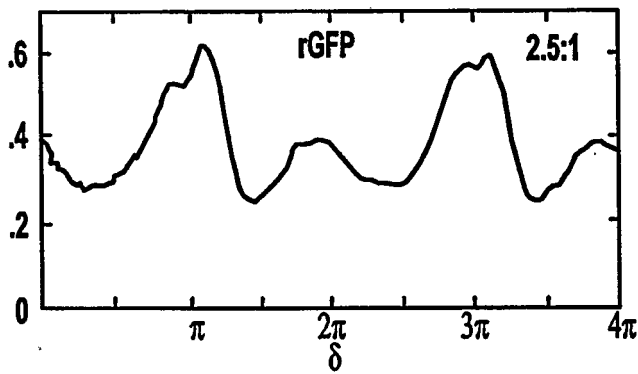


Figure - 4C

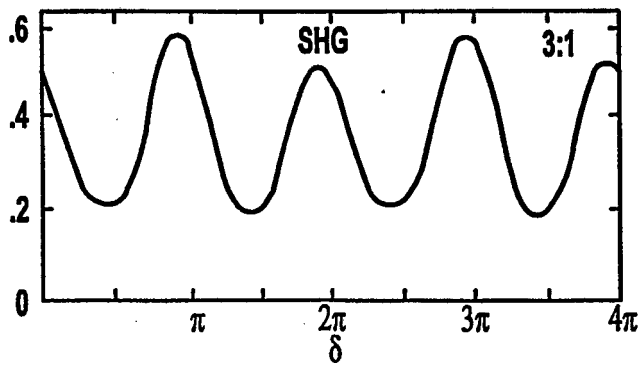


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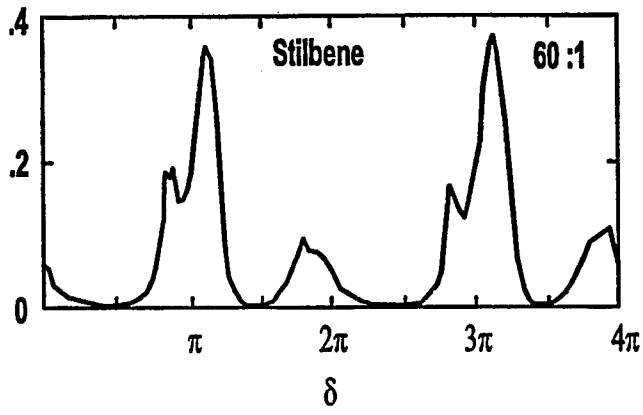


Figure - 4E

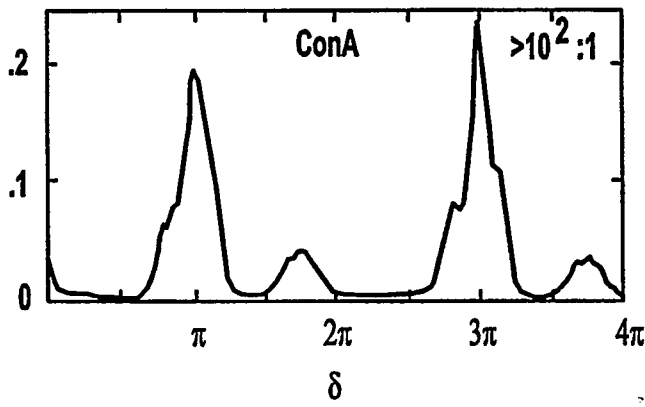


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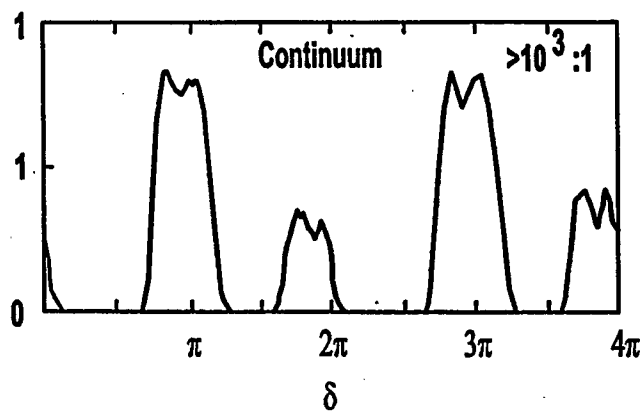


Figure - 4G

□ one vs. ▨ multiphoton

>1000 : 1

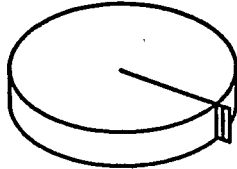


Figure - 5A

1 : 0.6

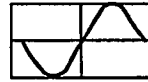
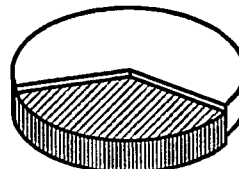


Figure - 5B

▨ two vs. ▨ multiphoton

>1000 : 1

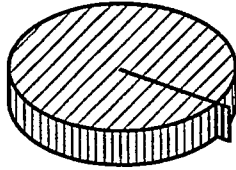


Figure - 5C

1 : 4

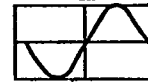
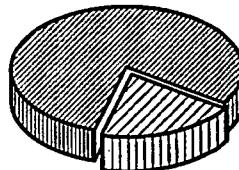


Figure - 5D

▨ two vs. ▨ three photon

1.4 : 1

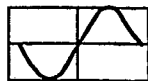
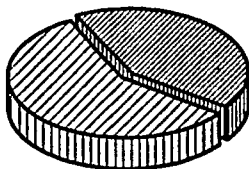


Figure - 5E

1 : 2.2

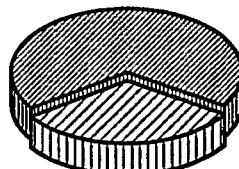


Figure - 5F

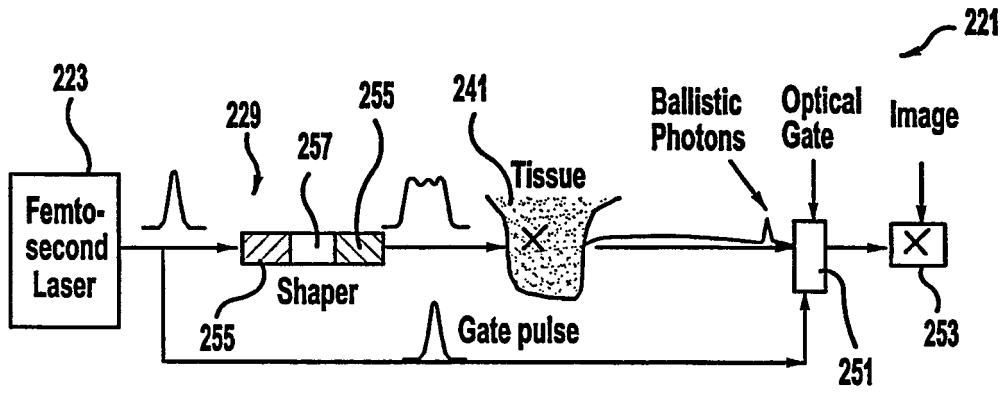


Figure - 6

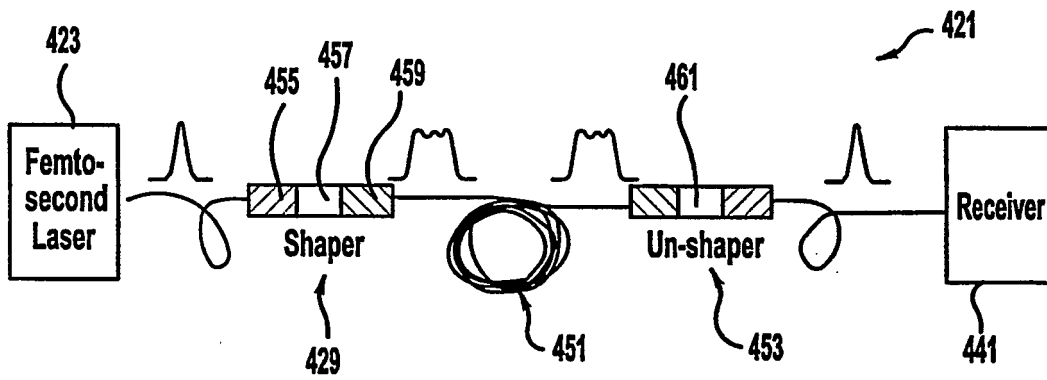


Figure - 10

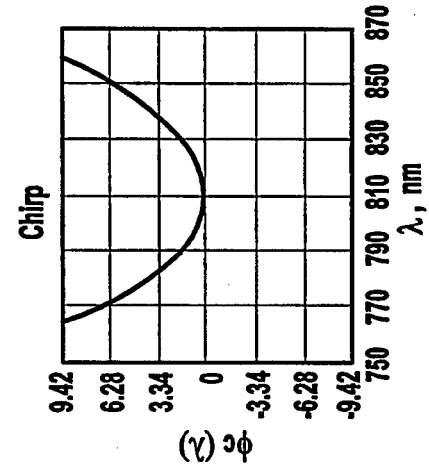


Figure - 7A

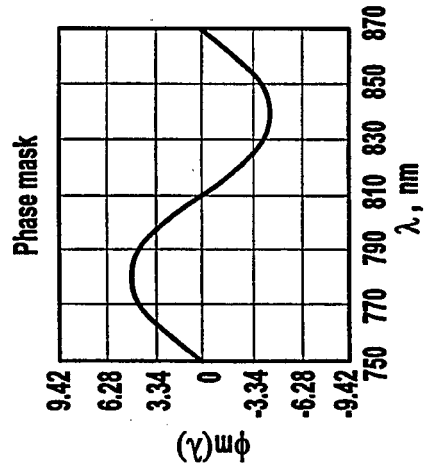


Figure - 7B

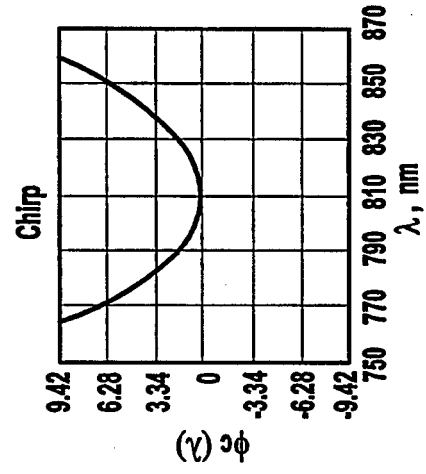


Figure - 7C

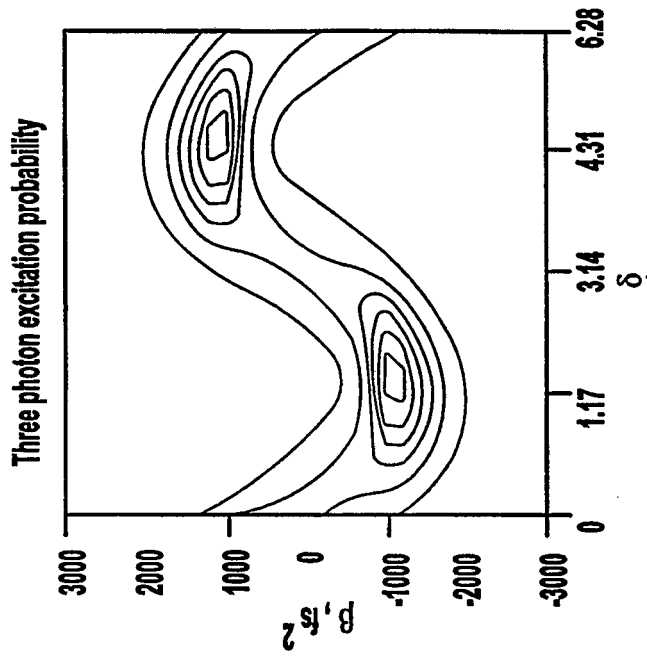


Figure - 8B

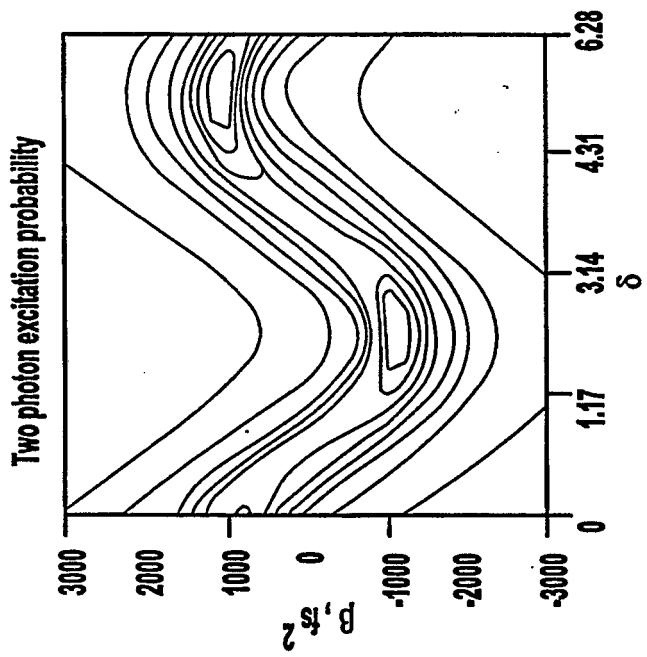


Figure - 8A

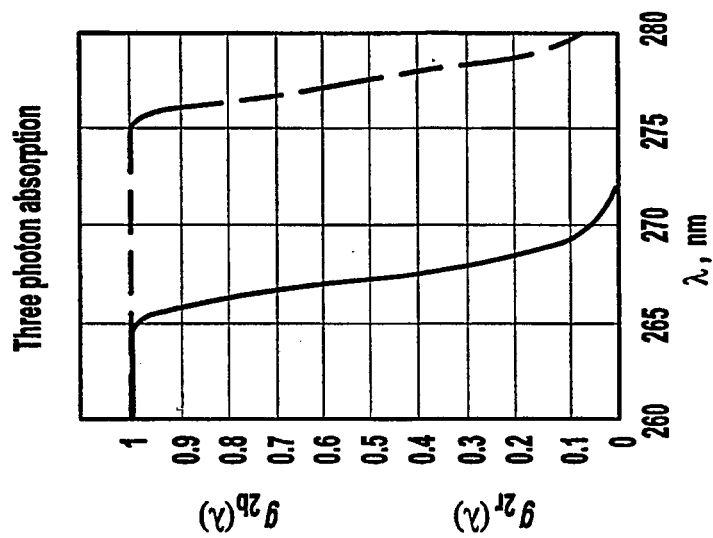


Figure - 9B

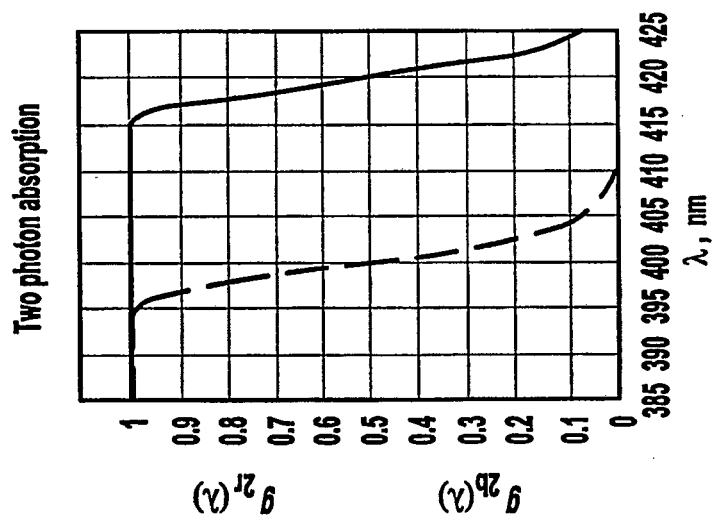


Figure - 9A

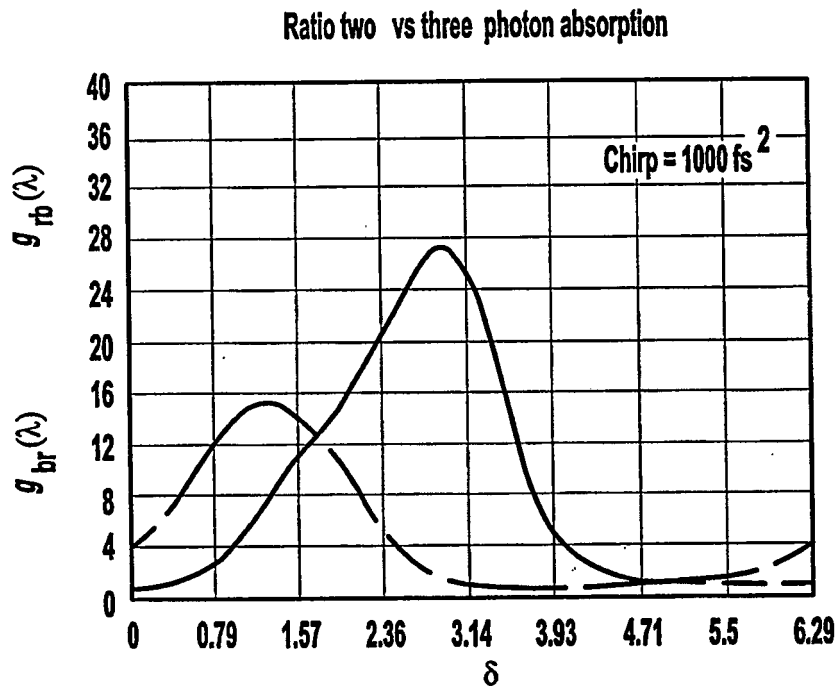


Figure - 9C

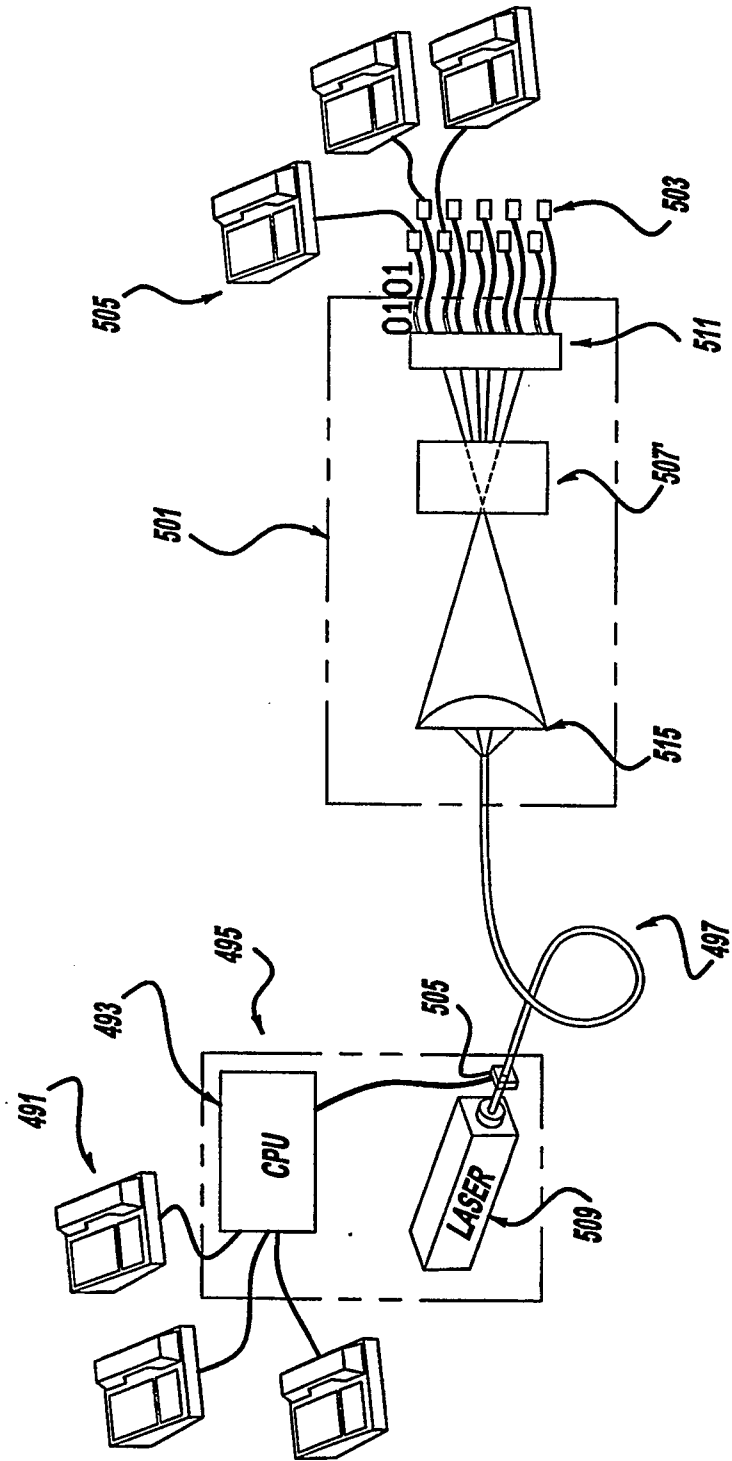


Figure - 11

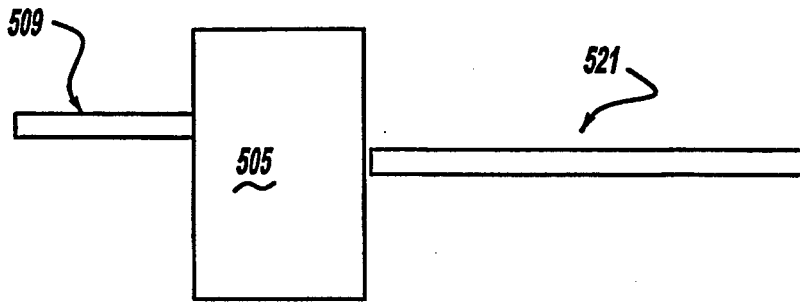


Figure - 12A

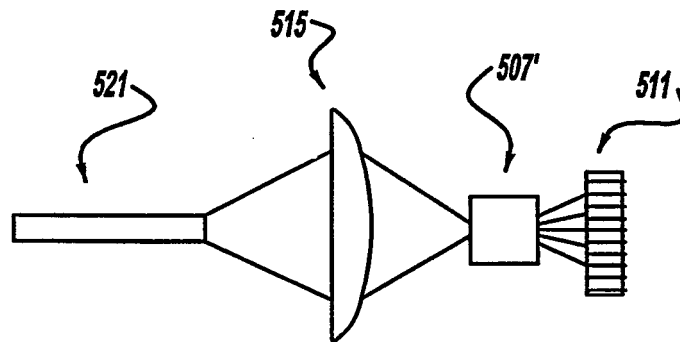


Figure - 12B

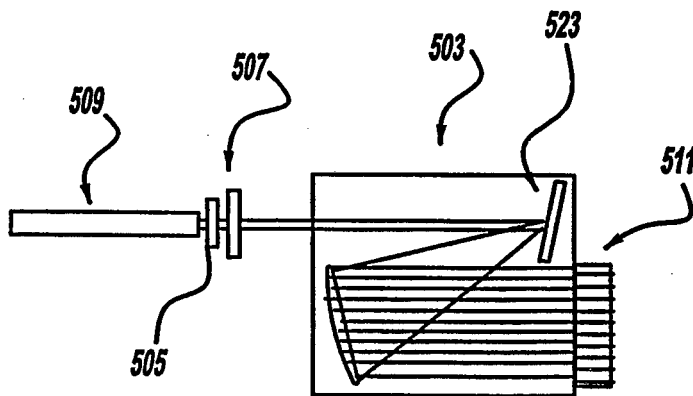


Figure - 14

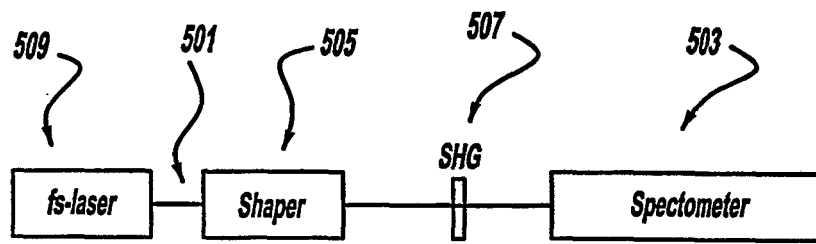


Figure - 13

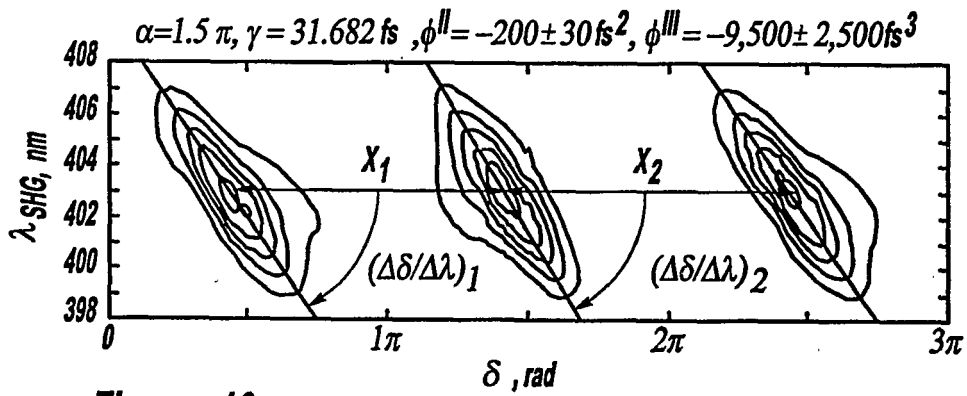


Figure - 16

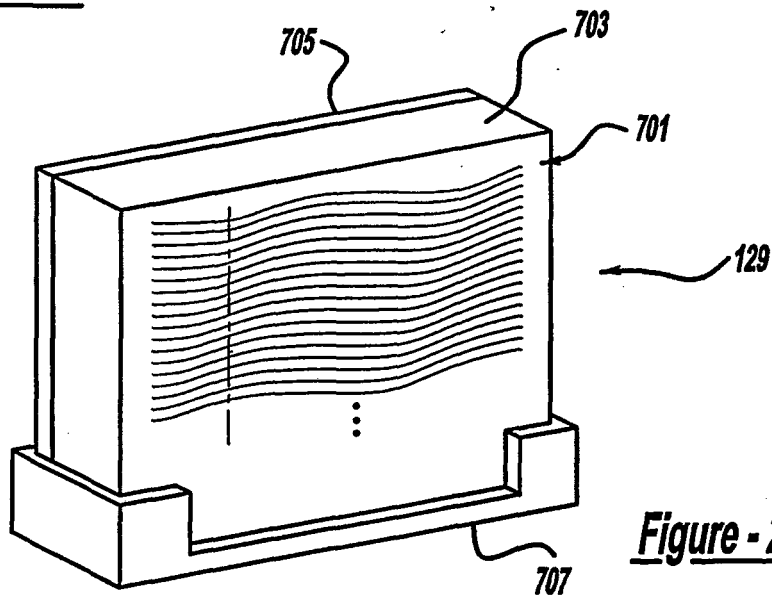


Figure - 20

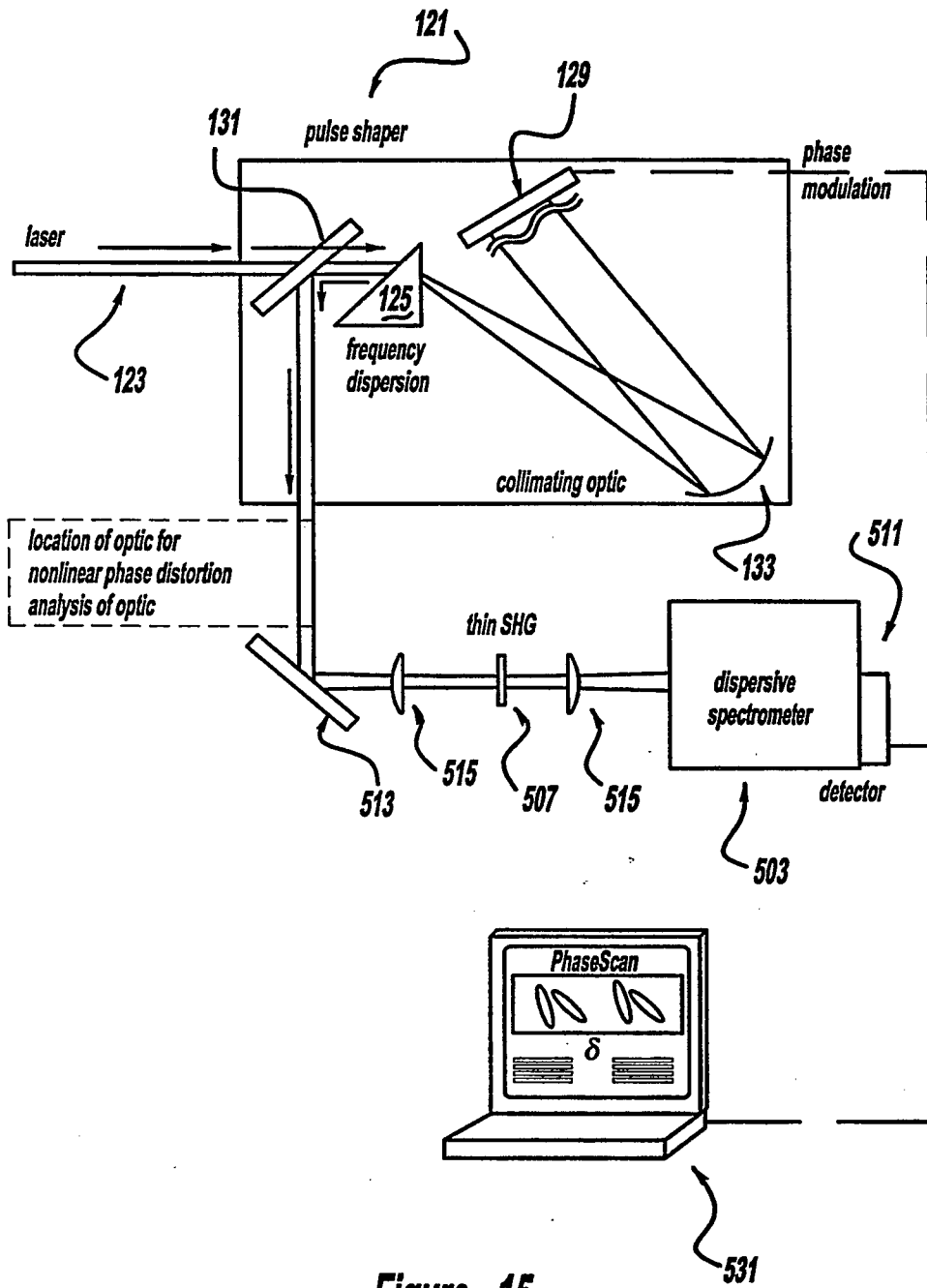


Figure - 15

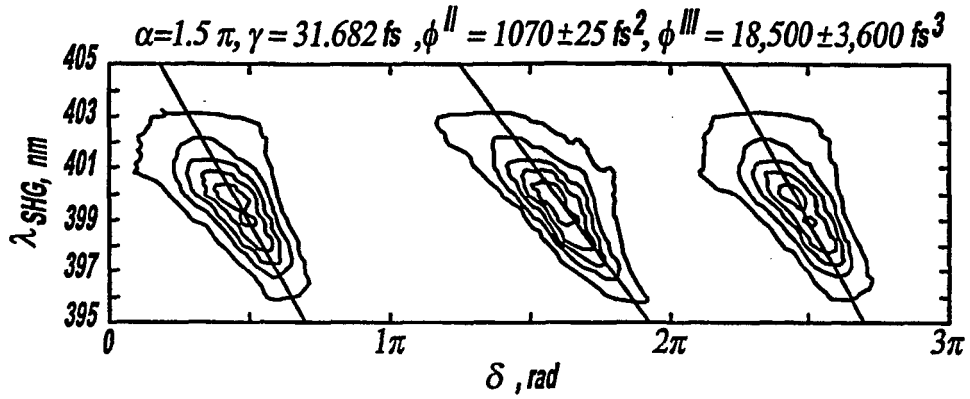


Figure - 17A

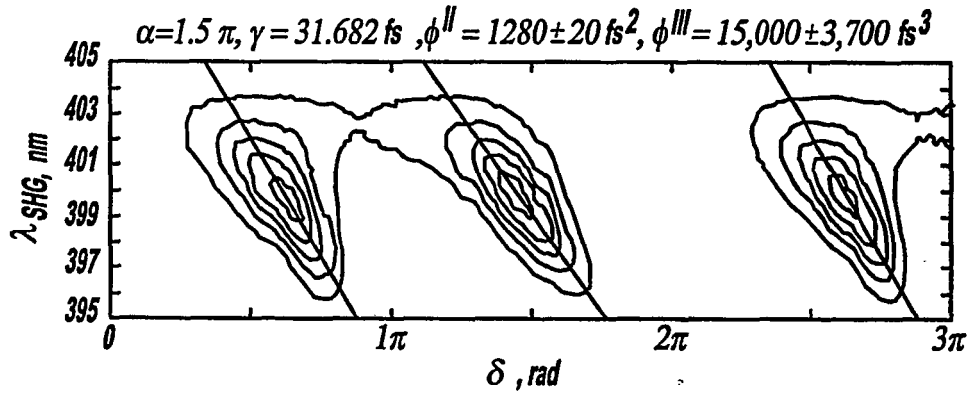


Figure - 17B

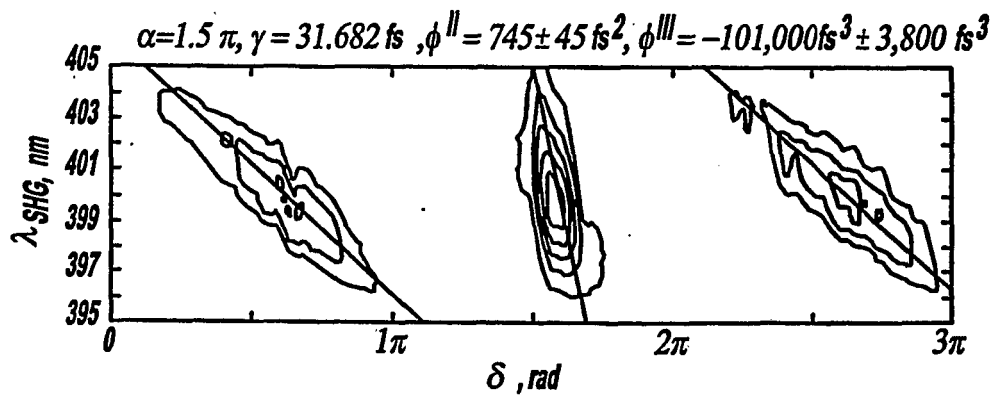


Figure - 17C

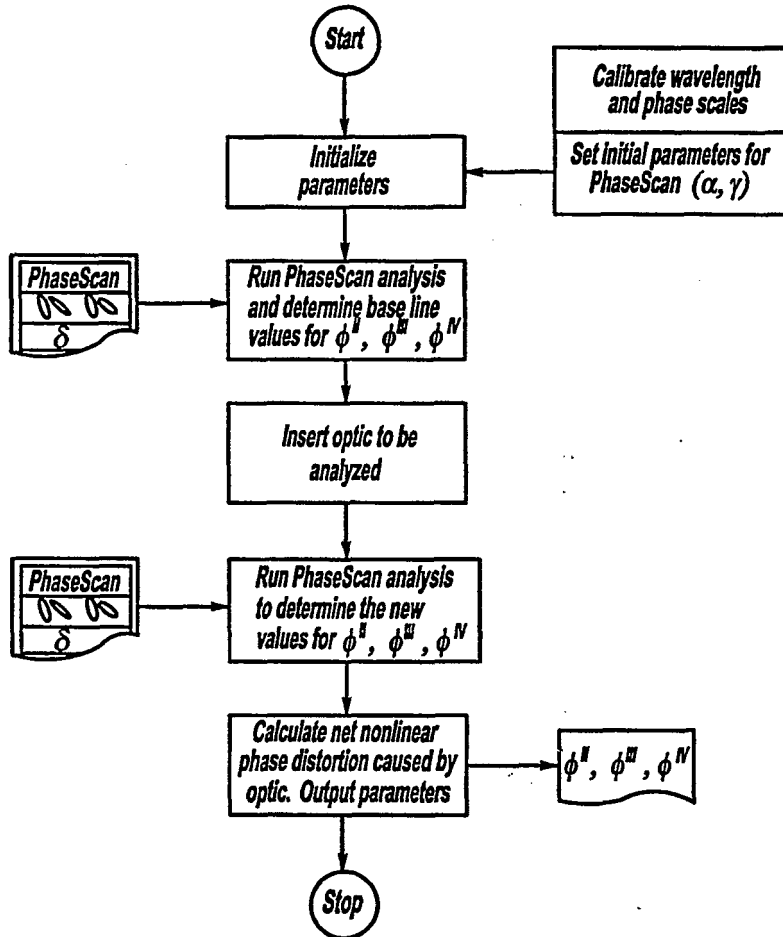


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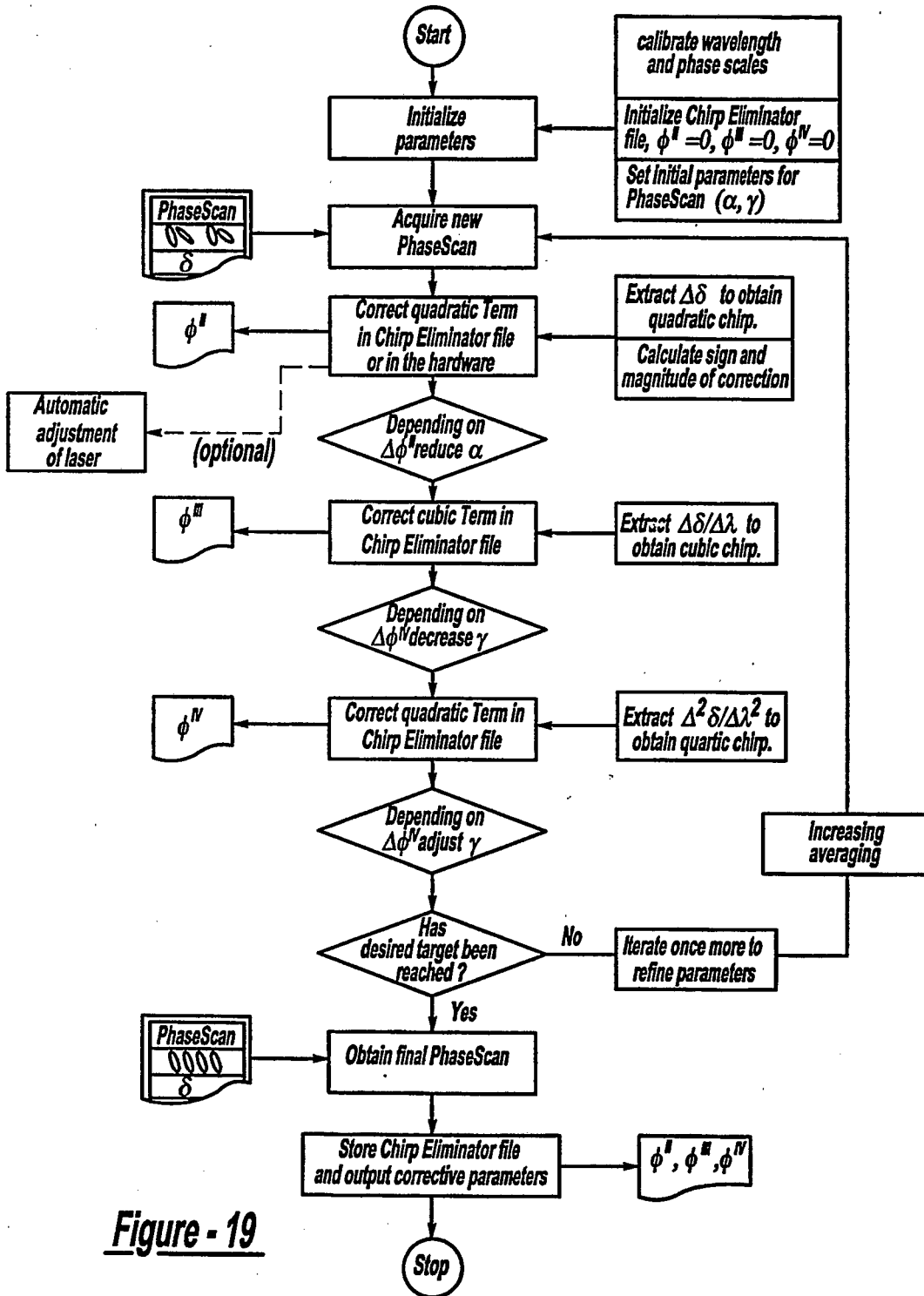


Figure - 19

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 6042603 A [0020]

Non-patent literature cited in the description

- **MATUSCHEK et al.** Back-side-coated Chirped Mirrors with Ultra-smooth Broadband Dispersion Characteristics. *Applied Physics B*, 2000, 509-522 [0019]
- **A. H. BUIST ; M. MULLER ; R. I. GHAUHARALI ; G. J. BRAKENHOFF ; J. A. SQUIRE ; C. J. BARDEEN ; V. V. YAKOVLEV ; K. R. WILSON.** Probing microscopic chemical environments with high-intensity chirped pulses. *Optics Letters*, 1999, vol. 24, 244-246 [0034]
- **MITRA et al.** Nonlinear Limits to the Information Capacity of Optical Fibre Communications. *Nature*, 28 June 2001, vol. 411, 1027-1030 [0047]
- **A. M. WEINER.** Femtosecond pulse shaping using spatial light modulators. *Rev. Sci. Instrum.*, 2000, vol. 71, 1929-1960 [0053]
- **B. H. CUMPSTON ; J. E. EHRLICH ; L. L. ERSKINE ; A. A. HEIKAL ; Z.-Y. HU ; I.-Y. S. LEE ; M. D. LEVIN ; S. R. MARDER ; D. J. MCCORD ; J. W. PERRY.** Electrical, Optical, and Magnetic Properties of Organic Solid-State Materials IV. *Mat. Res. Soc. Symp. Proc.*, 1998, vol. 488, 217 [0069]
- **B. H. CUMPSTON ; S. ANANTHAVEL ; S. BARLOW ; D. L. DYER ; J. E. EHRLICH ; L. L. ERSKINE ; A. A. HEIKAL ; S. M. KUEBLER ; I.-Y. SANDY LEE ; D. MCCORD-MAUGHON.** Two-Photon Polymerisation Initiators for Three-Dimensional Optical Data Storage and Microfabrication. *Nature* [0069]

专利名称(译)	使用超短激光脉冲的激光系统		
公开(公告)号	EP2341587B1	公开(公告)日	2014-06-04
申请号	EP2011158256	申请日	2003-10-02
申请(专利权)人(译)	受托人委员会操作密歇根州立大学		
当前申请(专利权)人(译)	受托人委员会操作密歇根州立大学		
[标]发明人	DANTUS MARCOS LOZOVY VADIM V		
发明人	DANTUS, MARCOS LOZOVY, VADIM, V.		
IPC分类号	A61N5/06 A61B5/00 G01N21/64 H01S3/00 G01B9/02 H01J49/16		
CPC分类号	H01S3/0057 A61B5/0066 A61B5/0073 A61N5/062 G01B9/02014 G01B9/02044 G01B9/02091 G01N21/6402		
优先权	10/265211 2002-10-04 US		
其他公开文献	EP2341587A3 EP2341587A2		
外部链接	Espacenet		

摘要(译)

本发明提出使用多光子脉冲间干涉相位扫描来进行激光脉冲表征。它还提出了一种用于激光系统的软件，包括适于使用该软件控制激光系统的控制单元 (531)，该软件使控制单元 (531) 基于在参考相位函数中引入参考相位函数来表征激光脉冲。激光脉冲。本发明还提出了一种可操作于在激光脉冲上执行多光子脉冲间干涉相位扫描的激光系统，包括使用所述软件控制激光系统的控制单元 (531)。

$$E_{\text{shaped}}(\omega) = E_{\text{input}}(\omega) r(\omega) e^{i\phi(\omega)}$$