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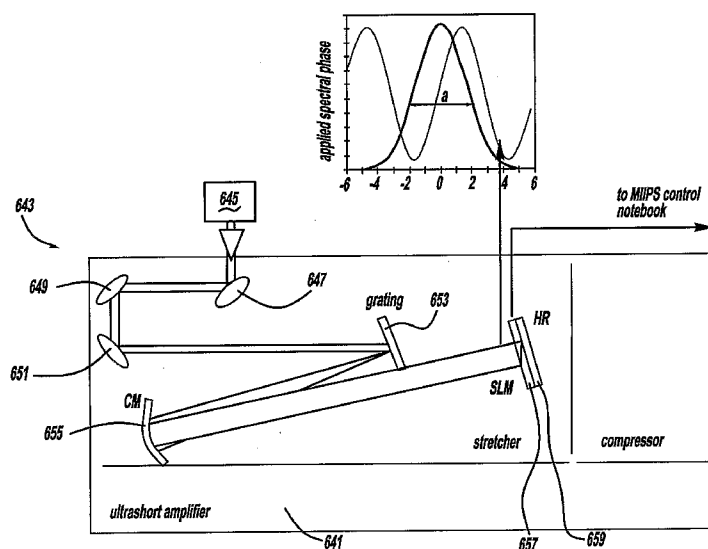
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(54) Title: CONTROL SYSTEM AND APPARATUS FOR USE WITH ULTRA-FAST LASER



(57) Abstract: A control system and apparatus for use with an ultra-fast laser is provided. In another aspect of the present invention, the apparatus includes a laser, pulse shaper, detection device and control system. A multiphoton intrapulse interference method is used to characterize the spectral phase of laser pulses and to compensate for any distortions in an additional aspect of the present invention. In another aspect of the present invention, a system employs multiphoton intrapulse interference phase scan. Furthermore, another aspect of the present invention locates a pulse shaper and/or MIIPS unit between a spectral dispersion point in a laser oscillator and an output of a laser amplifier.



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*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

## CONTROL SYSTEM AND APPARATUS FOR USE WITH ULTRA-FAST LASER

### BACKGROUND AND SUMMARY OF THE INVENTION

**[0001]** The present invention generally relates to a laser, and more particularly, to a control system and apparatus for use with an ultra-fast laser.

**[0002]** Conventionally, laser desorption mass spectrometry has been used with a fixed laser beam pulse shape and computers for simple chemical analysis processes on purified molecules with or without a matrix. The laser beam pulse shape was not considered an important parameter and was not modified; whatever fixed shape was set by the manufacturer for the ultraviolet laser was used in the tests. The general concept of typically laser selective ion formation from molecules in a molecular beam is disclosed in the following publication: Assion et al., "Control of Chemical Reactions by Feedback-Optimized Phase-Shaped Femtosecond Laser Pulses," *Science*, Vol. 282, page 919 (October 30, 1998). The pulse shaping process with a learning algorithm is disclosed in Judson et al., "Teaching Lasers to Control Molecules," *Physical Review Letters*, Vol. 68, No. 10, page 1500 (March 9, 1992). It is noteworthy, however, that the Assion article discloses use of an 80 femtosecond laser pulse and requires molecules to be isolated in a molecular beam, while the Judson article discloses use of a one nanosecond laser pulse and is purely conceptual as it does not include experimental results. Similarly, the findings by Assion et al. had great scientific interest, but the results were not sufficiently reproducible to be considered useful for analytical purposes.

**[0003]** It is also known to employ nanosecond lasers for matrix-assisted laser desorption ionization (hereinafter "MALDI"). Examples of this are disclosed in U.S. Patent No. 6,130,426 entitled "Kinetic Energy Focusing for Pulsed Ion Desorption Mass Spectrometry" which issued to Laukien et al. on October 10, 2000, and U.S. Patent No. 6,111,251 entitled "Method and Apparatus for MALDI Analysis" which issued to Hillenkamp on August 29, 2000; both of these patents are incorporated by reference herein. Furthermore, the traditional role of the laser in a mass spectrometer with MALDI is to provide energy to the matrix molecules, wherein this energy dissipates and causes

evaporation and ionization of the protein analyte dissolved in it. The laser, therefore, plays an indirect role that depends on energy transfer processes that may take from picoseconds to microseconds. Because excitation is indirect, pulse wavelength has not been found to cause significant differences in the outcome. Direct laser excitation of the proteins with nanosecond lasers typically causes the proteins to char.

**[0004]** Laser induced, selective chemical bond cleavage has also been explored but with fairly limited success. It is believed that very simple molecules, such as HOD (partially deuterated water), have had only the OH and OD bonds cleaved with a nanosecond narrow line laser to vibrationally excite the specimen and then an ultraviolet laser pulse was employed to perform the cleaving. The desired laser frequency for vibrational excitation could be determined a priori in the gas-phase sample. More importantly, the HOD molecule is unique because the energy can be deposited in one of the bonds and it remains there for very long times, which are longer than nanoseconds. For the HOD experiments using selective bond excitation, no appreciable pulse shaping was used. This method was not known to have been employed for a protein or MALDI process, and was not known to have been successfully used for any other atomic bonds in other molecules, especially not in a condensed phase. It is also noteworthy that MALDI, with a matrix, has been used in an attempt to perform limited bond cleavage, as is discussed in U.S. Patent No. 6,156,527 entitled "Characterizing Polypeptides" which issued to Schmidt et al. on December 5, 2000, and is incorporated by reference herein. However, the approach of Schmidt et al. does not modify and optimize the laser pulse shape or other laser properties to achieve limited bond cleavage.

**[0005]** In accordance with the present invention, a control system and apparatus for use with an ultra-fast laser is provided. In another aspect of the present invention, the apparatus includes a laser, pulse shaper, detection device and control system. A further aspect of the present invention employs a femtosecond laser and a spectrometer. In another aspect of the present invention, a femtosecond laser and binary pulse shaping are employed. A multiphoton intrapulse interference method is used to characterize the spectral

phase of laser pulses and to compensate any distortions in an additional aspect of the present invention. In another aspect of the present invention, a system employs multiphoton intrapulse interference phase scan to improve the laser pulse performance. Furthermore, another aspect of the present invention locates a pulse shaper and/or MIIPS unit between a laser oscillator and a laser amplifier. In yet another aspect of the present invention, the control system and apparatus are used in a MALDI process. Still another aspect of the present invention employs the control system and apparatus to cleave chemical bonds in a specimen and/or to determine the amino acid sequence of a protein specimen. Photodynamic therapy and fiber optic communication systems use the laser excitation apparatus with additional aspects of the present invention. A method of ionizing and determining a characteristic of a specimen is also provided.

**[0006]** 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, vibrations 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 convention 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.

**[0007]** The control system and apparatus of the present invention are further advantageous over conventional constructions since the present invention allows for analysis and identification of constituents of complex and unknown molecules, such as those used in a MALDI process or proteins, in a relatively quick and automated manner. The present invention advantageously determines optimum laser conditions for maximizing the sensitivity of MALDI based protein sequencing, and to examine ion formation efficiencies for various matrices using tailored laser pulses. The present invention is also advantageously used to control the degree and type of fragmentation for automated protein sequencing. Furthermore, the adaptive laser source permits the optimal desorption from an insoluble protein source and allows for ionization analysis of a protein with or without a matrix. 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

**[0008]** Figure 1 is a diagrammatic view showing a first preferred embodiment of a control system and apparatus of the present invention;

**[0009]** Figure 2 is a diagrammatic view showing the first preferred embodiment used for MALDI;

**[0010]** Figure 3 is an exemplary molecular structure cleaved by the first preferred embodiment control system and apparatus;

**[0011]** Figure 4 is a diagrammatic view showing a second preferred embodiment of the present invention that employs MIIPS;

**[0012]** Figure 5 is a diagrammatic view of a third preferred embodiment of the present invention applied to multi-photon microscopy;

**[0013]** Figure 6 is a simplified, diagrammatic view showing a fourth preferred embodiment of the present invention applied to optical coherent tomography and photo dynamic therapy;

**[0014]** Figure 7 is a diagrammatic view showing the fourth embodiment system of the present invention using BPS applied to optical coherent tomography and photodynamic therapy;

**[0015]** Figure 8 is a diagrammatic view showing a fifth preferred embodiment of the present invention applied to spectroscopy;

**[0016]** Figure 9 is a simplified, diagrammatic view showing a sixth preferred embodiment of the present invention applied to communications;

**[0017]** Figure 10 is a diagrammatic view showing the sixth preferred embodiment of the present invention applied to communications;

**[0018]** Figures 11a and 11b are diagrammatic views showing components in an alternative embodiment of the present invention applied to communications;

**[0019]** Figures 12a through 12c are schematic and graphical representations of two photon and three photon induced fluorescence employed with any of the embodiments of the present invention;

**[0020]** Figures 13a and 14a are diagrammatic views showing regular, non-MIIPS operation of an ultra-short laser;

**[0021]** Figures 13b and 14b are diagrammatic views showing improved operation of an ultra-short amplifier using upstream MIIPS employed in a seventh preferred embodiment of the present invention;

**[0022]** Figure 15 is a diagrammatic view showing an eighth preferred embodiment of the present invention used in an ultra-short amplifier;

**[0023]** Figures 16 through 19 are flow charts for the method and computer software operation employed with any of the preferred embodiments of the present invention;

**[0024]** Figure 20 is a diagrammatic cross-sectional view showing a ninth preferred embodiment of the present invention employing an optic head used with a remote spectrometer;

**[0025]** Figure 21 is a diagrammatic view showing an amplifier employed in a tenth preferred embodiment of the present invention;

**[0026]** Figure 22 is a diagrammatic view showing an amplifier employed in an eleventh preferred embodiment of the present invention;

**[0027]** Figure 23 is a diagrammatic view showing an amplifier employed in a twelfth preferred embodiment of the present invention;

**[0028]** Figure 24 is a diagrammatic view showing a thirteenth preferred embodiment of the present invention using a microscope;

**[0029]** Figures 25-28 are block diagrams showing control system variations of a fourteenth preferred embodiment of the present invention;

**[0030]** Figure 29 is a diagrammatic and perspective view showing a fifteenth preferred embodiment of the present invention in a self-contained housing; and

**[0031]** Figures 30 and 31 are diagrammatic views showing a detector with a powder optic employed in an alternate embodiment of the present invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

### Pulse Shaping System

**[0032]** 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 concave mirror 27, a laser beam pulse shaper 29 including a spatial light modulator, 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 is a spectrometer 39. 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 including the spatial light modulator for detection and sensing by spectrometer 39 for further evaluation, analysis, comparison and subsequent control by personal computer 37.

**[0033]** The laser is preferably an ultra-short femtosecond laser that can deliver high peak intensity (with a typical peak greater than  $10^{10}$  watts/cm<sup>2</sup>) 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 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 mode locked titanium sapphire oscillator. Chromium Fosterite, Chromium YAG, Chromium Lithium Sapphire, Ytterbium, and Tungston doped Ytterbium oscillators can alternately be used. Such lasers are 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.

**[0034]** 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, because 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.

**[0035]** 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.

**[0036]** 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 spatial light modulator can be obtained from CRI Co. and has a modulator electronic driver.

**[0037]** The AOM consists of an anti-reflection coated Tellurium Dioxide ( $\text{TeO}_2$ ) crystal with a piezo electric transducer glued onto one end. The central frequency of the acoustic wave is  $\alpha c/2\pi = 200$  MHz. The acoustic velocity  $v_s$  in the crystal is 4.2 km/s and the light pulse spends less than 10 ps in the crystal, so the acoustic wave moves less than  $0.002 \lambda$  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  $\phi$ , 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

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

where  $\alpha(\omega)e^{i\phi(\omega)} = A[y(\omega)/v_s]$ ;  $\alpha$  is the frequency, and  $e$  is a constant.

Fixed pulse shaping optics, such as chirped mirrors, can also be employed.

**[0038]** 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  $\phi$  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 39 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

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

and

$$f(t) = \int_{-\infty}^{\infty} f(v) e^{-i2\pi vct} dv \quad [3]$$

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

**[0039]** 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.

**[0040]** 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 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 a mirror, these applications do not require the complexity and expense of computer controlled pulse shapers after initial set up, although systems can still be employed.

#### Binary Phase Shaping

**[0041]** In the low intensity regime, laser control is dominated by interference of different nonlinear optical pathways connecting the initial and final states. The challenge is finding the proper phase for each frequency within the pulse to achieve constructive interference at the desired pathway and destructive interference elsewhere. Consider two-photon excitation of fluorescent probes, as used in two-photon microscopy, as the target for optimization and envision two chromophores with different two-photon absorption spectra. The goal is to achieve selective excitation by "focusing" the energy available at a specific region of the two-photon spectrum, while minimizing the energy outside of the desired spectral window.

**[0042]** The objective is to introduce phase modulation to cause the two-photon spectrum to be intense only inside the window defined by frequency  $2\omega_c$  and width  $W$ , and to minimize the background  $B$  outside the window. The contrast ratio  $C$  is defined as the intensity inside the window divided by the intensity of light outside the window.

**[0043]** The phase between photons of different frequencies takes only two values preferably 0 or preferably  $\pi$  to maximize or minimize a given pathway. Any two values whose difference is  $\pi$  work equivalently well. The method is defined as binary phase shaping (hereinafter "BPS"). In a preferred embodiment, BPS is used to solve the problem of selective multiphoton excitation with ultrashort laser pulses.

**[0044]** In order to control two-photon excitation, one needs to control the non-linear power spectrum of the laser  $E^{(2)}(\omega)$ , which can be measured by obtaining the second harmonic spectrum generated using a thin second harmonic generation (hereinafter "SHG") crystal. Selective two-photon excitation is possible when one is able to tune the narrowed non-linear power spectrum to optimize excitation of one chromophore versus another. The effect of spectral phase modulation on SHG can be divided into broad and narrow phase matching bandwidth. Sinusoidal phase modulation, a common function used for laser control, cannot produce contrast ratios greater than 0.5, and as the window is tuned away from the central frequency the contrast drops below 0.1.

**[0045]** Consider two phases, 0 and  $\pi$ , then the symmetry becomes clear. To maximize the SHG intensity at a frequency  $2\omega_c$ , the spectral phase needs to be symmetric or antisymmetric about  $\omega_c$ , such that the frequencies interfere constructively. To minimize the background intensity at all other frequencies, the spectral phase must be asymmetric with respect to all other frequencies away from  $\omega_c$ , so that destructive interference is maximized. In another preferred embodiment, prime numbers are used to generate the quasi-random phase changes required. The mask that is used to modulate the pulses is designed for a 128-pixel modulator. A proposed phase mask is based on the symmetry requirements of the problem, using the quasi-randomness of prime numbers. This mask is reflected about pixel 64 to obtain the values of pixels 65-128, and is designed to obtain a narrow second harmonic signal at the center of the spectrum, for example. Other preferred embodiments employ a 128-pixel SLM and still other embodiments employ a SLM with greater than 256 pixels.

**[0046]** A titanium-sapphire oscillator, which can be obtained from K&M Labs, is capable of generating pulses as short as 10 fs after a double pass prism

compressor is preferably employed. The spectral phase of the pulse is tailored using a computer-controlled pulse shaper. The pulses are centered near 800 nm. The spectral phase of each pulse is corrected using the MI phase-scan (MIIPS) method, which compensates phase distortions to obtain transform-limited (TL) pulses. The binary phase is introduced as an addition to the compensation phase. The shaped laser pulses, with energy  $\sim 0.5$  nJ per pulse and 87 MHz repetition rate, are focused mildly, to a spot size of  $\sim 100$  microns in diameter, on a 20 micron thin beta barium borate ( $\beta$ BBO) type I SHG crystal. The frequency-doubled light is collected with an optical fiber and dispersed on a compact spectrometer, preferably obtainable from Ocean Optics.

**[0047]** Before introducing phase modulation, spectral amplitude restriction is considered and the spectrum of the laser is narrowed using a slit at the Fourier plane. The phase mask is programmed on the SLM and it dramatically narrows the SHG spectrum. The contrast ratio for this mask is 2.5 when the SHG peak is centered. By shifting the position of the mask on the SLM, hence tuning the center of symmetry, it tunes the SHG spectrum.

**[0048]** The absolute value of the spectral amplitude  $|E(\omega)|$  of the electric field is calculated from the experimental power spectrum of the fundamental pulse  $I(\omega)$  using  $|E(\omega)| = I(\omega)^{0.5}$ . To simulate the experimental results, a double Fourier Transform method is used. The electric field in the time domain  $E(t)$  is calculated as the Fourier image of the complex spectral amplitude in the spectral domain, with the formula

$$E(t) = \int |E(\omega)| \exp[i\phi(\omega)] \exp(-i\omega t) d\omega, \quad [4]$$

where the spectral phase  $\phi(\omega)$  is the function that is introduced by the SLM. The power spectrum of the SHG is calculated using

$$I_{\text{SHG}}(\omega) = |\int E(t)^2 \exp(i\omega t) dt|^2. \quad [5]$$

The SHG amplitude is normalized using the maximum of the SHG intensity calculated for TL pulses,  $\phi(\omega) = 0$ .

**[0049]** A simple evolutionary learning computer program (hereinafter “ELC”) is programmed and it assumed a Gaussian electric field  $|E(\omega)|$  corresponding to a 10 fs pulse centered at 800 nm. Eight points are used to represent each pixel in order to simulate more closely the experimental resolution of our setup. The second harmonic intensity is calculated according to

$$I_{\text{SHG}}(2\omega_c) = |\int E(\omega_c - \omega) E(\omega_c + \omega) d\omega|^2 \quad [6]$$

normalized to the maximum SHG amplitude for TL pulses.

**[0050]** Binary phase shaping (hereinafter “BPS”) simplifies the calculations, especially if it is assumed the amplitude of the electric field to be a constant, that is, the spectral power is set equal to 1 in the allowed spectral region. Each spectral component of the electric field, linearly dispersed in the frequency domain, can be represented as a binary value ( $\pm 1$ ) determined by  $b_k = \exp(i\phi_k)$ , for  $\phi_k = 0$  or  $\pi$  respectively. The intensity of the SHG signal measured at frequency  $2\omega_k$  can be calculated with the formula

$$S_k = \left| \sum_{j=0}^N b_{k-j} b_{k+j} \right|^2 / N^2 \quad [7]$$

where the integral in Equation 6 is now replaced by a discrete sum,  $N$  is a parameter that depends on details of the model such as number of pixels. The problem of spectral selectivity can now be formulated as finding a vector  $b_k$  such that  $S_k = 1$  for  $\omega_k = \omega_c$  and  $S_k$  is minimized at all other frequencies.

**[0051]** In principle, the solutions found are members of the set of solutions that could be obtained by arbitrary phase and amplitude pulse shaping. For a pulse shaper with  $N$  pixels, one can generate  $(P * A)^N$  shaped pulses, where  $P$  and  $A$  are the number of different phases and amplitudes a pixel can take. If it is assumed 100 pixels, each taking 10 different amplitude values and 100 different phase values, the number of different pulses is of order of magnitude  $10^{300}$ . This number is extremely large, therefore, while in principle,

the field exists to achieve the desired photonic transformation or excitation, finding it is a great challenge.

**[0052]** The periodic nature of electromagnetic waves results in a great deal of redundancy in pulse shaping because nonlinear optical processes do not depend on the absolute phase or a linear variation of the spectral phase. This equivalence is expressed by  $\phi(\omega) \leftrightarrow \phi(\omega) + a + b\omega$ , where  $a$  and  $b$  are constants. This redundancy is filtered out by programming an ELC that works on the second derivative of the phase. The actual phase that is used in the SLM is obtained by integration setting  $a = b = 0$ . An ELC was used to optimize smooth phase functions for spectral narrowing, but could not obtain a contrast ratio greater than unity.

**[0053]** The advantage of BPS is that computational redundancies are greatly reduced. For BPS and 128 active pixels the search space is reduced to  $2^{128}$ . If there is two-fold symmetry, for example two-photon excitation, then the number is reduced to  $2^{64}$ . The final search space is of size  $10^{19}$ , a number that is at least 281 orders of magnitude smaller than would be considered for arbitrary phase and amplitude pulse shaping as discussed above. The resulting space is small enough that all possible outcomes could be computed, and a large portion evaluated experimentally. A simple ELC, such as the one used here can quickly converge towards significantly improved solutions.

**[0054]** BPS has significant technological advantages. A retardation equivalent to  $\pi$  is easy and fast to obtain and calibrate. Permanently etched masks can be made in advance and used for specific applications such as selective two-photon microscopy. Scanning the mask can yield two-photon excitation spectra. Laser control, especially with two-photon transitions, can be addressed with binary phase shaping. BPS makes it simple to analyze the problem and to propose rational solutions, as demonstrated here with a phase mask fabricated by the quasi-random gaps between prime numbers. Thus, a simple ELC is used to improve on the proposed solution efficiently because of the greatly reduced search space.

### Multiphoton Intrapulse Interference

**[0055]** A multiphoton intrapulse interference phase scan (hereinafter "MIIPS") system and method of the present invention characterize the spectral phase of femtosecond laser pulses. The phase across the spectrum of an ultrafast pulse can affect the multiphoton process in a number of ways. Phase can increase the pulse length and hence reduce the peak intensity of the pulse, thereby preventing saturation, a common result under high intensity excitation. Phase can also be used to synchronize changes in the electric field with intramolecular wave packet dynamics. Finally, phase can be used to cause interference in the way multiple frequencies combine to achieve multiphoton excitation.

**[0056]** The technique of Multiphoton Intrapulse Interference (hereinafter "MI") and its application to control multiphoton processes is based on rationally designing an electric field required to achieve an articular target with a minimum number of parameters. The method is further based on calculating the amplitude of the  $n$ th-order electric field and comparing it to the absorption spectrum of the molecules being controlled. This provides a strong physical understanding of the control process, which can be very useful in the interpretation of experiments where the field is optimized by computer programs based on evolutionary learning or similar methods.

**[0057]** Two-photon transitions can focus the energy from an ultrafast pulse into a narrow frequency distribution; just like Fresnel diffraction can be used to construct a focusing lens. Conceptually, MI takes advantage of the interference term that is associated with the phase of each frequency  $\nu_i$  within the pulse that contributes to the multiphoton process and can enhance or what may be as valuable, suppress a multiphoton transition. The effective electric field that drives the two-photon process through the induced (nonlinear) polarization is proportional to  $E^2(t)$  (in the absence of intermediate resonance at the one-photon level). Its Fourier transform  $E^{(2)}(\nu)$  determines the frequency response at the two-photon level.

**[0058]** Multiphoton Intrapulse Interference Phase Scan is capable of both pulse characterization and compensation of subsequent pulses. Within

minutes, the pulses are characterized and compensated to yield transform-limited (TL) or user-specified shaped pulses at the sample. This capability is extremely practical and can be incorporated in any laser setup.

**[0059]** MIIPS is a single-beam method that does not require an interferometer. To make a precise and accurate measurement of the spectral phase using MIIPS, a known phase delay is imposed on the frequencies that make up the pulse using a calibrated pulse shaper. The pulse shaper essentially behaves as two back-to-back spectrometers. In one embodiment, the pulse is dispersed with a prism and collimated with a 200-mm concave mirror. At the Fourier plane, where all the frequencies are isolated, their phases are manipulated by a computer-controlled LCD spatial light modulator (SLM). The SLM applies the reference phase function to the input pulse, and the resulting pulse is then reconstituted to the time domain by a second concave mirror and prism. The SLM can be updated every pulse (presently limited to 1 kHz). The LCD has a 250-ms response time, so in principle it can be updated at 4 kHz. The output beam is analyzed by placing a 0.01-mm-thick beta barium borate SHG crystal in its path, usually at the place where optimum pulses are required. In a sense, the pulse autocorrelates itself at the SHG crystal. For each reference phase function that is introduced by the computer-controlled SLM, the output spectrum from the SHG is dispersed in a spectrometer and recorded.

**[0060]** Pulse characterization involves the introduction of a reference phase-modulation function of the form  $\Phi = \alpha \cos(\gamma \Omega - \delta)$ , where  $\alpha$  is the magnitude of the phase delay,  $\gamma$  is the periodicity  $\Omega$  is the frequency detuning from the carrier frequency of the pulse, and  $\delta$  is the position in the spectrum at which the cosine function is equal to one. The reference phase function, with typical values  $\alpha = 2\pi$ , and  $\gamma =$  pulse duration, is programmed into the SLM and scanned for different values of  $\delta$  ranging from 0 to  $2\pi$ . For each value of  $\delta$ , the spectrum of the frequency-doubled pulse changes, achieving a maximum in the spectral region over which the SLM compensates for the phase distortions. The MIIPS trace corresponds to the collection of spectra as a function of  $\delta$ . MIIPS-generated trace of wavelength as a function of  $\delta$  shows changes in the SHG spectrum of the laser pulse intensity. In general, the distance between the

diagonal features is proportional to linear chirp and the angular deviation is proportional to quadratic chirp. Computer analysis of the trace is used to retrieve the spectral phase of the input pulse.

**[0061]** Qualitatively, the distance between the diagonal features determines linear chirp while the angle between the features determines the quadratic chirp. The full quantitative determination of the spectral phase can be obtained by double integration. Once the MIIPS system has characterized the pulse and retrieved the phase distortions inherent to the pulses, it can use that information to drive the SLM such that it compensates for the distortions. The first step in compensation is to take the phase determined from the first scan and program it into the SLM with a negative sign so that it subtracts the distortions. The system carries out a new phase scan to determine the remaining spectral phase modulation (usually about 10% of the original). Typically, three such iterations will yield transform-limited pulses. Because the laser is not focused in the pulse shaper, the method can be used with pulses that are relatively high in energy. Pulses ranging from about 100 pJ to about 10 mJ and pulse durations from less than 5 to about 500 fs can be used. Once the pulses are compensated (transform-limited), the laser can be focused to produce peak intensities from about  $10^{12}$  to about  $10^{18}$  W/cm<sup>2</sup>, depending on the input energy.

**[0062]** 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 4), a pulse shaper is employed to introduce a reference phase function designed to yield this information directly. The shaped pulses are frequency doubled by a thin SHG crystal 507 (see Figure 4) and the output is directed to spectrometer 503.

**[0063]** 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.

**[0064]** 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:

$$\phi(\omega) = \phi(\omega_0) + \phi'(\omega_0)\Omega + \frac{1}{2}\phi''(\omega_0)\Omega^2 + \frac{1}{6}\phi'''(\omega_0)\Omega^3 + \dots, \quad [8]$$

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,

$$\phi(\Omega) = \alpha \cos(\gamma\Omega - \delta) + \phi(\Omega) \quad [9]$$

where the first term is the reference phase function introduced by the shaper with maximum phase amplitude  $\alpha$ , period  $\gamma$  and the absolute position in the spectral window  $\delta$ .  $\phi(\Omega)$  is given by Equation 8.

**[0065]** The maximum SHG signal as a function of  $\Omega$  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 ( $\phi''$ ,  $\phi'''$ ) can be obtained in the laser pulse. The maximum signal in a (wavelength,  $\delta$ ) MIIPS trace describes a series of lines given by

$$\delta_{\max} = \delta_0 + (\lambda_{\max} - \pi c/\omega_0)\omega_0^2/(\pi c) \{ \gamma - \phi'''/(\alpha\gamma^2 \sin \delta_0) \}, \quad [10]$$

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

**[0066]** 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  $\delta$ . First the data is fit to a series of lines which follow  $\lambda_{\max}(\delta_{\max})$  as expected from Equation 10. The quadratic phase modulation (responsible for linear chirp)

is determined directly from the distances  $x_1$  and  $x_2$  between the SHG maxima, according to

$$\text{[0067]} \quad \phi'' = \alpha\gamma^2 \arcsin[(x_1 - x_2)/4]. \quad [11]$$

Note that the magnitude and sign of  $\phi''$  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  $\alpha\gamma^2$ .

**[0068]** The cubic phase modulation (quadratic chirp) is determined by the slope  $\Delta\delta/\Delta\gamma$  that the maximum SHG features make in the  $\lambda$   $\delta$  plane. Analytically, cubic phase modulation is given by

$$\phi''' = 0.5 \alpha\gamma^2 \pi c / \omega_0^2 \cos[(x_1 - x_2)/4] \{(\Delta\delta/\Delta\gamma)_1 - (\Delta\delta/\Delta\gamma)_2\}, \quad [12]$$

where the slopes are measured in  $\text{nm}^{-1}$ . 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. The MIIPS can be programmed to find the phase distortions on the laser pulses directly by double integration and to introduce a compensation phase function that eliminates the distortions. This mode of operation can be used to find arbitrary phase deformations and yield transform limited pulses, which in a MIIPS scan look like straight parallel lines separated by  $\pi$ . The fit to the experimental data is given by Equation 10, and the phase parameters are extracted with Equations 11 and 12.

**[0069]** The version of MIIPS illustrated in Figure 4 uses a thin SHG crystal 507, spectrometer 503, spatial light modulator 129 of the pulse shaper 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 are employed wherein the pulse energy is attenuated down to  $\sim 5 \mu\text{J}$ . For the test data herein, A 0.3 mm  $\beta\text{BBO}$  type I crystal is used for SHG 507 and the output is 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 is 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 are generated at the pulse compressor after regenerative amplification. In another variation, self-ultrafast switching is based on pulse phase modulation in the pulse shaper, the thin SHG crystal causing multiphoton intrapulse interference, dispersive optics, and a CCD camera detector. The simplicity and accuracy of this method make it practical for the evaluation of laser pulses close to transform limit and for the evaluation of phase distortion from optical elements.

**[0070]** Multiphoton intrapulse interference is not just about focusing the energy. The goal is to determine the field that the molecules experience. The control of nonlinear optical processes, using multiphoton intrapulse interference can be applied in diverse fields such as photochemistry, communications, and medicine.

**[0071]** 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 Figures 16-19, as discussed in greater detail hereinafter. 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 agreement with equations further makes 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 of arbitrary phase distortions;

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;

MII can be used to optimize the selective activation of PDT agents specifically at a particular depth, avoiding collateral damage; and

MII can be used to cause selective nonlinear optical excitation.

**[0072]** An automated pulse chirp determination for arbitrary smooth phase distortions is based on the use of a pulse shaper and obtaining a phase scan, wherein the spectrum of the SHG is a function of phase parameter  $\delta$  for  $\Phi(\omega) = \alpha \cos(\gamma\omega + \delta)$ . This method is non-iterative and it directly obtains the desired values without evolutionary learning calculations. Therefore this method is very stable and does not depend on overlap between two pulses in space and time. Moreover, the pulse analyzes itself in a thin SHG crystal. It should be appreciated that BPS, MII and MIIPS may be advantageously used to improve the performance of any of the end uses disclosed herein, including MALDI, sequencing, cleavage, control of nonlinear optical processes, photopolymerization, quantum computing, OCT, PDT, selective nonlinear optical excitation, spectroscopy, microscopy and communications.

### Second – Harmonic Generation with Powders

**[0073]** Chemical powders, adhered onto transparent quartz carriers, are employed in place of thin SHG crystal optic component. The powder embodiment is presently preferred to significantly reduce cost in high energy (for example, one nanojoule or greater) applications such as for MIIPS, nonlinear optical characterizations and FROG analysis. The chemical powder is preferably a collection of small crystals of Potassium Dihydrogen Phosphate (KDP or KD\*P, which can be obtained from Sigma-Aldrich Inc. as Code No. OPP076413) and deuterated potassium dihydrogen phosphate, or alternately including Beta Barium Borate powder and other materials with crystal structure that is non-centrosymmetric. One or more powder particles is glued onto a quartz substrate or alternately glass, microscope slide substrate using a silicone-rubber or cyanoacrylate ( $C_5H_5NO_2$ ) adhesive. Alternatively, the powder can be compressed into a pellet. Each powder particle size can be 1 to 1,000 microns and preferably is between about 10-100 microns per side, and more preferably between about 0.5 to 20 microns per side with a size distribution no greater than 20%, depending on the focusing length, intensity of the laser and the sensitivity of the detector. The significant cost benefits can be achieved as long as each powder particle is less than  $1\text{ mm}^3$ . This avoids the conventional need to grow and then machine or polish accurate angles onto larger sized, non-powder particles. For microscopy, even smaller particles can be employed as long as a very sensitive detector is used. Furthermore, the powder approach is advantageous by having large variety of random crystal orientations therein which creates improved average results for laser pulses shorter than 20 fs which is ideally suited for MIIPS where some beam pulse scattering is acceptable. The SHG output can be collected after transmission or the diffuse SHG signal can be collected as it reflects from this optic. While SHG optic use is preferred, the powders of the present invention may be employed with other optics such as mirrors, lenses or the like.

**[0074]** An alternate embodiment of a powder optic can be observed in Figures 30 and 31, employed in a MIIPS detector. A laser 951 is focused on the (pencil-like) portion 953. Inside of this portion there is a pellet or particle 955 of

frequency doubling powder. The powder contains micro-crystals (for example, a size smaller than 1 mm, but preferably smaller than 50 microns) of inorganic, non-centrosymmetric crystal lattice compounds such as potassium dihydrogen phosphate, beta-barium borate, lithium borate, or lithium iodate. The laser light gets frequency doubled at these crystals. The diffuse frequency doubled light is collected by concave mirror 957 and focused on an optical fiber 959 after transmitting through an optical filter 961 that transmits that light but not the fundamental light of the laser. The pulse is then transmitted to a compact spectrometer 963.

**[0075]** The preferred method of manufacturing the powder optic includes: first, purchasing the powder granules, second, crushing the desired amount of granules by hand with a mortar and pestal, third, separating the crushed granules with mesh screens, fourth compressing the desired sized granules into a pellet, and fifth, adhering the pellet to the glass slide. It is believed that about 10 micron sized granules are best for 10 fs pulses, 100 micron sized granules are best for 100 fs pulses, and the like ratio for other pulse durations. Compression is done by hand with a Carver press at about 100 atmospheres per cm<sup>2</sup> of pressure, and the preferred pellet size is about 1 mm thick by 5 mm diameter.

#### MALDI

**[0076]** Another embodiment of the present invention for use with a matrix-assisted laser desorption ionization (hereinafter "MALDI") device 35 is shown in Figure 2. More specifically, the MALDI device provides a time-of-flight mass spectrometer ("TOF MS") 39. A sample or specimen 41 to be analyzed is placed within mass spectrometer 39. Bursts or pulses of a laser beam 43 are emitted from laser 23, through the optics 25, 27, 31 and 33 (also see Figure 1), as well as through pulse shaper 29, and onto specimen 41; this causes fragmentation and ionization of a top layer of the specimen for detection and sensing by mass spectrometer 39 for further evaluation, analysis, comparison and subsequent control by personal computer 37.

**[0077]** A VESTEC 2000 MALDI TOF mass spectrometer is believed to be suitable for this invention, although most commercial MALDI instruments can

be adapted with the femtosecond laser, pulse shaper and feedback learning control method described herein. During extraction, all of the ions obtain the same energy in the 30-kV ion acceleration region, and because  $K.E. = \frac{1}{2} mv^2$ , the lightest ions achieve the highest velocity and, thus, reach the detector first. This transient (for example, having a duration of 300 microseconds) mass spectrum is recorded by a transient recorder at the detector. It is common practice to sum many (10-100) of this transient mass spectra to produce a sound spectrum from an ion-counting statistics criterion.

**[0078]** After the initial laser desorption pulse plume is generated, an additional ionization and fragmentation pulse brings about significant increases in signal ions in the specimen. The use of a second laser pulse with femtosecond duration for post-desorption/ionization excitation enhances sensitivity and provides some amino acid-specific fragmentation. Therefore, the present invention laser source is based on a pair of ultra-short, less than 50 femtosecond laser pulses, one for desorption/ionization of analyte molecules and the second for selective-fragmentation. Alternately, the first laser may be a nanosecond pulse used for desorption followed by a femtosecond pulse to be used for selective bond cleavage. A single laser method would be possible when the source for the molecular (for example, protein) ions is an electro-spray source which provides the gas-phase protein ions without a matrix.

**[0079]** The desorption beam is the fundamental at 800 nm, the second harmonic at 400 nm, or the third harmonic at 266 nm. The desorption beam can also be derived from the pump YAG laser at 532 nm or at 266 nm. No desorption laser is required when an electro-spray source is employed. Additionally, controlling the delay between the desorption and the shaped laser pulses can also serve as a parameter for control when using MALDI.

**[0080]** In a first variation of the present embodiment, learning feedback software can be employed in the present invention control system and apparatus as a preliminary investigation method for analyzing a pre-test unknown sample or specimen. For any new system, the test should start with pre-defined pulse shapes in order to obtain a basic understanding of the system. Among the pre-defined pulses, the shortest pulse is expected to ionize molecules on the surface

of the sample with minimum decomposition, the longest pulse is expected to mimic the nanosecond experiments where the singly protonated protein may be observed. It is also noteworthy to vary the delay between two laser pulses from a few picoseconds to a few nanoseconds in order to appreciate the time scales involved. Manual inputs will be initially performed by the system operator or user through entering input data into the personal computer. The microprocessor within personal computer 37 will then control laser 23 by receiving an essentially real time feedback input signal from mass spectrometer 39 and then perform calculations, comparisons and evaluations. These automated steps can be substituted with manual user calculations and decisions if desired based on personal computer outputs.

**[0081]** The objective of the software routine is to aid in the selection of sample targets for further testing iterations for subsequent criteria data input. An optional alternate embodiment subroutine includes shooting long laser beam pulses then quick short laser beam pulses, with a separation set by an optical delay of less than ten nanoseconds. The short pulse of approximately 50 femtoseconds is performed in order to look for fragmentation and the matrix mass. Laser beam pulses of between approximately ten and 100 picoseconds are performed to look for the parent mass. The ultrafast laser beam pulse durations employed with the present invention advantageously allow for approximately 1000 laser beam shots at a single sample or specimen without significant degradation of the specimen; this allows for quicker and less expensive usage of the apparatus while also encouraging statistically more accurate results. The long and short pulse combinations can be used in addition to or without the benefit of pulse shaping. Otherwise, the control system and apparatus are the same as discussed herein. The real time learning feedback method and computer software are employed to statistically optimize the repetitive identification of molecularly complex and unknown samples or specimens in a highly automated and relatively quick manner. Once statistical convergence has been determined by the personal computer, then the test is complete by determining the optimum pulse characteristics (whether they be

pulse shape, pulse duration or any other such variable laser beam characteristic) for the corresponding and now post-test identified specimen.

**[0082]** The time scale of some of the processes that occur during MALDI may be longer than the femtosecond pulses. In a first variation, the pulse shaper can be used to produce pulse sequences up to ten picoseconds apart. Optical delay lines can be used to increase this time delay in the nanosecond range if needed. In a second variation, the wavelength of the pulses being shaped is 800 nm. A second harmonic crystal is all that is needed to convert the wavelength to 400 nm, however, the shaper is capable of regulating the energy delivered to the sample without changing the carrier frequency (wavelength) of the laser.

**[0083]** In a second variation of the present embodiment, a complete set of binary phase functions is used to carry out an exhaustive evaluation of laser fragmentation. The resulting MS results will be analyzed for each binary phase. The resulting data will be mapped and each binary phase is evaluated for its ability to cause selective bond cleavage of post-translational modifications, disulfide bonds and peptide bonds. The goal of this approach is to find robust binary phase functions that can be used to cause selective bond cleavage. Exhaustive evaluation of binary phase functions is an efficient method for analyzing the search space of effective phase functions as will be discussed in greater detail hereinafter. A third variation of the present embodiment employs the previously discussed learning feedback software in combination with different binary phases. Controlling the delay between the desorption and the shaped laser pulses also serves as a parameter for control when using MALDI.

#### Protein Sequencing

**[0084]** Laser desorption mass spectrometry can be employed with the present invention for identification and protein sequencing. This is significantly enhanced and made possible by the ultra-fast laser pulses and learning feedback system used. The matrix has been shown to enhance the yield of charged protein for analysis by MS detection. The matrix:phosphor diester backbone interaction has been shown to play an important role. The use of liquid matrices such as glycerol and lactic acid for IR-MALDI may bring some

additional flexibility to sample preparation and delivery to the MALDI instrument. The "Ladder Sequencing" method involves a partial Edman degradation with phenyl isothiocyanate and using phenyl isocyanate as a terminating agent. Partial enzymatic hydrolysis of polypeptides using trypsin is another strategy for protein sequencing. Trypsin digestion attaches only bonds in which the carboxyl group is contributed by either a lysine or an arginine residue. Analysis of metastable species in matrix-assisted laser desorption ionization post-source decay (hereinafter "MALDI-PSD") using a reflectron TOF spectrometer leads to valuable structural information. The introduction of 'delayed extraction' in MALDI allows improved resolution, suppression of matrix background, reduction of chemical noise, and minimization of the effect of laser intensity on performance.

**[0085]** MALDI is a soft ionization technique which produces protonated molecules that undergo very little or no subsequent fragmentation due to the low amount of energy imparted during the ionization process. Therefore, MALDI can be used to analyze mixtures of peptides because the mass spectrum of one peptide is unlikely to overlap with the spectrum of another. Ideally, cleavage of the ionized peptide at each peptide bond (and disulfide) would provide a mass spectrum that could be interpreted, using knowledge of the masses of the amino acid residues, to deduce the sequence. However, as conceptually illustrated in Figure 3, cleavage on either side of the I-carbon is also possible to give fragment ions, which, while diagnostically useful, also complicate the spectrum. It is also noteworthy that cleavage at any designated bond can generate either an N-terminal ion (a, b, c) or a C-terminal ion (x, y, z), the predominance of which for a protonated peptide ( $MH^+$ ) depends on the locus of the more basic residues. In reality, the fragmentation process is more complicated than suggested in Figure 3; for example, creation of a y-ion involves hydrogen transfer from the N-terminal side of the peptide bond and retention of the ionizing proton. In addition, there can be fragmentation of the side chain on certain residues; for example, fragmentation involving cleavage at the  $\beta$ -carbon of leucine and isoleucine generates w-ions, which distinguish these two isomeric residues.

**[0086]** Recognizing the ion types as represented by the appearance of peaks in the mass spectrum is not critical, as most strategies for interpretation,

especially those using an algorithm, involve an iterative computational approach. However, the beginning of a C-terminal series of fragments can be distinguished from the start of an N-terminal series. The largest b-ion will be represented by a peak at high  $m/z$  value that differs from that representing  $MH^+$  by a number of mass units equal to the sum of the mass of an amino acid residue plus the mass of water due to expulsion of the C-terminal residue, which contains the hydroxyl group. On the other hand, the largest y-ion is represented at a high  $m/z$  value by a peak differing from that for  $MH^+$  by a number of mass units equal to only the mass of an amino acid residue.

**[0087]** In principle, the sequence of a peptide is deduced from a mass spectrum in which a complete series of any given ion type are represented. In practice, however, a complete series of any one type is rarely observed, but in fortunate situations, overlapping patterns of two or more incomplete series may give complete sequence information. Ideally, one would prefer to observe complementary information from series of N-terminal and C-terminal fragment ions to bolster confidence in the analysis.

**[0088]** Consider the MALDI-PSD mass spectrum as an unknown. It can be assumed at the outset that the major peak at  $m/z$  574 Da represents the protonated molecule, which was the precursor ion selected for PSD. The protonated molecules fragment during the PSD process and degrade into fragment ions. The procedure for analysis or data interpretation consists of merely examining the mass difference between each of the fragment ion peaks and the peak representing the protonated molecule. The goal is to find a fragment ion peak that differs in mass from the protonated molecule peak by either a residue mass or a residue mass plus water. A peak at a mass-to-charge ( $m/z$ ) value that differs from the protonated molecule peak by the mass of a residue mass plus water corresponds to the amino acid that was located at the C-terminus of the original peptide.

**[0089]** The protein sequencing can be conducted by use of the present invention with or without use of a matrix. The use of an ultrafast, femtosecond laser is envisioned to minimize any destructive burning of the specimen, thereby potentially rendering use of an expensive and time-consuming matrix as

unnecessary. Without a matrix (herein, also known as having "isolated molecules"), the identification and sequencing of the protein is simplified since the matrix characteristics do not have to be accounted for and filtered out of the calculations. A femtosecond laser in the range of approximately 20 femtosecond duration pulses allows for localization of the energy based on the speed of the pulse and the ability to quickly shape the phase and amplitude modulation of the pulse. Furthermore, the specimen fragmentation is primarily due to laser cleavage rather than enzyme or chemical cleaving. This is ideally suitable for insoluble proteins, glycosylated proteins which have been linked to cancer, (including the selective cleavage of the associated oligosacharides) direct protein analysis from silicate substrates, direct analysis of PAGE gels, direct sampling of membrane proteins from intact cells and bacteria, the direct sampling of genetically modified agricultural produce (such as grains), and even human matter such as hair, fingernails and fingerprints.

**[0090]** The personal computer employs a method and software for protein sequencing as follows. The foundation of this method is based on the fact that there are only 20 amino acids and that their masses are well known. First, the computer determines the molecular weight of the intact proteins specimen. This requires the generation of a single high-mass peak and minimization of the low weight background. Secondly, the computer automatically finds peaks that are an integer number of amino acids smaller than the parent protein; a laser beam pulse shape that causes some fragmentation can be employed. Thirdly, this procedure is continued from high to low masses. Finally, confirmation of results can be automatically obtained by a statistical optimization method (such as that previously described for the MALDI process) that attempts to optimize a given mass; the success of this optimization will depend on whether that fragment of the protein has an integer number of amino acids. Automatic adjustment for the N or C terminus is also automatically adjusted for by the computer as previously explained. Alternately, each single amino acid could be separately searched for. Thus, the present invention control system and apparatus is ideally suited for analyzing, identifying, sequencing and severing complex multi-molecular specimens in a highly automated manner.

### Selective Bond Cleavage

**[0091]** The ultra-fast laser of the present invention is used to enhance in-source photochemistry and fragmentation, however, random fragmentation would not be as useful as selective bond cleavage. Furthermore, selective peptide bond cleavage would be ideal for protein sequencing. Cleavage of amino acid side chains may be of value for de novo sequencing because it would allow a determination of the presence or absence of certain amino acids. Similarly, selective cleavage of phosphate groups, oligosaccharides and other post-translational modifications would be equally valuable. The ideal, of course, would be to achieve peptide bond cleavage without loss of side chains or other appended groups. This would allow, for example, to determine phosphorylation sites.

**[0092]** It is envisioned that selective bond cleavage can be realized when using shaped pulses that are capable of localizing the energy in a time scale that is short enough to prevent total energy randomization. For example, the protonated molecule of bradykinin potentiator C, as produced by MALDI, fragments poorly during PSD, and does not produce a suitable spectrum from which one could deduce the amino acid sequence. Thus, this 11-residue peptide is ideal for this application. Selective laser bond cleavage may have additional application as a synthetic route to specific products. Accordingly, the present invention provides a photonic scalpel to generate structurally diagnostic fragment ions, for example in proteins.

### Control of Nonlinear Optical Processes

**[0093]** As applied to all of the applications herein, selective control of one and multiphoton processes in large molecules, including proteins, is possible using simple pulse shaping. 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 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 having a fixed pulse shaping surface (for

example, a set of 800 nm wavelength sine curves) these applications do not require the complexity and expense of computer controlled pulse shapers after initial set up, although systems such as in Figure 1 can still be employed.

**[0094]** The underlying concept of the apparatus and associated method are shown in Figures 12a – 12c. Multiphoton transitions are optimized when the central bandwidth of the laser pulse  $\omega_0$ , is some fraction (half for two-photons, a third for three-photons, etc.) of the total energy of the transition as illustrated in Figures 12a and 12c. 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 12b, 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  $\phi(\Omega)$  can be imprinted on the pulse such that the phase of each frequency component  $\Omega$  acquires a specific value. The effect of pulse shaping on the probability for two-photon absorption (“2PA”) can be calculated as follows:

$$P_{2PA} \propto \left| \int_{-\infty}^{\infty} A(\Omega) A(-\Omega) \exp[i\{\phi(\Omega) + \phi(-\Omega)\}] d\Omega \right|^2 \quad [10]$$

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

**[11]**

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

where amplitudes and phases are introduced for two different detuning values  $\Omega_1$  and  $\Omega_2$ , as shown in Figure 12c. One photon transitions are not affected by the phase of the pulses, however, one photon processes are difficult to selectively achieve at high photon flux due to the onset of multiphoton processes.

**[0095]** A schematic representation of two photon and three photon induced fluorescence is illustrated in Figures 12a and 12b, 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  $\omega_0$  by an amount  $\Omega$ . Referring again to Figure 12c, 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.

#### Multi-Photon Microscopy

**[0100]** Two-photon microscopy provides significant possibilities for fluorescence imaging and photochemistry. It offers attractive advantages, including higher resolution, background-free signal, lower background scattering, better penetration in thick samples, and reduced photon-induced damage, which arise from the basic physical principle that the absorption depends on the square of the excitation intensity. Reference should be made to Figure 5. Two-photon microscopy is amenable to multiple-probe staining, whereby two-photon transitions excite different probe molecules that emit at different wavelengths, and for functional imaging of living cells. Phase-modulated femtosecond pulses can selectively excite one type of probe molecule only, leaving the others in their ground state. Multiphoton excitation is achieved by multiphoton intrapulse interference (MII) and this can be accomplished efficiently using binary phase shaping. Selective excitation is used to enhance contrast and achieves functional imaging of samples stained with fluorescent probes sensitive to their microscopic chemical environment.

**[0101]** Selective excitation with significant contrast ratios has been achieved here by optimizing the overlap between the power spectrum of  $E^2(t)$  and the two-photon absorption spectrum. The addition of a computer-controlled pulse shaper to the multiphoton microscope provides a number of important advantages. First, the pulse shaper is used to compensate unwanted phase distortions at the sample. Linear chirp, for example, has been shown to reduce signal intensity in two-photon microscopy. With a pulse shaper, linear, quadratic, cubic and higher order chirp is compensated to obtain the most efficient excitation. Second, the pulse shaper is used to control the output spectrum of the laser pulses by amplitude modulation. Third, the pulse shaper is used for selective probe excitation. Because the spectrum of the laser remains constant, phase modulation does not affect one photon processes such as absorption,

reflection and scattering. Selective excitation minimizes possible cross talk between different fluorescent probes in the sample. Finally, the pulse shaper is used to prevent three-photon and higher order nonlinear optical processes such as continuum generation. Higher order processes usually lead to sample degradation, and in the case of living samples to DNA damage. Suppression of three-photon transitions of four orders of magnitude has been achieved using the MII and BPS methods and this suppression can be coupled with optimization of two-photon signal from living specimens.

**[0102]** This method can be used to selectively excite either different probe molecules or identical probe molecules in different environments. In addition, this method can be used for selective excitation of luminescent probes such as quantum dots, metallic nanoparticles, and single molecules. The same principle can be extended to achieve functional imaging of semiconductor microchips by two-photon laser induced conductivity. Having a pulse shaper for multiphoton microscopy provides the flexibility of selective probe excitation or maximum signal enhancement by controlled modulation of the spectral phase of the femtosecond pulses. Even when for fluorescent labels with very similar absorption spectra, pulse shaping is shown capable of selective excitation. This level of selective excitation and enhancement can be adapted to different modes of two-photon and three-photon microscopy.

#### Multi-Photon Photo Polymerization

**[0103]** Microlithography involves the use of UV light to initiate polymerization. Two-photon induced polymerization has the advantage that it permits 3D polymerization of smaller features (down to 100 nm). Photonic band gap materials (hereinafter "PBG") are 3D constructions with features similar to the wavelength of light that exhibit very interesting behavior. Two-photon microlithography is one convenient method for the preparation of very sophisticated PBGs.

**[0104]** Two-photon absorption can be used in three-dimensional lithographic microfabrication (hereinafter "3DLM") through two-photon-induced polymerization (hereinafter "TPIP"). This is due to the fact that simultaneous two-photon absorption requires a very high photon flux, which is only present at

the point of the focus. Thus the TPI polymerization is confined to the focal volume. This high spatial resolution contributes to the ability of TPIP not only to scan the laser in the x and y direction but also to change the focal plane (z) without overwriting existing features. Therefore, 3DLM is obtained by a single processing step. 3D polymeric structures include a photonic band gap structure, waveguide structures and a micro-channel structure. It is envisioned that multiphoton intrapulse interference can be advantageously used to enhance this non-linear photopolymerization.

**[0105]** In contrast, currently, two-photon microlithography and related techniques can only initiate one type of polymer. If two different types were needed, one would need to rinse, change the monomer mixture, find the position of the feature with nanometer accuracy, and make the new feature.

**[0106]** In one embodiment, BPS is used in microlithography and related techniques such as micromachining and microfabrication to control the polymerization of two different polymers. Being able to alternate two different polymers allows greater flexibility in the construction of nanometer features such as, but not limited to, microelectromechanical systems (hereinafter "MEMS"). Controlling the deposition of two different polymers is enabled by the control of what wavelength two-photon excitation takes place.

#### Quantum Information Processing

**[0107]** One such important application of the concepts of coherent control is emerging in the area of quantum information processing. The selectivity in excitation, which is offered by shaped laser techniques, may also serve as the building blocks for the development of a quantum mechanical system, such as the first practicable quantum computer. In a prior optical scheme for quantum computing, computer controlled pulse shaping where information storage and retrieval through quantum phase is required. In case of an eight-state Rydberg atom wavepacket, the prior scheme can store information as a quantum phase in one or more flipped state, which could be subsequently retrieved in a single step in agreement with the Grover's ; this prior scheme is disclosed in J. Ahn, et al., *Science* 287 (2000), p. 463; and N. Bhattacharya, et al., *Phys. Rev. Lett.* 88 (2002) 137901-1.

**[0108]** A typical visualization of a traditional quantum computer network would have nodes consisting of quantum storage devices, where information can be stored for very long times either in ground or in some metastable excited states of atoms, molecules or ions. The quantum information can be transferred from one node of the network to the other using photons. The nodes would carry out the required computations and also serve as a storage or memory unit. The storage time is limited by decoherence time. Transferring quantum information between the two nodes without allowing for decoherence is very difficult. There are already some proposals in quantum communication to transmit and exchange quantum information between distant users, which includes distribution of quantum secure key information for secure communication. Teleportation allows an arbitrary unknown quantum state to be conveyed from one distant part to another with perfect fidelity by the establishment of a maximal entangled state of two distant quantum bits. However, the bottleneck for communication between distant users is the scaling of the error probability with the length of the channel connecting the users. The error results from amplitude and phase damping. An exemplary quantum computer example is U.S. Patent No. 5,793,091 entitled "Parallel Architecture for Quantum Computers using Ion Trap Arrays" which issued to Devoe on August 11, 1998, and is incorporated by reference herein.

**[0109]** Advantageously, optical pulse shaping of the present invention is an attractive route to quantum computing since shaped pulses can be transmitted over optical hardware and the same infrastructure can be used for computation and optical information transfer. The shaped pulses are split into a number of different parts which can carry different train of pulses at different timescales. This provides leverage to control the various nodes where molecular systems interact with shaped pulses to carry out various instructions and perform quantum computing activity at each node during the pulse duration. This further enables the processing of different quantum computational steps at various nodes simultaneously, such that the code is transmitted in parallel for distribution of the task over the network. At the end of the computation the results are read by sending in a "read pulse" and recombining the results. Essentially, this is

distributed quantum computing over the network using shaped pulses. Currently, 106 bits can be transmitted/encoded in a single burst of light with the present day optical pulse shaping technology. The repetition rate from the laser source is about 50 to 100 MHz. Thus, one would be able to use terabit/sec bit of communication channel through the existing infrastructure available with the optical community. Once such a quantum computer is available at remote site, these packets acting as "quantum software" can be transferred through high-speed communication channels. Thus, it is possible to carry out quantum computation at a remote distance with the proposed scheme of shaped pulses for terabit/sec communication and molecular control.

#### Optical Coherence Tomography

**[0110]** A preferred embodiment of the present invention uses a laser system 221 for laser excitation or ionization with Optical Coherence Tomography (hereinafter "OCT"). In general, Figure 6 illustrates the OCT application of system 221 wherein there is a femtosecond laser 223, a laser beam shaper 229, a human or animal tissue specimen 241, an optical gate 251 and an image 253. Laser 223 emits a laser beam pulse shorter than 1 picosecond. Shaper 229 is made of three parts; two dispersive elements 255 which sandwich a phase mask element 257. Shaper 229 essentially prevents multiphoton excitation which can damage the person's or animal's DNA, as will be discussed in more detail as follows. An unshaped laser beam pulse is used to gate the ballistic photons to render the image for tomography use. Optical gating can be accomplished by up-conversion in a frequency doubling crystal or with a kerr-gate in 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 and BPS processes 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. The pulse shaper is used to prevent three-photon and higher order nonlinear optical processes such as continuum generation. Higher order processes usually lead to sample degradation, and in the case of living samples to DNA damage. Suppression of three-photon transitions of four orders of magnitude has been achieved using the MI and BPS methods and this suppression can be coupled with optimization of two-photon signal from living specimens. Alternatively, a fluorescent contrast agent can be administered so that pulses shaped using BPS selectively excite the fluorescent agent targeted towards malignant tumors. The embodiment is expected to achieve functional deep tissue imaging.

**[0111]** Referring now to Figure 7, a system setup for functional imaging using BPS is shown. The tissue has been injected a fluorescent contrast agent that is preferentially absorbed by tumors. The fluorescent is a pH sensitive dye or derivatized quantum dots. No time grating is required.

#### Photodynamic Therapy

**[0112]** Another embodiment of the present invention uses a system also shown as 221 for laser excitation or ionization with photodynamic therapy (hereinafter "PDT"). PDT is a treatment that involves the combination of visible light and a photosensitizer. Each factor is harmless by itself, but when combined with oxygen, can produce lethal cytotoxic agents that can inactivate tumor cells. This enables greater selectivity towards diseased tissue as only those cells that are simultaneously exposed to the photosensitizer, light and oxygen are exposed to the cytotoxic effect. The dual selectivity of PDT is produced by both a preferential uptake of the photosensitizer by the diseased tissue and the ability to confine activation of the photosensitizer to this diseased tissue by restricting the illumination to that specific region. Therefore, PDT allows for the selective destruction of tumors while leaving normal tissue intact.

**[0113]** PDT is based on the concept that (1) certain photosensitizers can be localized (somewhat preferentially) in neoplastic tissue, and (2) subsequently, these photosensitizers can be activated with the appropriate wavelength (energy) of light to generate active molecular species, such as free radicals and singlet oxygen ( $^1\text{O}_2$ ) that are toxic to cells and tissues. PDT is a

binary therapy, and a potential advantage of PDT is its inherent dual selectivity. First, selectivity is achieved by an increased concentration of the photosensitizer in target tissue, and second, the irradiation can be limited to a specified volume. Provided that the photosensitizer is nontoxic, only the irradiated areas will be affected, even if the photosensitizer does bind to normal tissues. Selectivity can be further enhanced by binding photosensitizers to molecular delivery systems that have high affinity for target tissue. For photoactivation, the wavelength of light is matched to the electronic absorption spectrum of the photosensitizer so that photons are absorbed by the photosensitizer and the desired photochemistry can occur. Except in special situations, where the lesions being treated are very superficial, the range of activating light is typically between 600 and 900 nm. This is because endogenous molecules, in particular hemoglobin, strongly absorb light below 600 nm and therefore capture most of the incoming photons. The net effect would be the impairment of penetration of the activating light through the tissue. The reason for the 900 nm upper limit is that energetics beyond this wavelength are insufficient to produce  $^1\text{O}_2$ , the activated state of oxygen, perhaps critical for successful PDT.

**[0114]** 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 excitations 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 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, and is incorporated by reference herein. 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 and BPS processes 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 tuning and associated nonlinear spectrum tuning of the laser beam pulse. The pulse shaper is used to prevent three-photon and higher order nonlinear optical processes such as continuum generation. Higher order processes usually lead to sample degradation, and in the case of living samples to DNA damage. Suppression of three-photon transitions of four orders of magnitude has been achieved using the MII and BPS methods and this suppression can be coupled with optimization of two-photon signal from living specimens.

**[0115]** General applications of lasers for biomedical purposes are well known for diagnostic tools, surgical tools and for imaging purposes. The immediate extension of ultrashort pulse shaping technology for biomedical applications holds many promises, to further necessitate looking into its domain of influence. Though very few applications for ultrafast pulse shaping technology are currently in use, there are very strong indications as to where it would lead. One of the most commonly adopted methods, for imaging, in recent times for three-dimensional profile measurement is optical coherence tomograph or a white light interferometer, which uses a broadband, low coherence light source. Recently the principle of femtosecond pulse shaping by spectral modulation has been used in conjunction with the joint transform correlator to make a spatio-temporal joint transform correlator. The advantage of such a technique has been that it essentially removed the need of 1-D depth scanning and thereby avoided the long measurement times involved. Consequently, this eliminates the electronic computation needed to obtain the object image, and so it can be implemented as an all-optical set-up. Initially, this was demonstrated as a surface measurement set-up, however, as a natural extension, it was easily extended for providing tomographic sectioning of biological samples. In fact, with the use of principles of pulse shaping, a depth resolution of 70  $\mu\text{m}$  was achieved. Furthermore since there is no contact between the probe and the tissue, it is a useful non-invasive technique, which provides the physician with near-histological resolution imaging of sub-surface tissue morphology, potentially aiding in biopsy site selection and thus approaching the goal of "optical biopsy".

### Nonlinear Optical Excitation Spectroscopy

**[0116]** In one embodiment of the invention, the goal is to develop laser systems capable of generating ultrashort pulses with unprecedented control over the spectral profile and phase properties of the pulses. Specifically, the systems are capable of generating ultrashort pulses that are within 1% of the transform limit, as determined by accurate pulse characterization, by a novel method that incorporates phase characterization and compensation in a single pulse shaping/characterization unit. The same unit will provide calibrated synthesis of arbitrary pulse shapes. One embodiment of the invention, a laser system forms an integral part of a microscope capable of functional imaging, a method whereby pulses are tailored to excite chromophores sensitive to their microscopic chemical environment (pH,  $\text{Ca}^{++}$ ,  $\text{Na}^+$  gradients).

**[0117]** In another embodiment of the invention, a laser system is amplified and shaped by a two-dimensional spatial light modulator. The system is capable of providing single-shot multiphoton excitation spectra over a 20-30 nm range, with 0.05 nm resolution. Two-photon excitation spectra of molecules are usually acquired point by point and are prone to order-of magnitude errors. The system is capable of acquiring 1000 spectra per second over 30 nm excitation regions, and referencing them to a standard. The system improves the accuracy and speed of nonlinear frequency resolved excitation spectroscopy and cross section measurements by orders of magnitude. This information is central to selection and utilization of nonlinear optical materials.

**[0118]** Nonlinear optical excitation spectroscopy (hereinafter "NOES") involves the measurement of nonlinear processes such as two- or three-photon excitation cross-sections and nonlinear optical susceptibilities as a function of wavelength. These measurements are of great importance for the characterization of nonlinear optical materials and nonlinear optical chromophores such as laser dyes and quantum dots. Two-photon excitation spectroscopy, for example, requires a tunable laser source that is both narrow in frequency but highly efficient in multiphoton excitation. Typically, a narrow bandwidth tunable laser is used to obtain data from 700 to 950 nm, acquiring the data point by point. Nonlinear spectroscopy is extremely sensitive to transverse

mode quality, spectral phase, characteristics of the focal spot, pulse-to-pulse intensity variations, and wave front deformations; all of which can cause higher or lower order processes that contaminate the result. All of these factors make point-by-point acquisition prone to systematic errors.

**[0119]** To solve these problems, an embodiment of the invention is based on binary phase masks based on the principles of intrapulse interference (MIIPS) and then optimized using learning calculations afforded by an evolutionary learning calculation. An embodiment of the invention acquires spectra across a large bandwidth in a single laser shot. The high data throughput permits very accurate calibration to some of the best-known standards such as the nonlinear optical crystal KDP and the laser dye Rhodamine 6G. The laser system is not scanned; in fact, the amplitude of the laser field remains unchanged throughout the experiment. This permits outstanding calibration of all the factors that could affect nonlinear output.

**[0120]** A diffractive two-dimensional programmable phase modulator originally designed by Hamamatsu for optical computing, is ideally suited for this task. The PPM X8267 is a 1024x768 pixel electrically-addressed phase modulator using an image transmitting element to couple and optically-addressed PAL-SLM (parallel aligned nematic liquid crystal spatial light modulator). The number of pixels available for pulse shaping is critical in the design. The generation of well-defined pulses requires the introduction of a well-defined phase functions. Pixilation effects, where a smooth phase is replaced by a jagged, under-sampled phase can be detrimental. The PPM units are illuminated by a spatial image, which is projected into the PAL-SLM. The projection system provides high accuracy reproduction without pixel borders, making it ideal for pulse shaping purposes. The femtosecond laser that is modulated is spectrally dispersed by a 300 lines/mm gold coated diffraction grating and collimated by a gold-coated cylindrical mirror forming a reflective  $2f$  arrangement. The PAL-SLM is placed at the Fourier plane (where best spectral resolution is achieved). The reflected light is collected by an optical arrangement identical to the input one. Chromatic aberrations and group velocity dispersion are kept to a minimum by the all-reflective optical design. Nonlinear optical

distortions and optical damage are minimized by the use of cylindrical rather than spherical optics. The spectrums are dispersed on the horizontal dimension. The pixels in the vertical dimension contain different phase masks that scan the wavelength where nonlinear excitation takes place.

**[0121]** An embodiment of the invention, illustrated in Figure 8, produces amplified sub-20 fs pulses ( $\sim 10^6$  times more energy per pulse than laser System A), but at a repetition rate of 1 kHz. The bandwidth of the pulses is 50 nm FWHM, and is used to obtain NOES with about 0.2 nm resolution. The seed pulses are produced by a K&M Labs oscillator which is pumped by a Verdi laser (Coherent). The amplifier is an Odin, multipass amplifier from Quantronix, pumped by their Quantronix Darwin Q-Switched Nd:YLF, capable of delivering 1 mJ per pulse at 1 kHz. The Quantronix system is quoted for sub-35-fs performance. However, the amplifier is capable of preserving most of the oscillator bandwidth. The amplifier design is based on the multi-pass platform that Kapteyn and Murnane used to demonstrate generation of 17 fs pulses. To achieve the very short pulse duration a grating and prism compressors are used.

**[0122]** The laser system is installed on a 5' x 12' vibrationally isolated optical bench (Newport). Pulse characterization is carried out by frequency resolved optical gating (hereinafter "FROG"), SHG-FROG, and MIIPS. For FROG, an optical delay line (Aerotech) is used. Data collection is accomplished using an Ocean Optics spectrometer, a boxcar averager/integrator (SRS), a 500 MHz digital oscilloscope (Infinium, Hewlett Packard), and controlled with a personal computer running LabView, with a GPIB IEEE 488 controller.

**[0123]** Two-dimensional pulse shaping allows single-shot NOES data to be acquired from nonlinear optical materials, two-photon excitation spectra of laser dyes, biologically tagged fluorescent markers, quantum dots, optical switches and other optical materials. The wavelength range is limited to the 700 to 900 nm window by the pump pulses. The laser system is used to pump a non-collinear optical parametric amplifier, producing tunable broad bandwidth pulses from 450 to 1300 nm. These pulses are directed to the two-dimensional pulse shaper when characterization of a material is required at very different wavelengths.

**[0124]** The MIIPS method, described previously, requires the scanning of a reference phase across the spectrum of the laser. This usually requires acquisition of the SHG output spectrum for ~100 different phase function positions. To achieve this task in a single shot, the vertical dimension is divided into 128 different sections. Each section, containing 6x1024 pixels, contains the reference phase function. The key is that the phase function is displaced in each of the sections to provide the data as a function of  $\delta$  required for MIIPS. Once the femtosecond laser pulse undergoes the two-dimensional phase modulation it is focused with a short focal length ~100 mm cylindrical mirror on a thick SHG crystal. On the horizontal axis, the thick SHG crystal causes a spectral dispersion that is analogous to the one used in the GRENOUILLE. On the vertical axis, one obtains different sets of sets of SHG spectra because of the different phase functions encoded by the PAL-SLM. The entire two-dimensional image, containing the one-shot MIIPS data is then imaged onto a CCD for collection and analysis.

#### Communications

**[0125]** With reference to Figure 9, another preferred 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 un-shaper 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.

**[0126]** 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.

**[0127]** 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.

**[0128]** Using the BPS method, the data density that can be achieved per pulse is equal to or less than the number of pixels in the SLM divided by 2.

For example, in an embodiment in the SLM 429 has 256 pixel resolution, the maximum data density is 256/2 or 128 bits per pulse. In this embodiment, if the pulse rate is 100 MHz, the data rate or bandwidth would be  $10^{10}$  bits per second. Other embodiments of the invention vary the data rate or bandwidth based on pixel resolution and/or laser pulse rate. As laser pulse rates increase and as SLM pixel resolution increases, the bandwidth achievable by this invention will increase. It is advantageous that only a nonlinear optical detector would be able to decode the signal and, in contrast, a simple light detector would not be able to determine any information from the pulses. The fact that it can be used asynchronously is ideal for mobile or distant, and intermittent communications.

**[0129]** Referring to Figures 10, 11a and 11b, another 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. For example, photonic band gap materials such as optical fibers with holes therein may allow for use of approximately 10 femtosecond pulses.

**[0130]** Pulse shaper/phase mask 505 encodes each laser beam pulse phase, using a binary phase mask. The second harmonics contains multiple peaks, by way of example, but not limitation, in the frequency domain, thus revealing the encoded message. 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.

**[0131]** 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 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.

**[0132]** 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/sub-detectors. 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 microprocessor 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.

#### MIIPS Improvements

**[0133]** Another preferred embodiment of the present invention control system and apparatus enhances the ultra-fast laser output by placement of a MIIPS box or unit upstream of an amplifier's output. As used herein, it should be appreciated that the phrases "MIIPS box" and "MIIPS unit" can be used to include, but are not limited to, separately housed MIIPS components or some of the components thereof used to perform MIIPS being integrated into an amplifier housing, or other laser device, either physically between or in the optical path between the oscillator and final amplifier of the laser, or offset therefrom but with similar functioning. In one variation of this embodiment, a separate MIIPS box is placed directly between an ultra-short, femtosecond oscillator and an ultra-short amplifier. This is illustrated in Figure 13b. The present invention accurately measures output phase distortions using the MIIPS method which then employs the programmable, computer software to correct the distortions at the pulse shaper in the MIIPS box or by directly moving optics such as an amplifier's compressor and/or stretcher gratings. The computer controller and its software

can also be used to determine specific output conditions such as laser pulse duration, central wavelengths, spectral shape (for example, Gaussian, Lorentzian or Sech-sq), or the like. The pulse has specific phase characteristics such as transform limited or with a specific user-specified phase. Furthermore, the output is optimized and detected at the downstream, output side of the amplifier or, alternately, at a more distant downstream location such as at the specimen using a wireless, SHG crystal with a compact spectrometer.

**[0134]** Figures 13a and 14a represent conventional use without MIIPS. This should be contrasted to the representation of Figures 13b and 14b wherein MIIPS is used upstream of the laser output. The term “ultra short or femtosecond laser” as used herein includes an oscillator and one or more amplifiers. Furthermore, the term “upstream” as applied to the laser herein includes any position along a laser beam pulse’s path before the output of the final amplifier, and the term “downstream” as used herein with regard to the laser is any position along the laser beam pulse’s path after emission output from the final amplifier (see Figure 21). Use of MIIPS on the upstream laser side provides significant pulse-duration shortening and efficiency improvements, is much easier to use, but with minimal intensity loss, penalty, especially as compared to conventional approaches of shortening pulse duration without the present invention. Upstream use of MIIPS also achieves significantly shorter pulse durations as compared to downstream use of MIIPS (see Figures 1, 2 and 4-11 for downstream examples), substantially without other componentry changes. The advantage of MIIPS use in this manner is that it compensates for losses in the amplifier and it provides a better sense of the amplifier parameters that needs to be adjusted. It is also noteworthy that in order to obtain the best performance (in other words, shortest pulse) out of an amplifier, one needs to reduce the effect of spectral narrowing typically caused in regeneratively amplified systems. This method of the present invention easily compensates for spectral amplitude narrowing by measuring the output and correcting by amplitude modulation control using a dual mask shaper without the need for typical input or output polarizers as the amplifier only takes in one polarization. The present invention system directly interfaces with structure and compressor

optic gratings or prisms since it can reliably measure the pulse phase in an accurate manner. Moreover, the present invention can accurately be used with pulses that are 50 fs and even as short as 3 fs, while also adjusting amplitude modulation to correct spectral dispersion. The MIIPS and device and method, especially on the upstream side of the laser, does not require synchronization while achieving greater transmission efficiency.

**[0135]** More specifically, Figure 13b shows an amplitude shaping ultra-short laser pulse, ultra-short being between about 1 fs to sub-10 ps, from an ultra-short laser oscillator using a spatial light modulator (SLM) in order to minimize gain narrowing in an ultra-short laser amplifier. The ultra-short laser oscillator as referred to in the preceding sentence is also known as a “seed” laser and the amplifier as used herein can be any of an optical parametric amplifier, a regenerative amplifier, a multi-pass amplifier or the like, preferably a Legend brand amplifier which can be obtained from Coherent Inc. An ultra-short laser oscillator normally has a large bandwidth that is partially lost in the ultra-short laser amplifier due to the inevitable gain narrowing therein. In the figure,  $\tau_a$  is the pulse duration at position a of the initial spectrum and  $\tau_b$  is the pulse duration at position b of the downstream and amplified spectrum. It is noteworthy, however, that the laser performance is significantly improved by placing the MIIPS box in the beam path between the oscillator and the amplifier.

**[0136]** The upstream MIIPS placement allows for the introduction of an inverse Gaussian amplitude profile or other optimized profile on the seed spectrum by a dual or single mask spatial light modulator which increase amplification efficiency of the spectrum “wings” in the seeded spectrum. Therefore, larger bandwidths are emitted from the amplifier. This method is ideally conducted in an iterative manner automatically by comparing outputs and making further corrections. The central spectrum graph in Figure 13b, entitled “amplitude modification” shows a central “hole” which is introduced using the phase/amplitude modulator. The voltages in the pixels are set so that only phase delay or amplitude modulation is obtained. The computer controller automatically varies the voltage so that the transmission changes at different frequencies. The profile and location in the spectrum are important and the

profile should be dictated by the output of the amplifier, preferably optimized in an iterative manner with a series of sequential femtosecond pulses. The MIIPS exemplary box is physically split into two component sub-assemblies: one includes the shaper, which can be a grating prism, curved mirror and/or SLM; the other is the detector that generates the second harmonic, records its spectrum and then sends the corresponding signals to the computer controller. The MIIPS detector can be in the box, a remote unit placed at the output of the laser, or it can be placed remotely at the specimen which may be a few feet or even miles away from the laser. The second-subassembly of the MIIPS box includes a thin SHG crystal or powder of an SHG crystal to create the second harmonic. The preferred compact spectrometer can be obtained from Ocean Optics as Model No. USB200. In another variation, MIIPS is used to compare theory and experimental results to fine tune the pulse shaper, especially for binary pulses; this allows the MIIPS unit to retrieve and/or imprint complex spectral phases onto ultra-short laser pulses where complex spectral phases can have discontinuities or are of a binary nature, preferably in an iterative manner. The upstream positioning of the MIIPS box with the present embodiment significantly improves operation of the one or more ultra-short amplifiers employed while minimizing gain narrowing, thereby resulting in shorter pulse duration and wider pulse bandwidth, at a significantly reduced cost.

**[0137]** Figures 14a and b further compare downstream MIIPS use (see Figure 14a) with the improved upstream MIIPS use (see Figure 14b) in a further variation of the presently preferred embodiment of the present invention. A spatial light modulator and MIIPS unit are located between an ultra-short laser oscillator and ultra-short laser amplifier for measuring, pre-compensating and correcting the spectral phase distortions and for delivery of amplified arbitrarily shaped pulses in order to obtain transform limited pulses while gaining the maximum bandwidth of these pulses. The output of the amplifier is measured and its MIIPS trace is recorded and corrected by the software in the computer controller, in an iterative manner while introducing specific spectral phase functions on the SLM. Figure 14a compares the upstream and downstream spectral phases of the laser beam pulse during regular, non-MIIPS operation of

all ultra-short amplifiers, demonstrating resulting inevitable spectral phase distortion. Figure 14b, in contrast, graphically demonstrates the shorter pulses in flat spectral phases and wider bandwidth of the laser beam pulse employing MIIPS located upstream in the laser.

**[0138]** A further preferred embodiment of the present invention is illustrated in Figure 20. A preferred Ocean Optics, compact spectrometer 601 is remotely located and attached to an optic head 603 coupled by a fiber optic cable 615. The compact spectrometer is electrically connected to the controller as is the MIIPS unit. Head 603 includes a focusing lens or mirror 605, SHG crystal 607, and a spectral filter 609. The remote spectrometer, which saves space within the MIIPS box, employs head 605 which can be placed anywhere along the laser beam path to provide an evaluation signal to the MIIPS unit as required for the specific usage application. Alternately, the compact spectrometer can be detachable from the MIIPS box and placed at a differing, downstream location where it samples the pulse. A wireless communication interface can be employed between the spectrometer and computer to avoid long cables.

**[0139]** Figures 21 through 23 disclose preferred variations of the laser employing the MIIPS unit on the upstream laser beam path between the oscillator and the amplifier. Figure 21 illustrates a chirped pulse amplifier 661 with regenerative amplification 663. A femtosecond input pulse is emitted by an oscillator 665 which is then directed to a faraday isolator 667, reflected by high reflection mirrors and transmitted through a retro-reflecting mirror pair 669. The pulse is then sequentially transmitted to a grating 671, SLM 672 and curved mirror 673. The pulse is also reflected by mirrors to a regenerative amplification section 663 including a Ti-doped Sapphire crystal 675, mirrors and pockel cells 677. A nanosecond input pulse is sent from a pump laser 679 through lenses 681 and mirrors to regenerative amplification section 663. The amplified femtosecond pulse is subsequently transmitted through lenses 683 and mirrors to a compressor section 685, including a grating 687 and mirrors. The downstream pulse output is then detected by the SHG crystal and spectrometer unit 689. In this variation, the main reflector of a conventional stretcher has been

replaced by a reflective SLM. The reflective SLM can be a deformable mirror. Alternative, other reflective SLM designs exist such as the parallel aligned nematic liquid crystal ("PAL") SLM from Sony (LCX012BL). The SLM is under control of a CPU controller 688 which performs a MIIPS scan using a remote detector 689 that samples the amplifier output and obtains the spectrum of the second harmonic of the input beam. The SLM is capable of introducing a spatially varying phase delay and also of introducing a spatially varying change in amplitude. The controller also automatically adjusts the angle of a grating and/or the spacing in the stretcher to compensate for quadratic and cubic phase distortions.

**[0140]** Figure 22 illustrates a variation employing a chirped phase amplifier with regenerative amplification. Unlike the immediately prior variation, the present one locates an SLM 672', a transmissive LCD for example, in front of the main reflector 691 of the stretcher. The CPU controller automatically controls the SLM for performing a MIIPS scan using a remote detector that samples the amplifier output and obtains the spectrum of the second harmonic of the input beam. The SLM is capable of introducing a spatially varying phase delay and of introducing a spatially varying change in amplitude. The CPU automatically adjusts the angle of the grating and/or changing the spacing in the stretcher to compensate for quadratic and cubic phase distortions.

**[0141]** The next variation shown in Figure 23 uses a chirped pulse amplifier with multi-pass amplification 693. In this variation, an SLM 695 is located in front of a main reflector 697 of the stretcher and otherwise acts like to that of the immediately preceding variation. It should also be appreciated that a reflective SLM can alternately replace a reflector at a compressor for shaping and MIIPS, instead of being at the stretcher. This would allow for improved phase and amplitude control but at a small reduction in output energy.

**[0142]** Figure 15 shows another variation of the presently preferred embodiment wherein a stretcher is separated from a compressor within an ultra-short amplifier 641 of laser 643. A femtosecond oscillator 645 of laser 643 emits an ultra-short laser beam pulse which is reflected off of mirrors 647, 649 and 651, separated by grating 653 and collimated by curved mirror 655. The pulse is

then directed to SLM pulse shaper 657, backed by a highly reflective mirror 659. The mirrors, grating, curved mirror, SLM and highly reflective mirror are all located within the stretcher section of the amplifier. The MIIPS measurements and determinations cause an adjustment in the optics of the stretcher and/or compressor of the amplifier to achieve a desired level of chirp. The MIIPS software in the controller controls translation movement of the grating pair, for example, in the ultra-short amplifier's compression section thereby decreasing or increasing linear chirp to compensate for phase distortions in the pulses; this corrects for, by way of example, large linear chirp group velocity dispersion (hereinafter "GVD"). Similar MIIPS characterization (such as measurements) and compensation allow for automated controlling of the tilt angle and incidence angle of a large highly reflective mirror (see 659 in Figure 15) in the structure of the ultra-short laser amplifier which influences quadratic chirp ( $\text{fs}^3$ ) in conjunction with the MIIPS unit measurements. This minimizes the SLM requirements thereby effectively reducing the load burden of large correction parameters and allowing for more fine tuning with the MIIPS unit. The compressor gratings and mirrors can therefore be adjusted to compensate for quadratic dispersion and sometimes cubic dispersion. The controller automatically calculates the quadratic and cubic dispersion and then uses the grating and mirror mechanical adjustment in the compressor to make a rough and coarse initial correction; thereafter the SLM pulse shaper makes the fine tuned corrections in especially the high order phases.

**[0143]** The upstream placement of the MIIPS unit is ideally suited for use with a tunable and amplified laser. An electronically integrated system interface includes a MIIPS unit with motorized and micrometer actuators that translate gratings and/or mirrors to compensate for changes in the output wavelength of the laser. The actuators are automatically driven by energization signals from the computer controller, in a real-time, closed loop manner based on comparisons of the detected signals from the spectrometer and desired value calculations. The MIIPS detection can take place at the specimen. When the specimen is observed through a microscope objective, MIIPS can compensate

for the GVD introduced by specific objectives at the specific wavelength of emission of the tunable laser source.

**[0144]** Another preferred embodiment of the present invention control system and apparatus employs concave or cylindrically curved gratings instead of a lens or curved mirror/flat grating in a  $2f$  or  $4f$  configuration of the pulse shaping portion of the MIIPS unit. This minimizes the number of required optics and yields a more compact footprint or packaging size of the pulse shaper portion of the MIIPS unit. The particular curvature of the curved grating will serve the dual purposes of resolving the beam spectrally while also focusing resolved beams on the SLM. Thus, a focusing element (for example, a lens or mirror) can be eliminated, while it should be appreciated that this is independent of the SLM which may be a deformable mirror but preferably a liquid crystal modulator. A suitable concave grating can be obtained from Newport Inc. or Edmund Optics Inc.

**[0145]** One of the goals of the variations disclosed with regard to Figures 13 and 14 is to maximize the Full Width At Half Maximum (hereinafter "FWHM"), in other words the frequency bandwidth, of the laser pulse in order to obtain the shortest duration pulses. Another preferred embodiment seeks to achieve the opposite result where a laser system produces a greater bandwidth and employs MIIPS with amplitude control to reduce the bandwidth to a desired value. This would provide very reproducible results with laser outputs that are always exactly the same. In this exemplary embodiment, an SLM uses MIIPS, and optionally BPS, to optimize the amplitude of an amplified ultra-short laser source to the desired specification of the user. The MIIPS unit measures the spectrum and subsequently narrows the pulse bandwidth via the SLM pulse shaper. For example, if the amplified laser output is 30 nm FWHM, centered at 800 nm, the present use of MIIPS is expected to deliver a pulse output centered at 780 nm with a 5 nm bandwidth through the integrated or stand-alone MIIPS unit.

**[0146]** Figure 24 represents a tunable, femtosecond laser, using MIIPS methodology, applied by way of a non-limiting example, to an optical microscope 879. An exemplary inverted microscope can be obtained from Nikon Inc. as

Model No. TE200 and TE300. The laser pulse enters the microscope through a port and is reflected thereafter toward the objective. A tunable Chameleon-XR brand laser, obtained from Coherent Inc., or Mai Tai brand laser which can be obtained from Spectra-Physics Inc., may also be employed. This system can be applied to imaging as well as microscopy. The laser beam pulse output of a tunable oscillator 871 is directed to a pulse shaper 873. Shaper 873 has a rotating and translating grating 875 that receives the input pulse and rotates it according to its wavelength in order to maintain the alignment of the shaper. A programmable CPU controller 877 is connected with the laser and automatically directs the grating to the correct angle. The output pulse is thereafter directed from the shaper to an imaging device, for example microscope 879. The microscope is connected to and communicates with controller 877 sending signals indicative of which microscope objective is being used. The phase distortions introduced by the microscope objective at the wavelength of excitation are stored in a memory database in controller 877 and automatically adjusted by translation of the grating in the shaper, then the higher order terms by the shaper. The system automatically performs a MIIPS characterization measurement to fine tune the compensation and calibration of the system. A MIIPS detection box or unit 881 at the output of the objective has a nonlinear medium to generate the second harmonic and it also has a compact spectrometer directly therein or remotely coupled thereto used to obtain the spectrum of the second harmonic and send the corresponding signals to the controller for extracting the phase compensation based on the MIIPS software. This allows for automatic compensation, correction and producing of transform limited pulses at the microscope sample position using the MIIPS technique. This optionally allows for further optimization of the spectral phase of ultra-short pulses to maximize or minimize excitation of the microscope sample, such as selective 2-photon excitation. For selective PDT, by way of example, the MIIPS box can be optionally placed upstream of the amplifier, downstream amplifier or inside the amplifier's stretcher.

**[0147]** Figures 26 through 28 illustrate various preferred configurations of the control system employing MIIPS-based pulse shaping. Turning to Figure

25, a femtosecond laser oscillator, pulse shaper, optical setup, MIIPS detector and CPU controller are provided. The controller communicates with the shaper, optical setup and MIIPS detector to calibrate the pulses at the location of the sample. The controller further ensures that the pulse with the desired phase and amplitude properties interacts with the specimen, while correcting any phase deformations that could be introduced by the optical setup. The configuration of Figure 26 uses chirped pulse amplification where the pulse shaper and MIIPS detector are placed downstream after the amplification and compression. The controller obtains data from the detector and converts it into phase information from which it automatically controls hardware in the compressor to minimize quadratic and cubic phase deformations. The controller subsequently directs the shaper to compensate for higher order deformations and to introduce a compensation phase. The pulse shaper may then be used to introduce phase and amplitude modulation as desired by the user.

**[0148]** The programmable software instructions used with any of the MIIPS controllers described herein is illustrated in Figures 16 through 19. These software instructions are preferably run in an automated and closed loop manner in real-time, however, manual user input, variation and result verification may alternately be desirable especially upon initial setup of a new specimen type or in a laboratory-type setting. The software utilizes MIIPS, and optionally BPS, principles of introducing a well known spectral phase function via the SLM pulse shaper to the ultra-short femtosecond pulses with the intention to measure the unknown spectral phase inherent in the original ultra-short pulses, and subsequently compensate by pulse shaping the pulses and iterative or one shot-direct manner. It should further be appreciated that MIIPS and/or BPS methodology is applicable to all of the end use applications disclosed herein; this includes MALDI, sequencing, cleaving, microscopy, OCT, PDT, quantum computing, photo polymerization, and communications. It is equally applicable that upstream or downstream placement of the MALDI unit, or components thereof, can also be employed for all of the end-use applications disclosed herein depending upon the desired pulse duration, existing equipment and other case-by-case requirements.

**[0149]** Figure 16 represents a MIIPS software flow chart where after a new phase scan is acquired the data is used to extract the maxima from the phase scan for a function parameter to obtain the second derivative of the phase  $\phi^{(1)}$ . The phase across the entire spectrum  $\phi(\omega)$  is obtained by double integration. By applying  $-\phi(\omega)$  the phase in the pulse is corrected. If the correction is small enough then the target phase residue has been achieved. However, if the phase residue is still large the phase is corrected and a new phase scan is performed. Next, Figure 17 is a software flow chart including a first cycle, where the quadratic and cubic phase distortions are corrected by optic hardware in the laser. Furthermore, Figure 18 illustrates a software flow chart employing computer calculations which fine tune a phase function so that one can obtain precisely the nonlinear optical response predicted by theory. This specific flow chart method does not use MIIPS but instead uses MII to control 2-photon processes such as second harmonic generation. MII adjusts the phase parameters, however, the adjustments could alternately involve scanning certain parameters and manually evaluating their effects on the pulse output. Finally, Figure 19 is a software flow chart employing calculations used when the user wants to specify the output spectrum of the laser. This can be used as a stand-alone application or together with phase control. In this figure, the output spectrum refers to the linear spectrum of the pulse and not to the SHG spectrum. The pulse shaper in this application modulates the amplitude of the pulse.

**[0150]** A method of operating the laser system of the present invention in an iterative manner using MIIPS includes the sequential steps of introducing a reference phase into a train of pulses, measuring a characteristic of the output pulses, calculating a spectral phase from the measured characteristics, introducing a compensation phase approaching a desired phase, and repeating the previous steps multiple times to more closely approach the desired phase. This process improves a time-bandwidth product of the output pulse to approximately 1.1 or less, with 1.0 being the optimum desired target. The first iteration can be done fairly quickly in an automated manner with the controller; for example in about 15 seconds or less.

**[0151]** Referring now to Figure 27, a laser system is provided which uses chirped pulse amplification. The shaper is placed upstream before the stretcher. The controller obtains data from the detector and converts it into phase information. The controller thereafter directs the hardware in the compressor to minimize quadratic and cubic phase deformations which it then uses to control the shaper to compensate for higher order deformations and to introduce a compensation phase into the pulse. The shaper subsequently can be used to introduce phase and amplitude modulation as desired by the user. Furthermore, the Figure 28 configuration also uses chirped pulse amplification and the pulse shaper is located upstream before the stretcher. The controller obtains data from the MIIPS detector which it converts into phase information. The MIIPS detector, however, is located after an optical setup that is external to the laser, where the optical setup preferably includes a simple lens and mirror combination but could alternately include a telescope or microscope. The controller subsequently controls hardware in the compressor to minimize quadratic and cubic phase distortions which it uses to direct the shaper to compensate for higher order deformations and to introduce a compensation phase. This configuration may be optionally be used to also introduce phase and amplitude modulation as desired by user, and can be employed to ensure that the laser pulse interaction with the specimen has no undesired phase modulation.

**[0152]** An additional preferred embodiment of the present invention employs MIIPS and optionally BPS, in existing optical parametric amplifiers (hereinafter "OPA") in order to tune the central wavelength of the output and to correct for phase distortions of the beam output. The processes in OPAs are nonlinear by nature and a desired wavelength can be achieved by shaping the spectral phase of light input in the OPA or non-collinear optical parametric amplifier (hereinafter "NOPA") using calculations involving MIIPS and BPS. The SLM controlled by MIIPS and BPS in  $2f$  or  $4f$  configurations can be placed upstream before the OPA/NOPA or integrated into the OPA/NOPA; it can also be used to affect only non-classical light (in the nanosecond pulse duration

range), affect only white light generation, affect only blue light generation, or both, depending on the end use application.

#### Calibration of a Phase-Only SLM Inside a Pulse Shaper

**[0153]** This calibration is desired before MIIPS is performed, to determine the amount of voltage needed to achieve phase retardation. The SLM can be calibrated before the installation into the laser system if the input laser parameters are known ahead of time. Ideally the calibration should be done on the complete system when it is fully integrated.

#### **[0154]** Procedure:

1. Have the femtosecond laser being shaped transmit through the shaper setup.
2. Flip-up into position a zeroth-order half wavelength plate to rotate the polarization of the input beam to 45 degrees.
3. Flip-up into position a polarizer set at 45 degrees at the output of the shaper.
4. Drive the voltage of all the pixels in the SLM from 0 to the highest allowable voltage.
5. As the voltage is driven up, record the output spectrum from the shaper at the fundamental wavelength range. Make sure that the resolution in the spectrometer is sufficient to record changes on the individual pixels.
6. Calculate the calibration curve for each pixel given the transmission curve obtained from the corresponding wavelength range in the spectrum.

**[0155]** When the polarization is rotated away from the incident, horizontal direction, it is attenuated by the second polarizer. A rotation of 90 degrees results in zero transmission. This polarization dependence is used for calibration of the pulse shaper. Ramping the voltage of the liquid crystal plate results in the transmission function, which can be used to accurately calibrate the dependence of retardance on voltage.

**[0156]** The total retardation  $\phi$  is determined experimentally taking advantage of changes in the transmission given by

$$T(V) = \cos^2[\pi R(V) / \lambda], \quad [12]$$

where  $R(V)$  is the retardance as a function of voltage introduced by the SLM unit. By scanning the voltage  $V$ , one can measure  $T(V)$  and calculate  $R(V)$  (except for a constant that can be set to zero). Finally, one can calculate the phase delay  $\phi$  according to

$$\phi(V) = \pi R(V) / \lambda. \quad [13]$$

The software module takes into account the differences in the index of refraction for the different frequencies in the laser pulse. This is especially important for tunable laser systems or for pulses that are 50 fs and shorter. The calibration is performed for each pixel in the shaper at the frequency of light that transmits through it. The result is a calibration that can be trusted to better than 0.01 radians.

7. When the calibration is complete, flip the half wavelength plate out of the input beam and the polarizer out of the output beam. The system is now ready for MIIPS.

**[0157]** Calibration of a phase-amplitude SLM inside a pulse shaper. This procedure is carried out with the amplifier turned off.

1. Have the femtosecond laser being shaped transmit through the shaper setup.
2. Drive the voltage of all the pixels in the SLM mask 1 from 0 to the highest allowable voltage, while the SLM mask 2 is kept at the highest allowable voltage.
3. As the voltage is driven up, record the output spectrum from the shaper at the fundamental wavelength. Make sure that the resolution in the spectrometer is sufficient to record changes on an individual pixel.
4. Drive the voltage of all the pixels in the SLM mask 2 from 0 to the highest allowable voltage, while the SLM mask 1 is kept at the highest allowable voltage.

**[0158]** Calculation of the calibration curve for each pixel given the transmission curve obtained from the corresponding wavelength range in the spectrum is as follows: When the optical axis of the liquid crystal mask is oriented at a  $45^\circ$  angle with respect to the polarization of the incident electric

field, polarization rotation is introduced in addition to retardance. When two such SLM units are lapped back-to-back and in opposite angles of rotation, and they are flanked by input and output polarizers, one can control phase and amplitude of the transmitted light. Ramping the voltage of one of the liquid crystal plates while maintaining the other at a constant voltage results in the transmission function, which can be used to accurately calibrate the dependence of retardance on voltage. The total retardation  $\phi$  is determined experimentally taking advantage of changes in the transmission given by

$$T = \cos^2[\pi(R_1(V_1) - R_2(V_2))/\lambda], \quad [14]$$

where  $R(V)$  is the retardance as a function of voltage introduced by each SLM unit; by fixing  $V_2$  and scanning  $V_1$ , one can measure  $T(V_1)$  and calculate  $R_1(V_1)$  (except for a constant); and by measuring  $T(V_2)$  while keeping  $V_1$  constant, one can obtain  $R_2(V_2)$ . Knowing  $R_1(V_1)$  and  $R_2(V_2)$ , one can calculate the phase delay  $\phi$  according to

$$\phi = \pi(R_1(V_1) + R_2(V_2))/\lambda. \quad [15]$$

**[0159]** The software module takes into account the differences in the index of refraction for the different frequencies in the laser pulse. This is especially useful for pulses that are 50 fs and shorter. The calibration, therefore, is performed for each pixel in the shaper at the frequency of light that transmits through it.

#### Hardware Packaging and Stabilization

**[0160]** A preferred packaging arrangement for the control system and apparatus of the present invention is shown in Figure 29. A totally enclosed and self-contained sheet steel housing 701 has a slidable or rotatable door 703 allowing access to an application chamber 705 which contains a support upon which a specimen is placed by the user. A set of feet or rollers 707 support housing 701 off of a factory, hospital or laboratory floor. CPU controller 709 is located within housing 701 and an input keyboard 711 and mouse 715, and output CRT screen 713 are located on the outside of or attached within but externally operable from outside housing 701. Other input and output devices such as buttons, on/off/warning lights and printers may also be provided fully or

partially external to housing 701. Power supplies 717, an oscillator pump 719, an oscillator 721, an amplifier pump 723 and amplifier 725 are further mounted to a shelf 727 within housing 701. Amplifier 725 includes a stretcher and shaper section 731, a regenerative amplifier section 733 and a compressor section 735. SHG optics 741 and a compact spectrometer 743 are preferably mounted onto a second shelf 745 inside housing 701. The laser beam pulse output is indicated by line 747 and is preferably carried between components by fiber optic cables or the like. The portion of housing 701 containing at least the amplifier and SHG optics are hermetically sealed and temperature controlled. The remainder of housing has a filtered air flow, ventilation system, with fans, to cool the power supplies and CPU. Shelves 727 and 745 are preferably made from a thermally stable, breadboard-type material and are coupled to each other by way of thermally stable columns 751. A set of vibrational isolators 753 support at least shelf 727 off of the bottom of housing 701, and additional vibrational isolators can be employed at optional additional coupling areas between one or more of the shelves and side walls of housing 701. Each vibrational isolator 753 is preferably a Newport Inc. Model I-2000 device.

**[0161]** A water chiller 755 is located within housing 701 and is fluidically coupled to a set of pipes 757 running in a serpentine path under shelf 727 and optionally, shelf 745. The chilled water system maintains the desired temperature range of 28°C +/- 1°C to all of the oscillator and MIIPS components. The application chamber can be used for at least MALDI, mass spectrometry, micro-machining, PDT for blood and other fluids, breath analysis, biohazard analysis of emissive signatures, chemical agent analysis by mass spectrometry, sequencing, cleaving, photo-polymerization, and the like.

**[0162]** The present invention ideally reduces thermally and vibrationally induced changes in the optical systems. Thus, room temperature variations affecting the dimensions and alignment of optic components due to temperature of the equipment is minimized or maintained constant. The present invention further saves expense since the components within the housing can be temperature controlled while the surrounding factory environment can be open to the outside atmosphere or at temperatures more comfortable for the users.

**[0163]** While various embodiments have been disclosed herein, it should be appreciated that other modifications may be made that are covered by the system and methods of the present invention. For example, alternate lasers, chemicals, optics, software and programmable controllers can be employed as long as they function as described. As a further example, phase characterization of the output pulse with or without the automatically operated, computer controlled mirror and grating movement for tuning oscillator optics can alternately be used with frequency resolved optical gating ("FROG") or spectral phase interferometry for direct electric-field reconstruction ("SPIDER") phase measurements that are then used to calculate a compensation phase that is introduced with a pulse shaper instead of using the preferred MIIPS method. Moreover, the SLM can be placed in an upstream location in the oscillator anywhere at or after an optic disperses a spectrum of the laser beam pulse. In another variation, a first pulse shaper can be placed in an upstream location and a second pulse shaper can also be placed in a downstream location. The description of the invention is merely exemplary in nature and, thus, variations that do not depart from the gist of the invention are intended to be within the scope of the invention. Such variations are not to be regarded as a departure from the spirit and scope of the invention.

## CLAIMS

The invention claimed is:

1. A laser system comprising:
  - a) a laser oscillator operable to emit a laser beam pulse;
  - b) an amplifier operably receiving the pulse; and
  - c) a shaper operable to shape the pulse, the shaper using multiphoton intrapulse interference phase scan for pulse characterization and compensation in a path of the pulse between a point in the oscillator where a spectrum of the pulse is dispersed and the amplifier output.
2. The system of Claim 1, wherein the shaper introduces phase values separated by  $\pi$  at different frequency components.
3. The system of Claim 1 further comprising optics of the amplifier that are moved to compensate for phase distortions based on the phase scan.
4. The system of Claim 1 further comprising a programmable controller operably varying a characteristic of the shaper, and the shaper is part of a multiphoton intrapulse interference phase scan unit.
5. The system of Claim 1 further comprising an initially unknown specimen receiving the shaped pulse which is automatically detected, wherein the specimen is at least one of: (a) a chemical molecule, and (b) a biological molecule.
6. The system of Claim 1 wherein the oscillator, amplifier and shaper are employed in a communications network.
7. The system of Claim 1 wherein the oscillator, amplifier and shaper are used in a MALDI unit.
8. The system of Claim 1 wherein the oscillator, amplifier and shaper are used in a protein sequencing unit.
9. The system of Claim 1 wherein the oscillator, amplifier and shaper are used in an optical coherence tomography unit.
10. The system of Claim 1 wherein the oscillator, amplifier and shaper are used in a functional imaging unit.

11. The system of Claim 1 wherein the oscillator, amplifier and shaper are used in a nonlinear optical excitation spectroscopy unit.

12. The system of Claim 1 wherein the oscillator, amplifier and shaper are used in a photodynamic therapy unit.

13. The system of Claim 1 wherein the pulse has a duration of less than fifty one femtoseconds.

14. The system of Claim 1 further comprising generating an optical tomography image produced by the shaped pulse passing through tissue.

15. The system of Claim 1 wherein the pulse shaper enhances two photon absorption by a therapeutic substance and substantially prevents three photon induced damage of adjacent healthy tissue.

16. The system of Claim 1 wherein the pulse is shaped to enhance targeted multiphoton damage to modify or destroy certain molecules in the living tissue.

17. The system of Claim 1 wherein multiphoton intrapulse interference operably activates desired photodynamic therapy agents at desired tissue depths.

18. The system of Claim 1 wherein the amplifier further comprises a stretcher and the shaper is located inside the stretcher.

19. The system of Claim 1 wherein the amplifier further comprises a compressor, and the shaper is located inside the compressor.

20. A laser system comprising:  
at least one laser operably emitting at least one laser beam pulse of a duration less than about 51 femtoseconds;  
a pulse shaper varying the laser beam pulse; and  
a matrix-assisted laser desorption ionization device receiving the shaped pulse and operably causing specimen fragmentation and ionization.

21. The system of Claim 20 further comprising a programmable controller connected to the shaper and the device, and detected feedback from the device being analyzed by the controller in order to identify an initially unknown specimen.

22. The system of Claim 20 when at least one of the pulses has a duration of less than 10 femtoseconds.

23. The system of Claim 20 further comprising at least a portion of a protein molecule is identified by a programmable controller connected to the device, wherein the laser includes an amplifier.

24. The system of Claim 20 further comprising introducing multi-photon intrapulse interference to the pulse through the shaper.

25. The system of Claim 20 wherein phase distortions of the laser output are measured and the pulse shaper is used to compensate for the phase distortions.

26. A laser system comprising:  
at least one laser operable to emit at least one laser beam pulse having a duration of less than 51 femtoseconds;  
a pulse shaper operable to vary the shape of the pulse; and  
a detector operably detecting characteristics of a specimen targeted by the shaped pulse;  
wherein the shaped pulse causes selective fragmentation or cleaving of the specimen.

27. The system of Claim 26 further comprising a programmable controller connected to the shaper and the detector, and detected feedback from the detector being analyzed by the controller in order to identify an initially unknown specimen.

28. The system of Claim 26 when at least one of the pulses has a duration of less than 10 femtoseconds.

29. The system of Claim 26 further comprising selective atomic bond cleavage is performed using the shaped pulse, and molecular sequencing is performed using the cleaved specimen.

30. The system of Claim 26 further comprising introducing multi-photon intrapulse interference to the pulse through the shaper.

31. The system of Claim 26 wherein phase distortions of the laser output are measured and the pulse shaper is used to compensate for the phase distortions.

32. A laser system comprising:  
a laser operably emitting a laser beam pulse;  
a pulse shaper operably varying a characteristic of the pulse; and  
a microscope operably receiving the shaped pulse;  
wherein the shaper assists in creating multi-photon intrapulse interference in the pulse to control multi-photon excitation.

33. The system of Claim 32 wherein the pulse shaper assists in suppressing three photon or greater transitions in the pulse.

34. The system of Claim 32 wherein the shaped pulse selectively excites probe molecules.

35. The system of Claim 32 wherein the pulse has a duration less than 51 femtoseconds.

36. The system of Claim 32 wherein the pulse has a duration less than 10 femtoseconds.

37. The system of Claim 32 further comprising:  
a detector; and  
a programmable controller connected to the shaper and detector;  
wherein the controller, detector and pulse shaper act to measure phase distortions output by the laser and the pulse shaper compensates for the phase distortions.

38. The system of Claim 32 further comprising a programmable controller connected to the pulse shaper compensating for phase distortions at the specimen introduced by different microscope objectives, by subtracting a phase distortion associated with each objective, the associated phase distortion being stored in memory of the controller.

39. The system of Claim 32 further comprising a controller connected to the pulse shaper, the laser being tunable, and the controller and shaper compensating for phase distortions of the laser beam pulse at a specimen as a laser wavelength is tuned to different frequencies.

40. A laser system comprising:  
a laser operably emitting a laser beam pulse;  
a pulse shaper operably shaping the pulse; and

a polymerization device;

wherein the pulse shaper assists in causing multi-photon intrapulse interference in the pulse and the pulse causes selective photo polymerization.

41. The system of Claim 40 wherein the pulse has a duration less than 51 femtoseconds.

42. The system of Claim 40 wherein the pulse has a duration less than 10 femtoseconds.

43. The system of Claim 40 further comprising:

a detector; and

wherein the controller, detector and pulse shape act to measure phase distortions output by the laser and the pulse shaper compensates for the phase distortions.

44. The system of Claim 40 further comprising using the shaped pulse to perform selective multi-photon microlithography.

45. The system of Claim 40 further comprising using the shaped pulse to perform three-dimensional lithography microfabrication through multi-photon-induced polymerization.

46. The system of Claim 40 further comprising using binary pulse shaping with the pulse shaper to control polymerization of at least two polymers with different characteristics.

47. A system comprising:

a laser operably emitting a laser beam pulse;

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

a quantum mechanical system, the shaped pulse being used to manipulate information stored in the quantum mechanical system.

48. The system of Claim 47 wherein the pulse has a duration less than 20 femtoseconds, and the shaped pulse assists in data storage within memory of the quantum mechanical system.

49. A laser system comprising:

a laser operably emitting a laser beam pulse having a duration less than 51 femtoseconds;

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

a detector operably detecting a characteristic related to the pulse;  
wherein an inverse, substantially Gaussian amplitude profile is introduced by the pulse shaper to the pulse.

50. The system of Claim 49 wherein the pulse shaper includes a spatial light modulator which is located in an upstream position and the spatial light modulator assists in suppressing gain narrowing in amplification of the pulse.

51. The system of Claim 49 wherein the pulse shaper is part of a multiphoton intrapulse interference phase scan unit.

52. A laser system comprising:

a laser beam pulse; and

a multi-photon intrapulse interference phase scan unit comprising a pulse shaper, a controller and a compact spectrometer, the pulse shaper operably varying a characteristic of the pulse;

the compact spectrometer being detachably coupled to the controller, the compact spectrometer operably detecting the characteristics associated with the pulse.

53. The system of Claim 52 wherein the pulse has a duration less than 51 femtoseconds and the compact spectrometer is upstream of an output of a laser amplifier.

54. The system of Claim 52 wherein the compact spectrometer is remotely located away from the pulse shaper and controller, and an input head is attached to the remote spectrometer by an optical fiber, the head of the spectrometer further comprising a lens and a second harmonic generation optic.

55. A laser system comprising:

a laser beam pulse;

a pulse shaper operably varying a characteristic of the pulse;

a laser amplifier comprising at least one movable optic and an automatic actuator;

a detector operably detecting a characteristic associated with the shaped pulse;

and

a controller automatically receiving a signal from the detector based on the shaped pulse and automatically causing the actuator to adjust the optic of the amplifier.

56. The system of Claim 55 wherein the optic is at least one of: (a) a grating, (b) a mirror, and (c) a part of a stretcher.

57. The system of Claim 55 wherein the optic is at least one of: (a) a grating, (b) a mirror, and (c) a part of a compressor.

58. The system of Claim 55 wherein the pulse shaper is part of a multi-photon intrapulse interference phase scan unit which compensates for undesired distortions in the pulse.

59. The system of Claim 55 wherein the optic movement provides a rough optimization of the pulse, and the pulse shaper provides a fine optimization of the pulse, and the duration of the pulse is less than 51 femtoseconds.

60. A laser system comprising:  
a laser beam pulse; and  
a pulse shaper;  
the pulse shaper including at least one curved grating.

61. The system of Claim 60 wherein the grating is concave.

62. The system of Claim 60 wherein the grating is cylindrically curved.

63. The system of Claim 60 wherein the pulse shaper operably introduces multi-photon intrapulse interference to the pulse.

64. A laser system comprising:  
a multi-photon intrapulse interference phase scan unit operably compensating for distortions of an amplified output, and introducing additional binary pulse shaping; and

a laser amplifier amplifying a shaped pulse from the multi-photon intrapulse interference phase scan unit.

65. The system of Claim 64 wherein the pulse has a duration less than 11 femtoseconds.

66. A laser system comprising a femtosecond, chirped pulse amplifier, and a spatial light modulator located within the amplifier operably compensating for phase distortions in a laser beam pulse.

67. The system of Claim 66 further comprising a stretcher and the spatial light modulator being located in the stretcher.

68. The system of Claim 67 further comprising a grating and a programmable controller, wherein the programmable controller automatically adjusts the position and orientation of an optic in the stretcher to compensate for at least one of quadratic and cubic phase distortions in the pulse.

69. The system of Claim 66 further comprising a detector operably detecting a characteristic of the laser beam pulse emitted from the amplifier and obtaining the spectrum of the second harmonic of the input beam.

70. The system of Claim 66 wherein the spatial light modulator is reflective.

71. The system of Claim 66 wherein the amplifier uses multi-pass amplification.

72. The system of Claim 66 wherein the amplifier uses regenerative amplification.

73. The system of Claim 66 wherein the spatial light modulator introduces amplitude modulation to control a central wavelength and a bandwidth of an amplified laser output.

74. A laser system comprising a femtosecond compressor, and a spatial light modulator located within the compressor operably shaping a laser beam pulse.

75. The system of Claim 74 further comprising a grating and a programmable controller, wherein the programmable controller automatically adjusts at least one of the position and orientation of an optic in the compressor to compensate for at least one of quadratic and cubic phase distortions in the pulse.

76. A laser system comprising:  
a laser operable to emit a pulse having a duration less than 51 femtoseconds;

an optic unit operable to automatically measure and compensate for spectral phase distortion of the pulse; and

a detector operable to calibrate the pulse at a target specimen location.

77. The system of Claim 76 wherein the optic unit introduces multi-photon intrapulse interference to compensate for distortions in the pulse and binary pulse shaping into the corrected pulse.

78. The system of Claim 77 further comprising a second optic unit introducing the binary pulse shaping.

79. The system of Claim 76 wherein the optic unit is operable to manipulate the amplitude of the pulse to control a central wavelength and a bandwidth of the pulse at the target specimen location.

80. The system of Claim 76 wherein the optic unit includes a pulse shaper and a second harmonic generation optic.

81. An optical system comprising:

a substantially transparent substrate; and

a laser beam pulse-varying powder particle secured to the substrate, the powder particle have a size less than  $1\text{ mm}^3$ .

82. The system of Claim 81 wherein the powder generates a second harmonic and a laser beam pulse interacts with the powder.

83. The system of Claim 81 wherein the powder includes Potassium Dihydrogen Phosphate and the substrate includes quartz.

84. The system of Claim 81 wherein the powder includes Barium Borate and the substrate includes quartz.

85. The system of Claim 81 wherein the powder includes an inorganic compound with a noncentro-symmetric crystal lattice.

86. The system of Claim 81 further comprising a laser system operably generating a laser beam pulse having a duration of less than 51 femtoseconds, the pulse being varied by the powder and multiples of the powder particle are secured to the substrate.

87. A laser system comprising:

a substantially enclosed and self-contained housing;

a laser located in the housing;

a cooling system at least partially located in the housing to cause desired thermal stabilization of the laser; and

a vibration isolator located in the housing to reduce vibration being transmitted between the housing and the laser.

88. The system of Claim 87 further comprising a laser beam pulse shaper and an amplifier located in the housing.

89. An electronic control system comprising a programmable controller sending a signal related to introducing a known laser pulse spectral phase function, the controller determining an unknown laser beam spectral phase, and the controller automatically sending a signal related to compensation for laser pulse deformation.

90. The system of Claim 89 further comprising a pulse shaper and a spectrometer communicating with the controller.

91. The system of Claim 89 further comprising laser beam pulses, each having a duration less than 51 femtoseconds, being varied in response to the compensation signal.

92. The system of Claim 89 further comprising an optic retrieving a spectral phase of output pulses and communicating the retrieved phases to the controller.

93. A method of using a laser comprising:

(a) emitting a laser pulse having a duration less than about 100 femtoseconds; and

(b) correcting spectral phase distortions using multi-photon intrapulse interference phase scan, after step (a); and

(c) amplifying the pulse, after step (b).

94. The method of Claim 93 further comprising using the pulse to achieve non-linear optical excitation of materials.

95. The method of Claim 93 further comprising using the pulse in optical coherence tomography.

96. The method of Claim 93 further comprising using the pulse in photodynamic therapy.

97. The method of Claim 93 further comprising using the pulse in MALDI.

98. The method of Claim 93 further comprising additional shaping of the pulse with binary phase functions.

99. A method of operating a laser system comprising:

- (a) introducing a reference phase into at least one pulse;
- (b) measuring a characteristic of the output pulse;
- (c) calculating a spectral phase from the measured characteristics;
- (d) introducing a compensation phase approaching a desired phase;

and

(e) repeating steps (a) – (d) to more closely approach the desired phase.

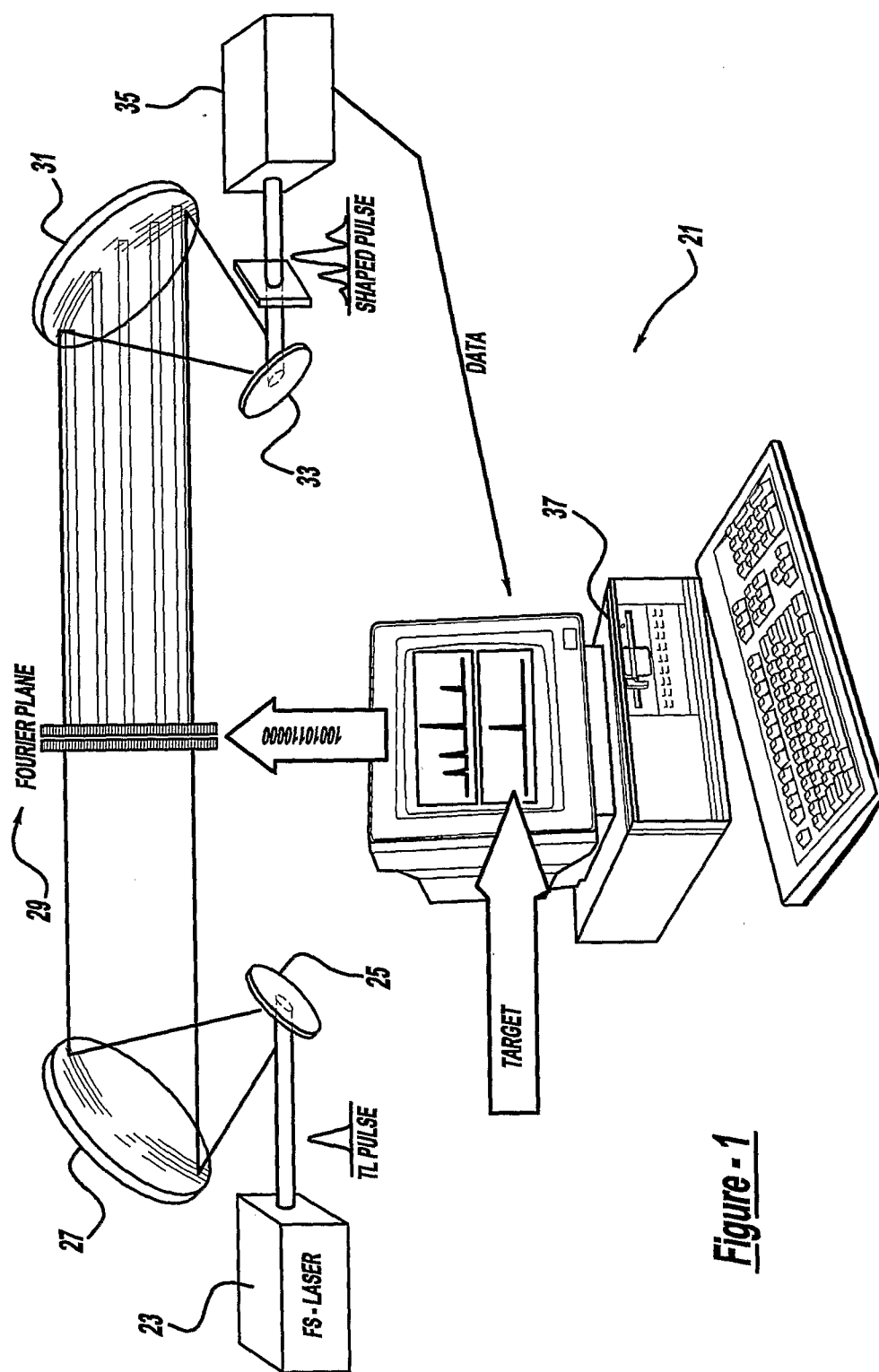
100. The method of Claim 99 further comprising improving a time-bandwidth product of the output pulse to about or less than 1.1.

101. A method of using a laser system comprising emitting a nanosecond pulse onto a specimen in order to eject material from the specimen, and subsequently emitting a shorter duration femtosecond pulse onto the specimen in order to analyze a characteristic of the ejected material.

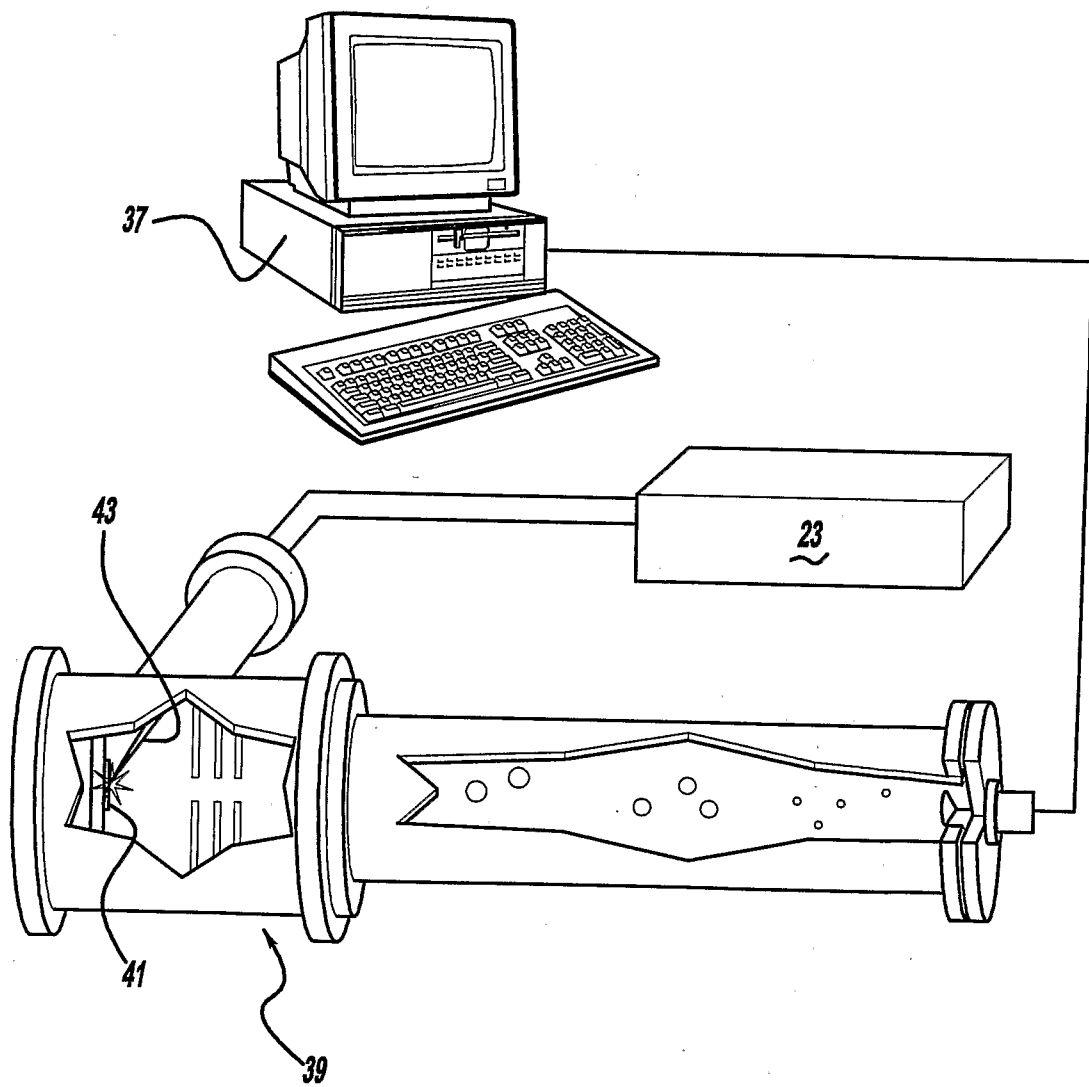
102. The method of Claim 101 wherein a time delay of the nanosecond pulse and the femtosecond pulse is varied.

103. The method of Claim 101 wherein the femtosecond pulse has a duration less than 51 femtoseconds, further comprising shaping the femtosecond pulse.

104. The method of Claim 101 further comprising using the pulses in a MALDI process.

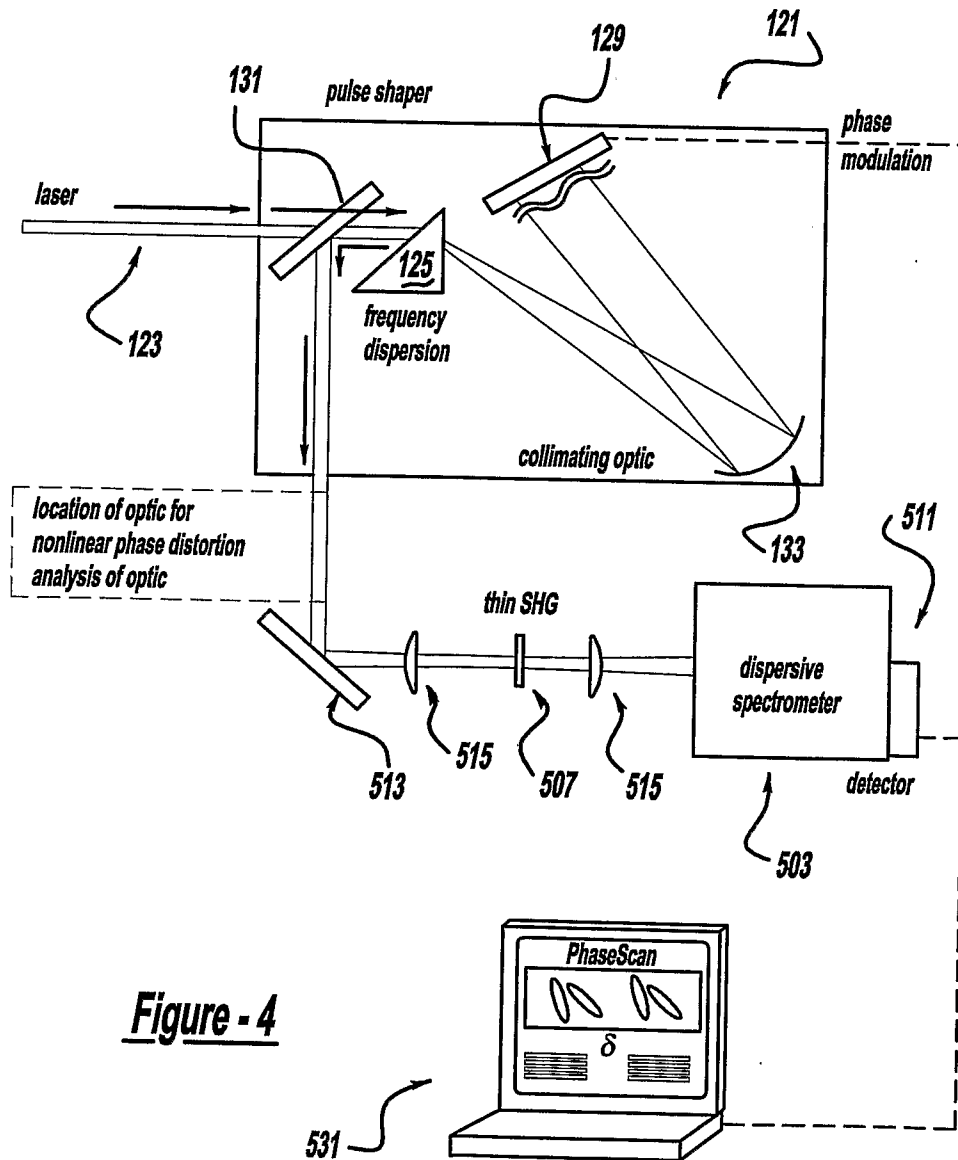
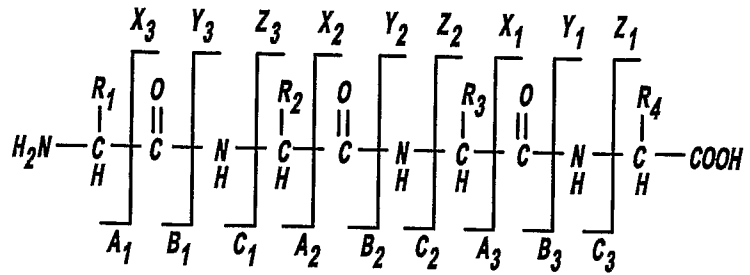


**Figure - 1**

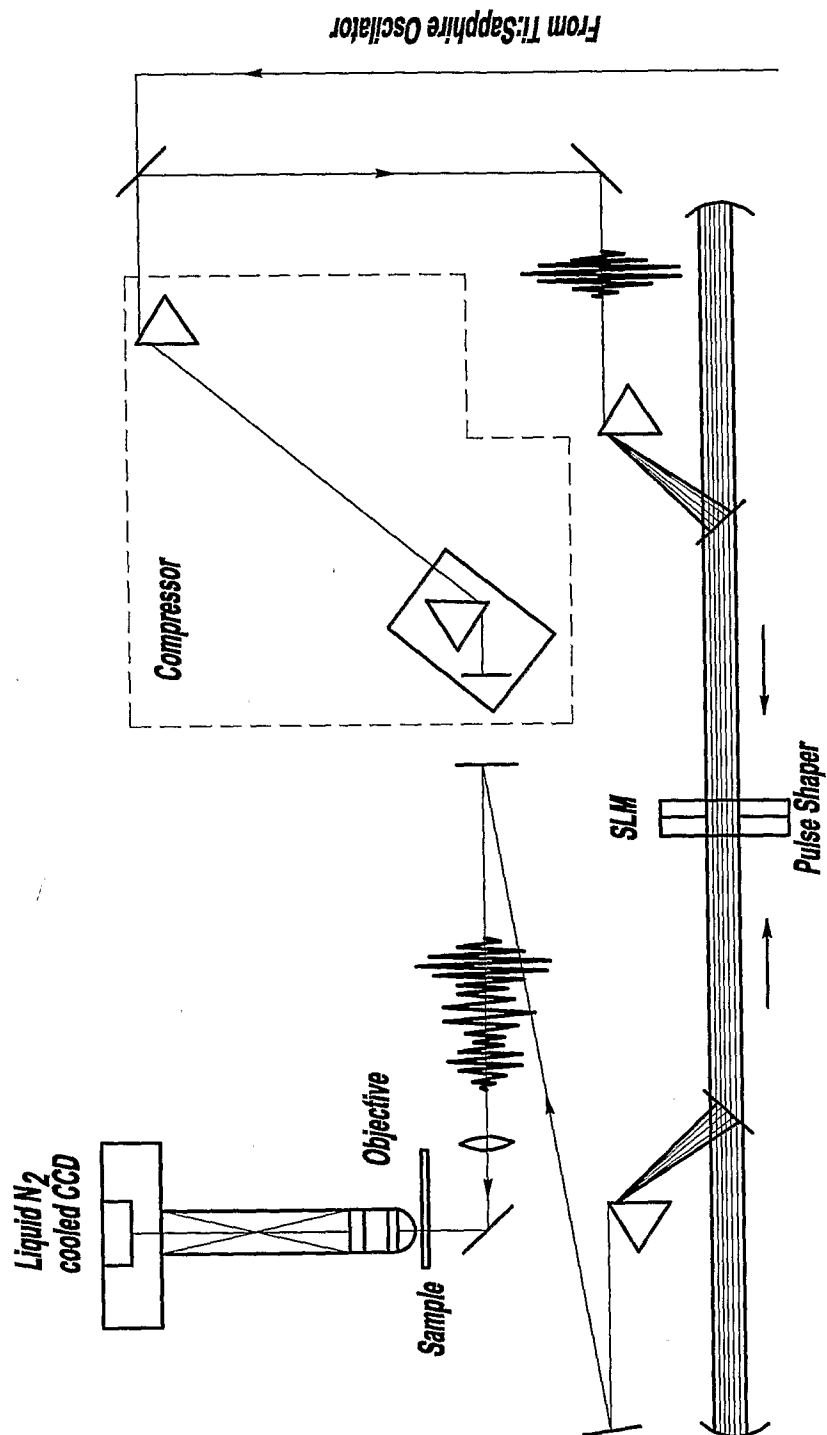


**Figure - 2**

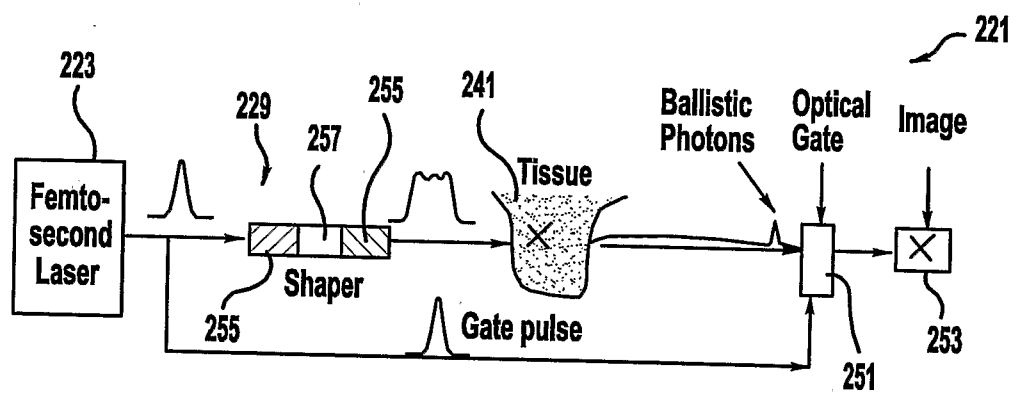
**Figure - 3**



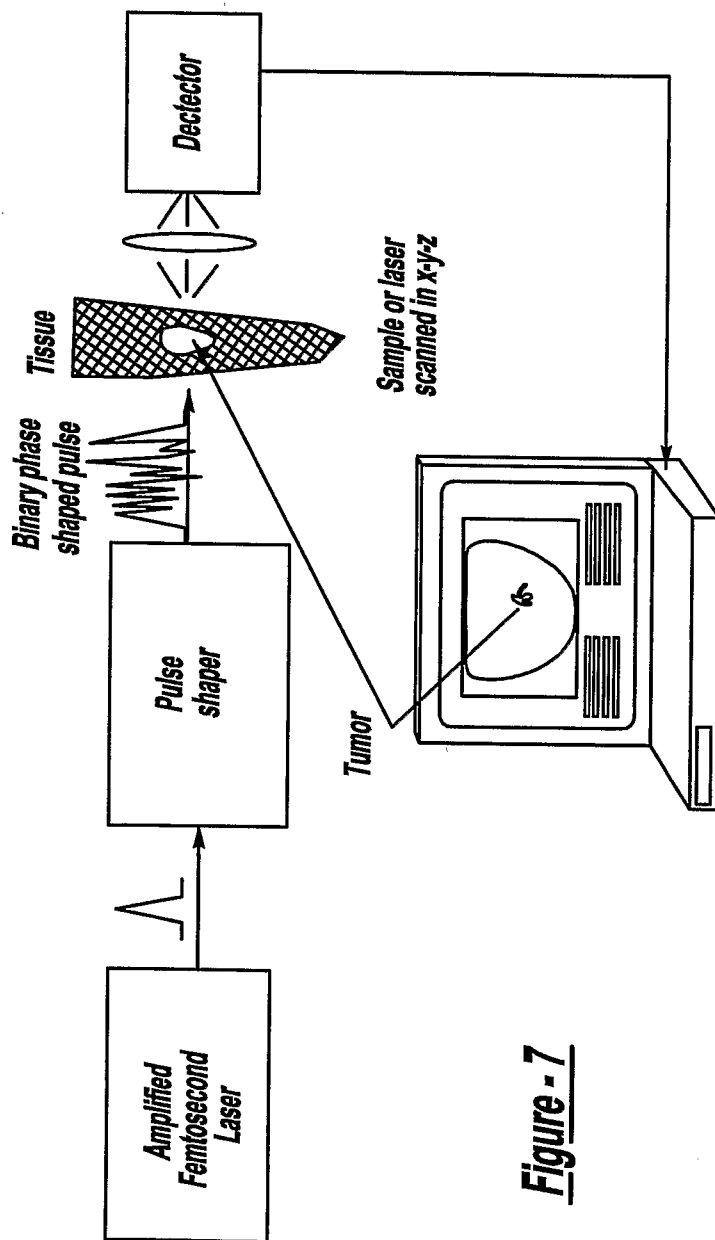
**Figure - 4**



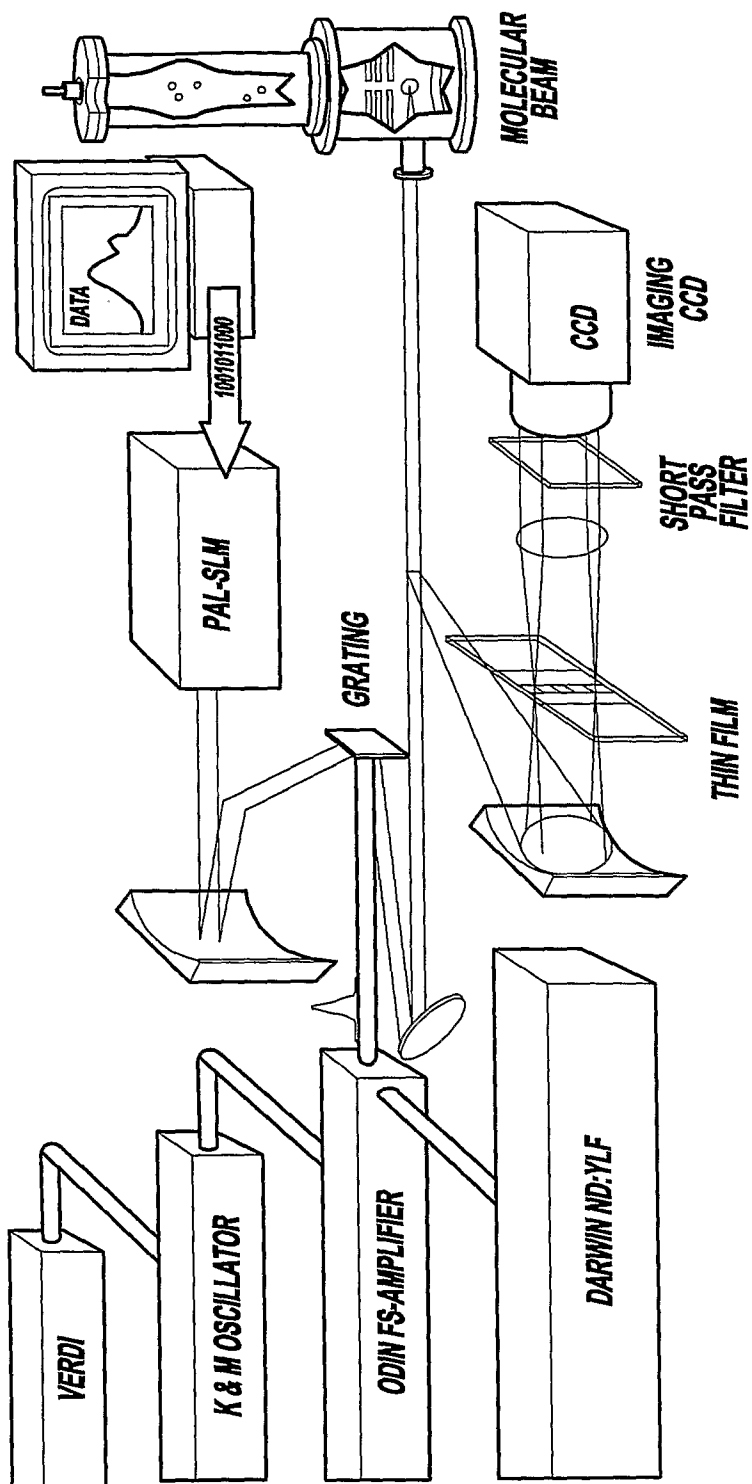
**Figure - 5**



**Figure - 6**



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**Figure - 8**

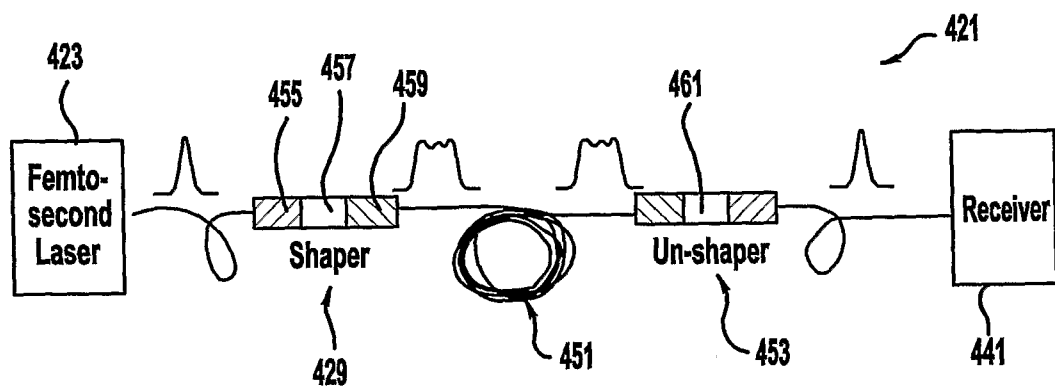


Figure - 9

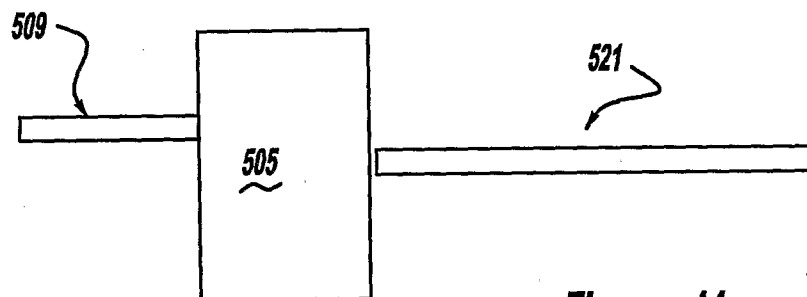


Figure - 11a

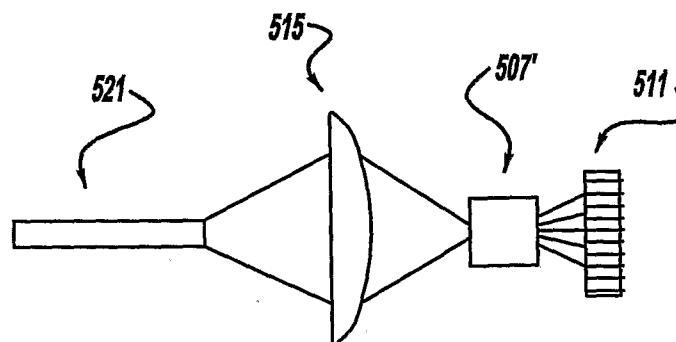


Figure - 11b

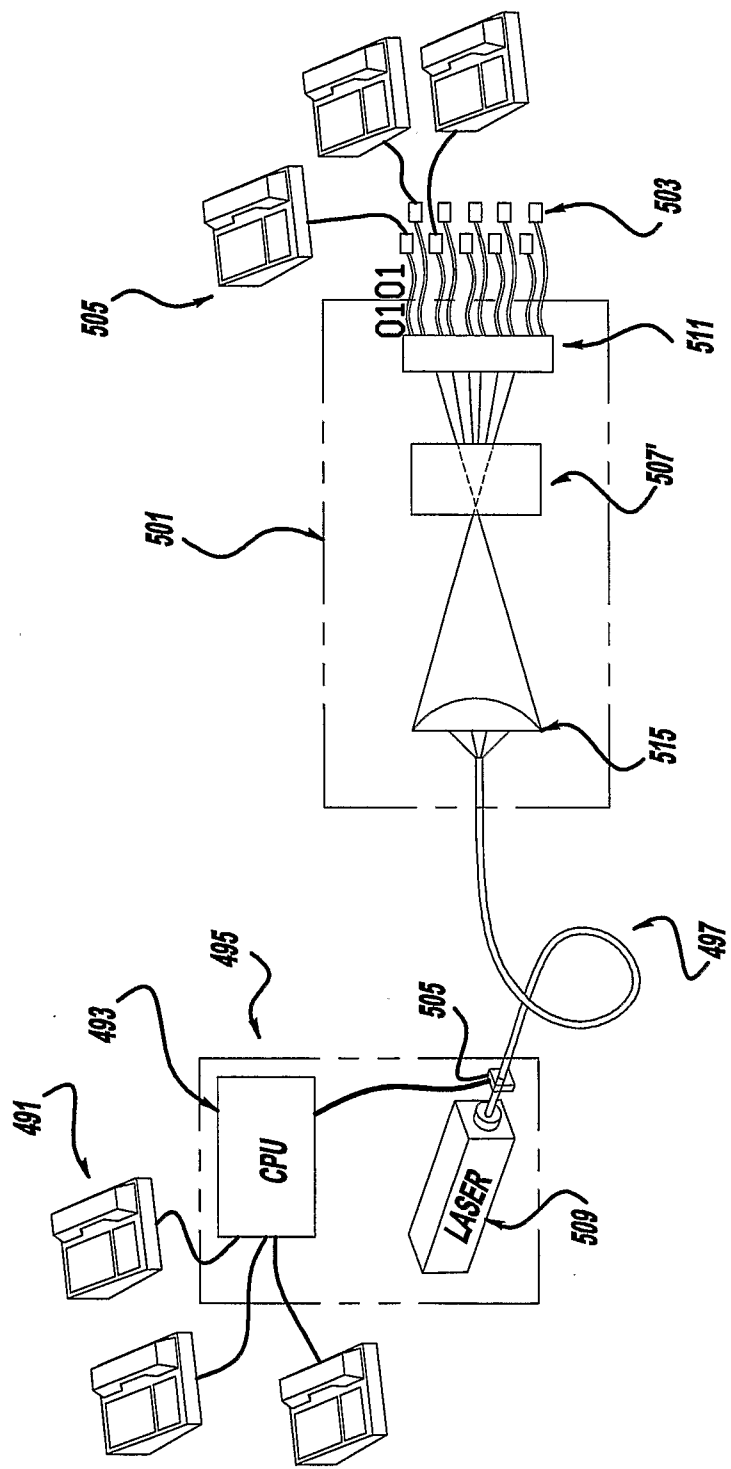
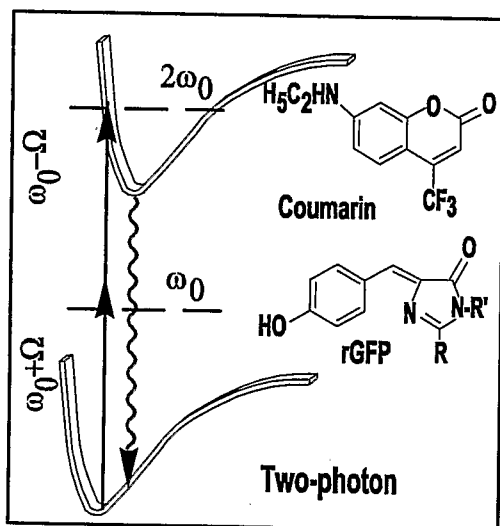
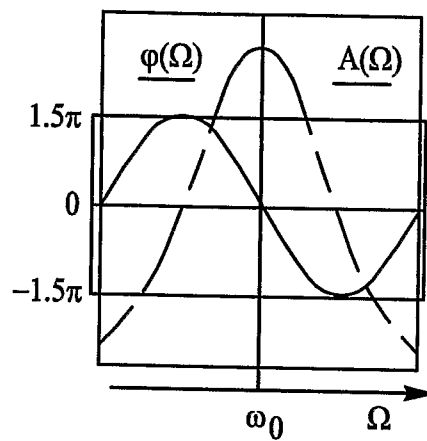
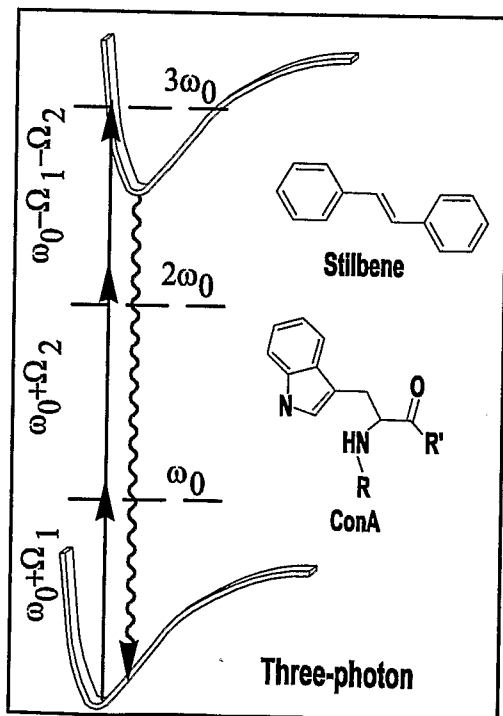
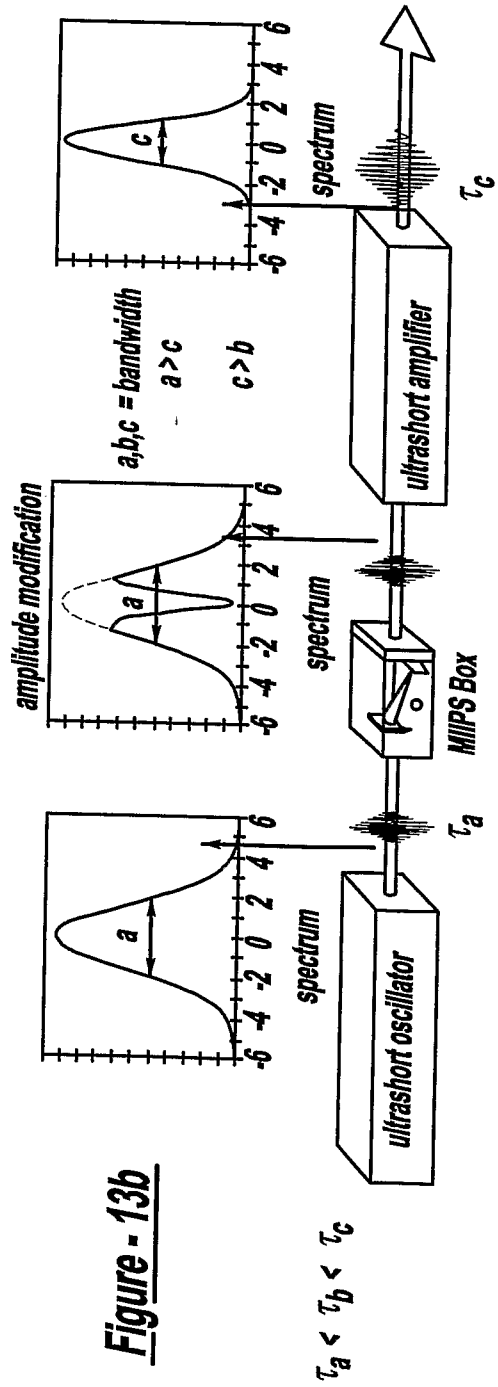
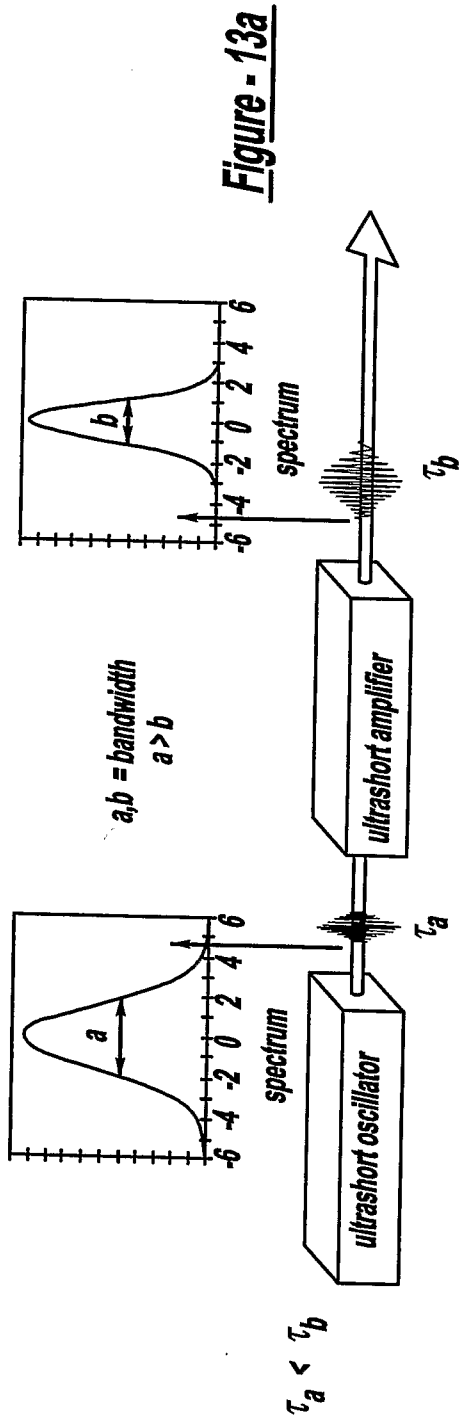
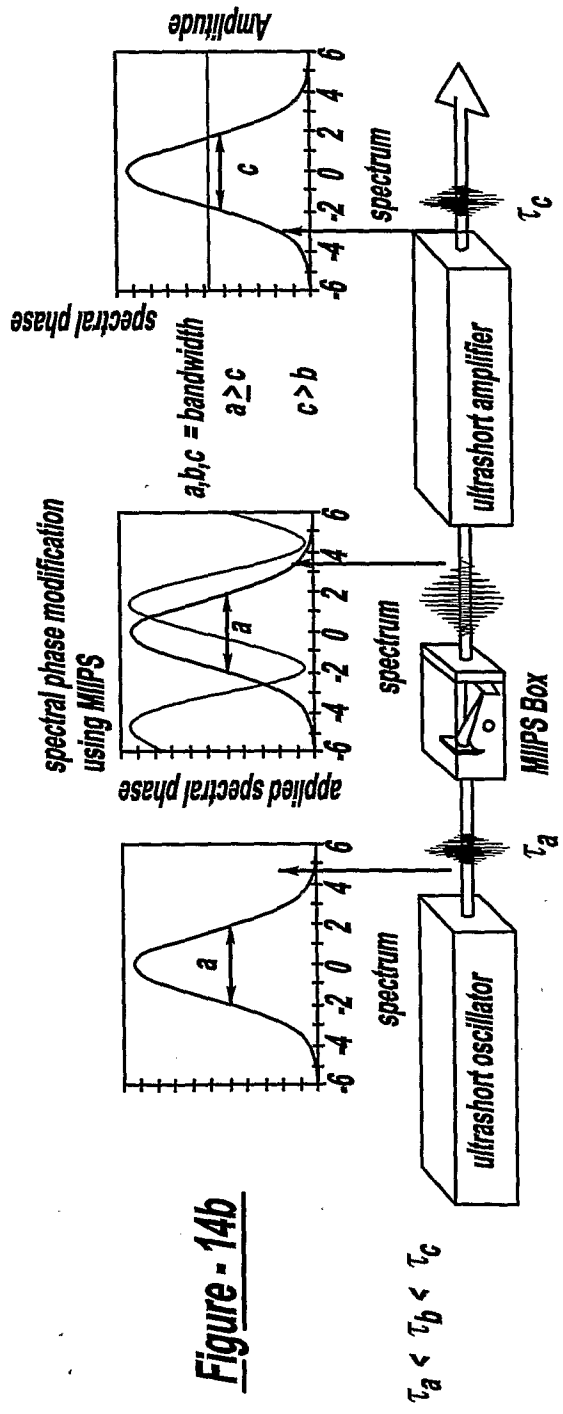
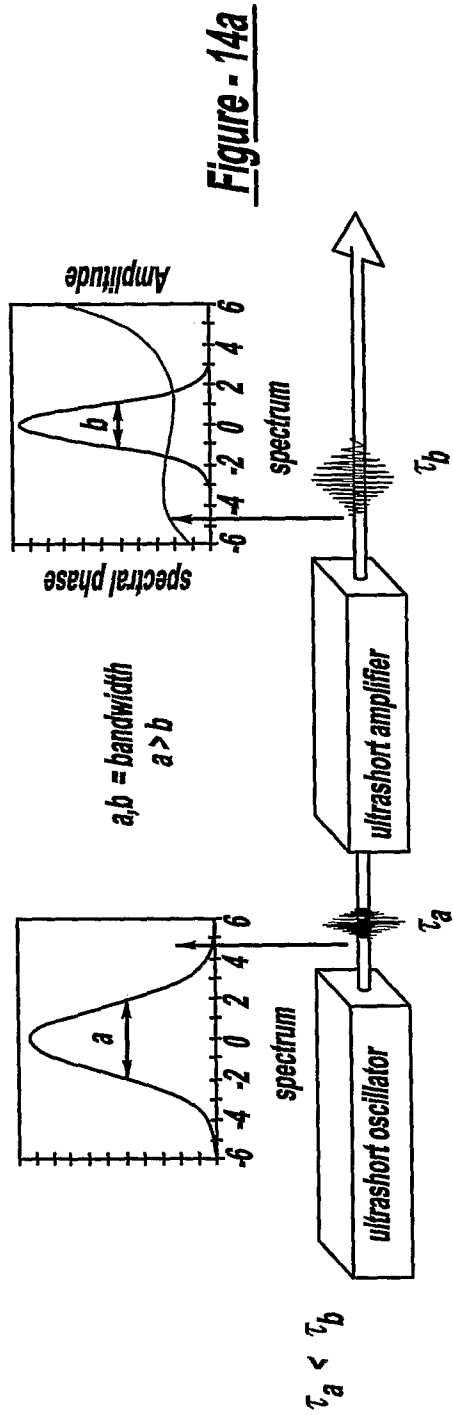


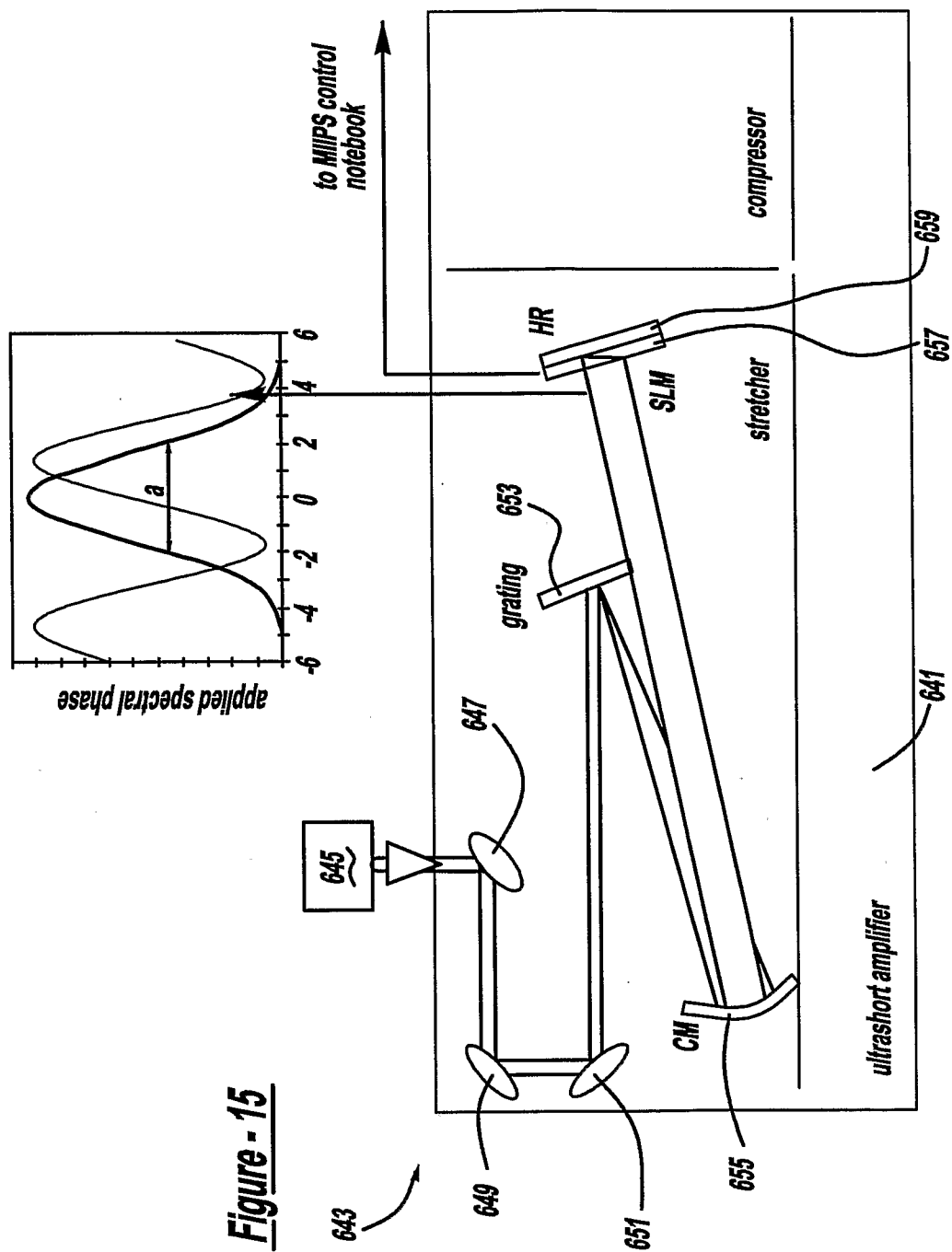
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Figure - 12aFigure - 12bFigure - 12c

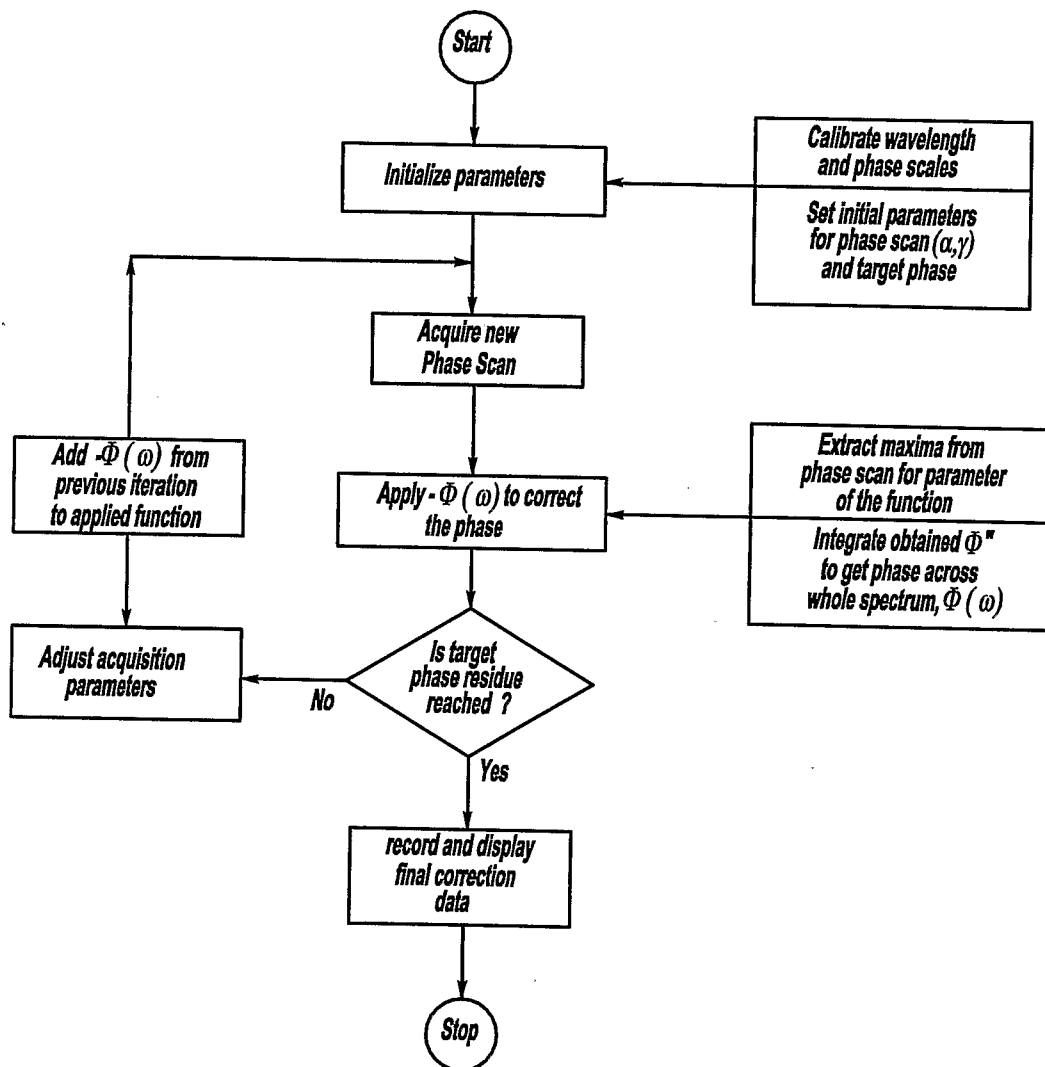




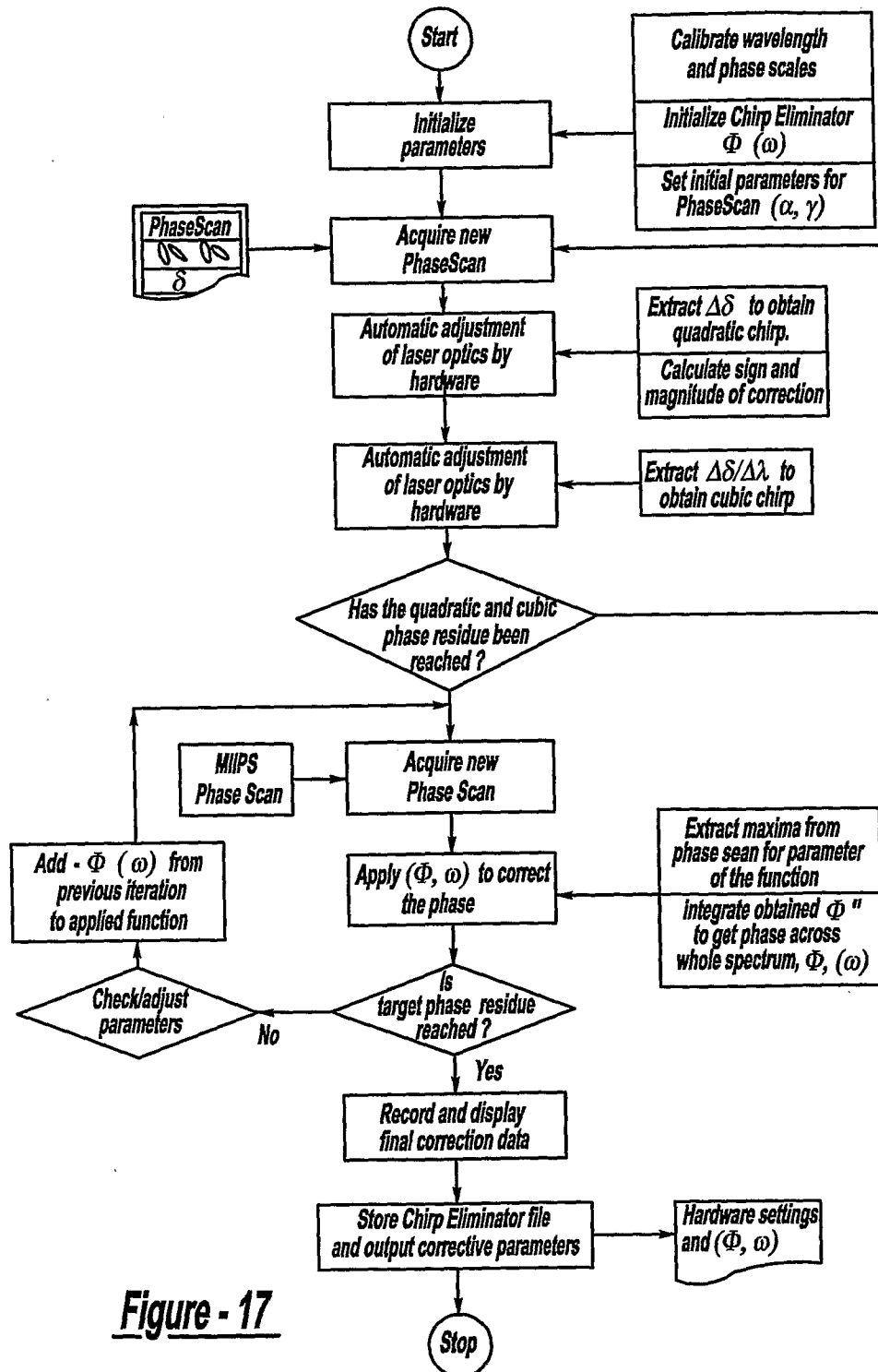


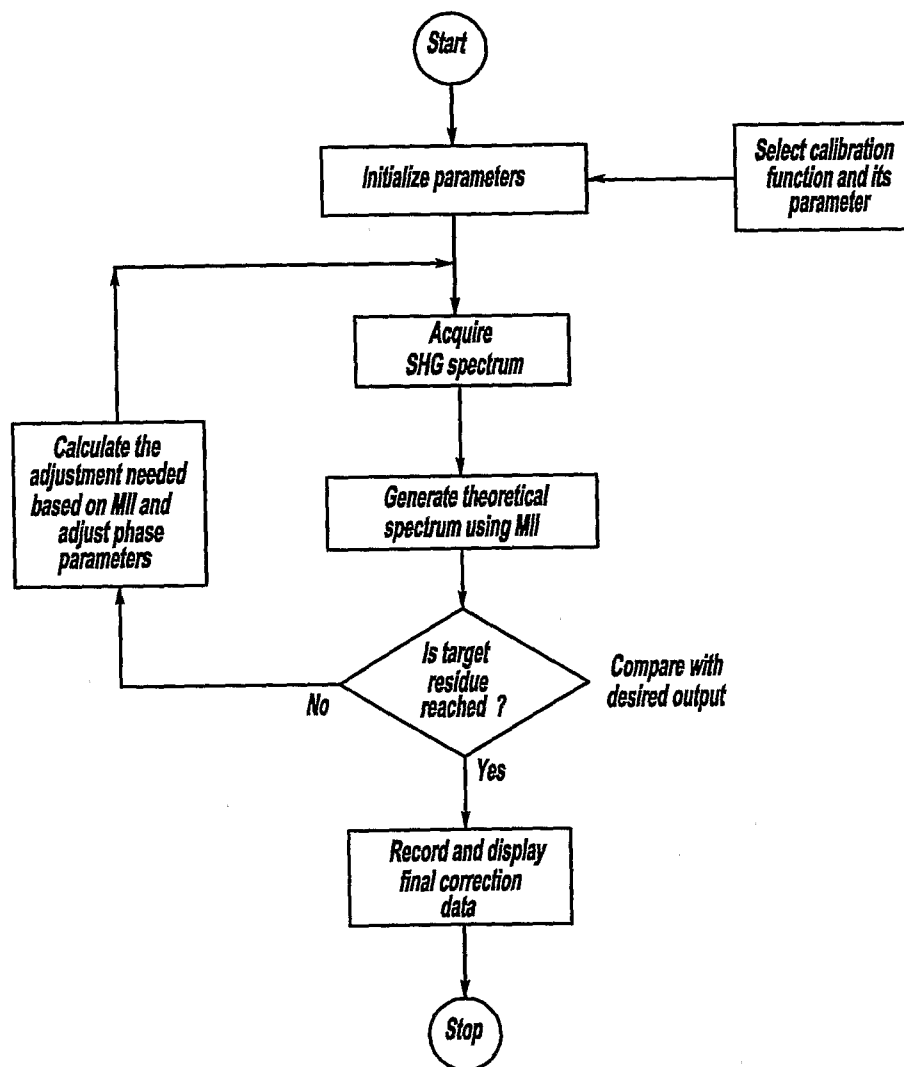
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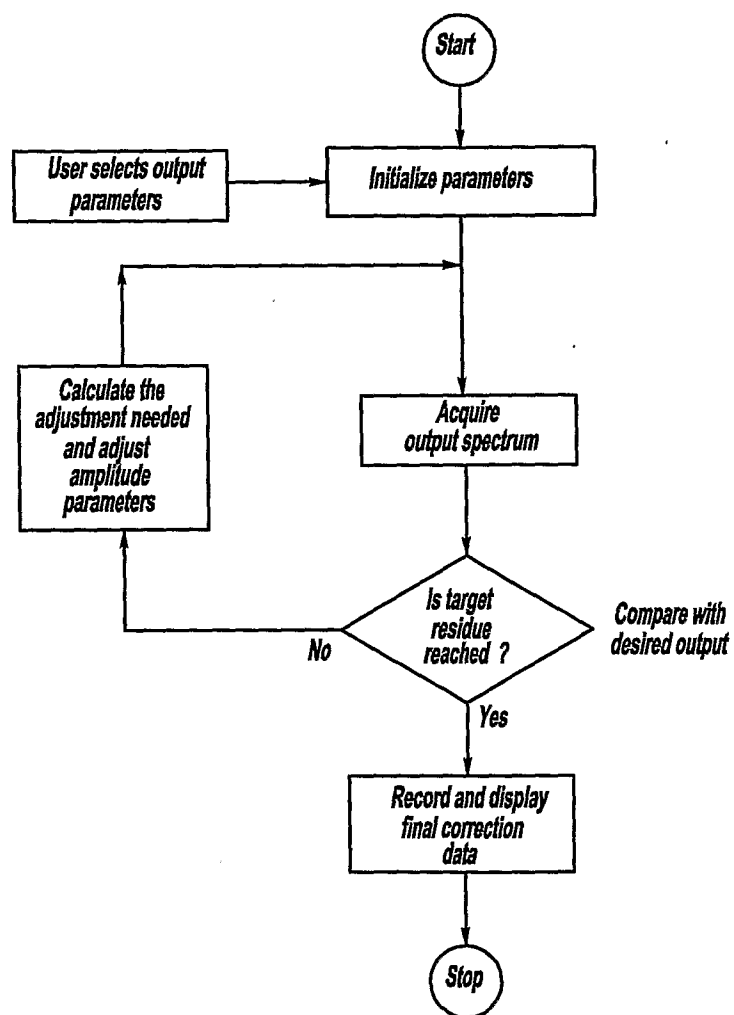
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**Figure - 16**

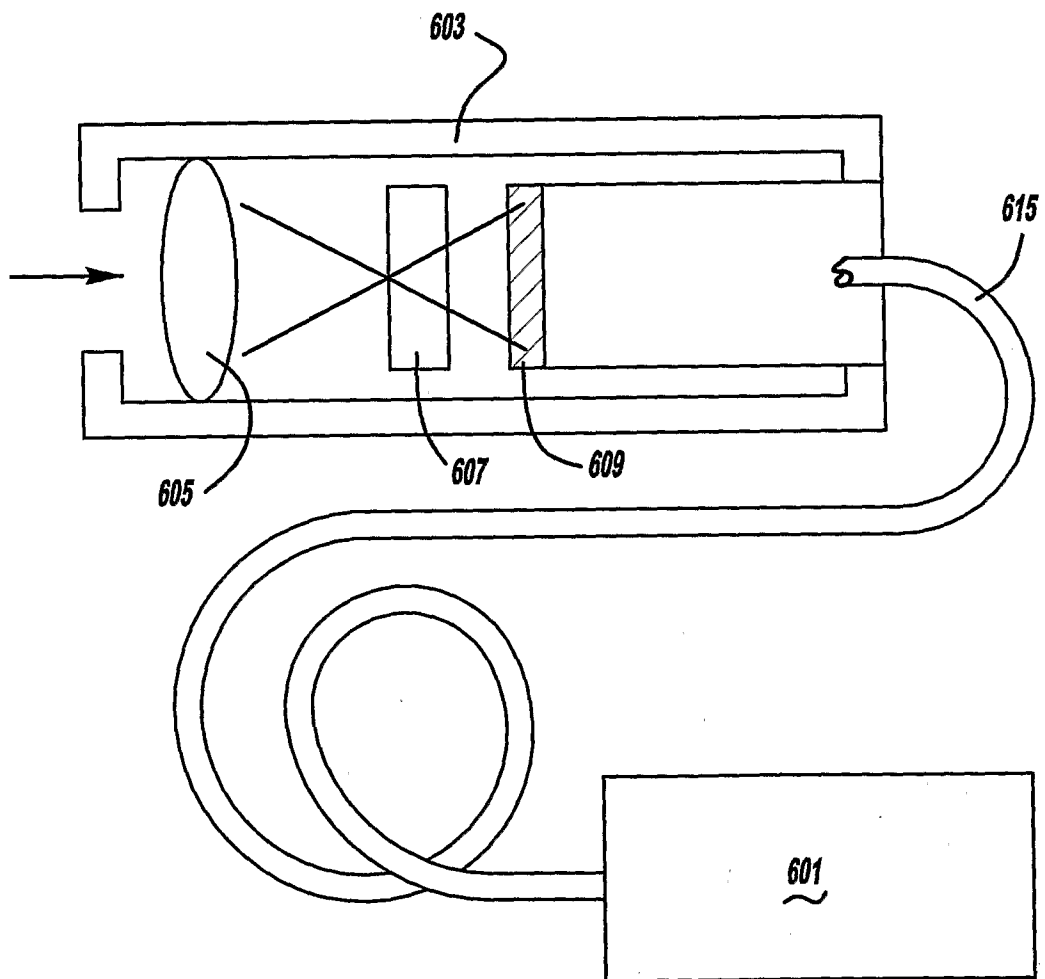
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**Figure - 17**

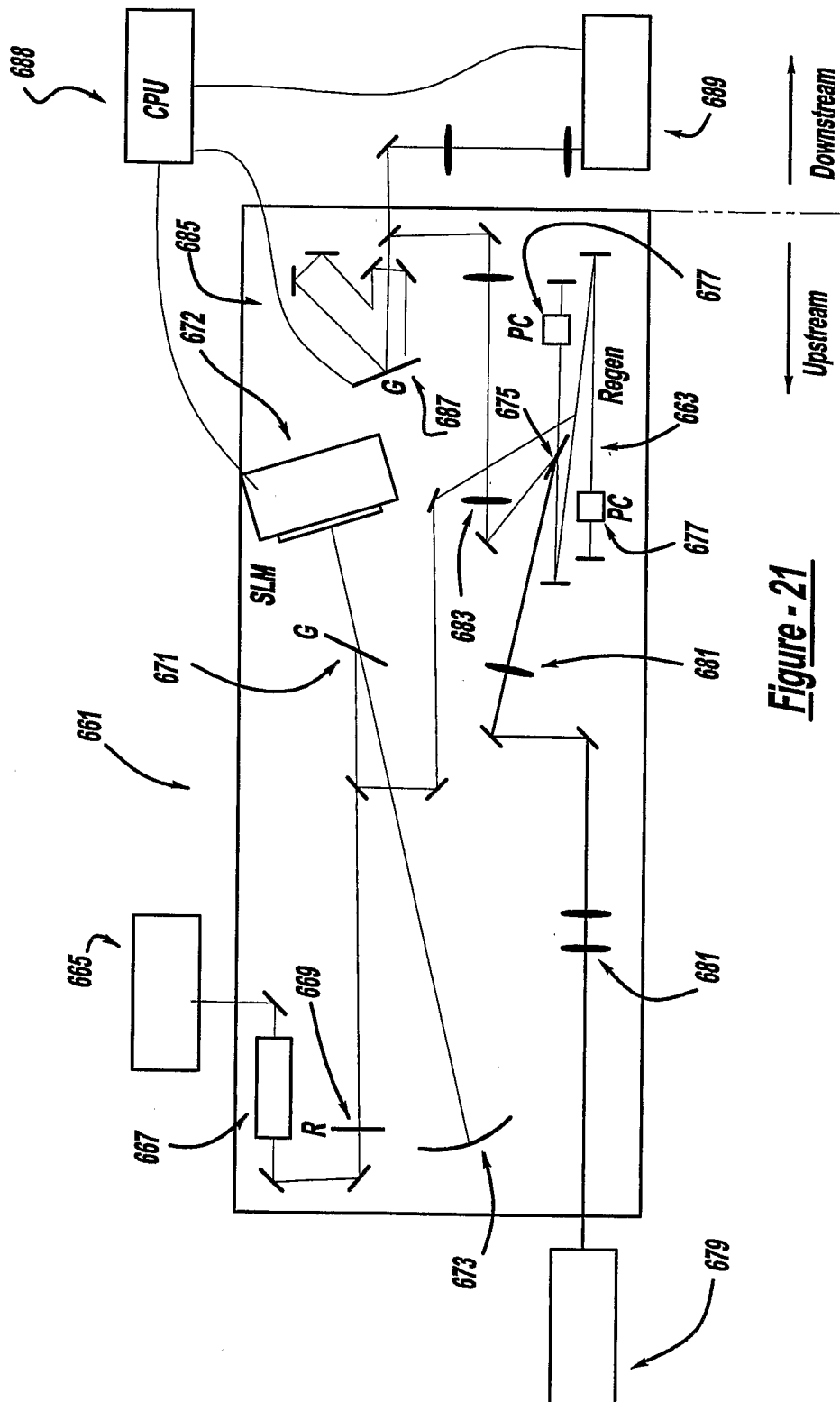
**Figure - 18**



**Figure - 19**



**Figure - 20**



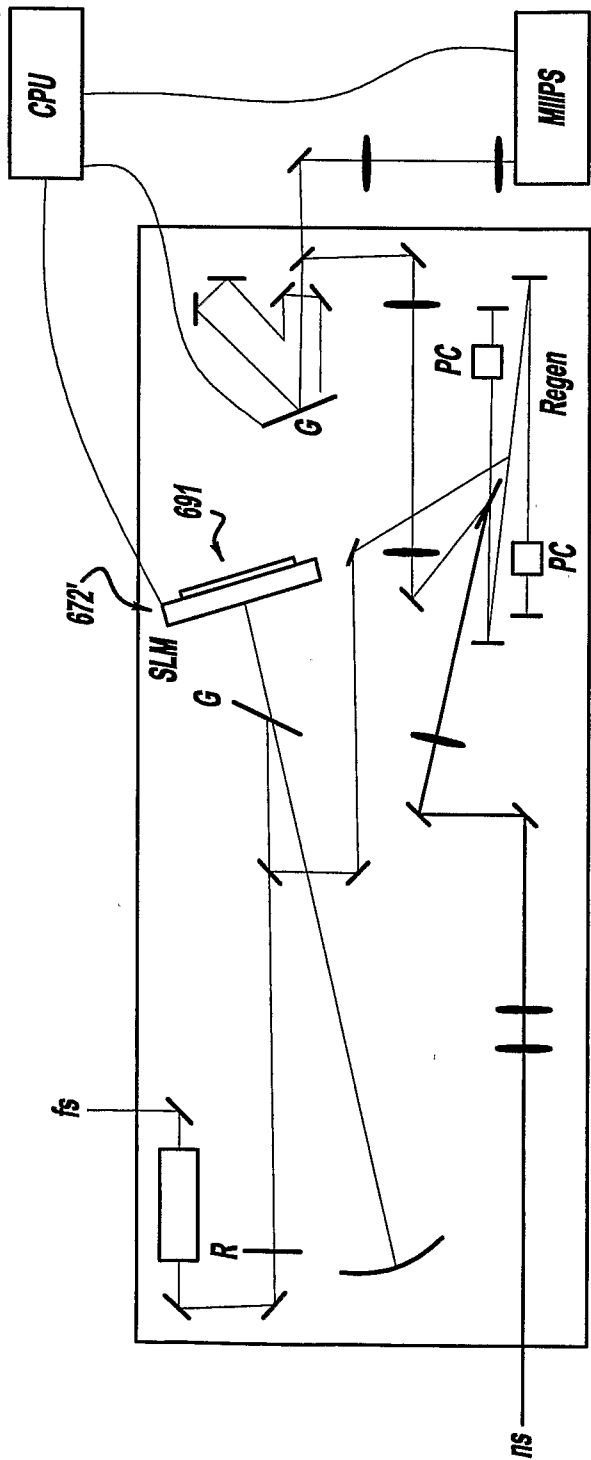


Figure - 22

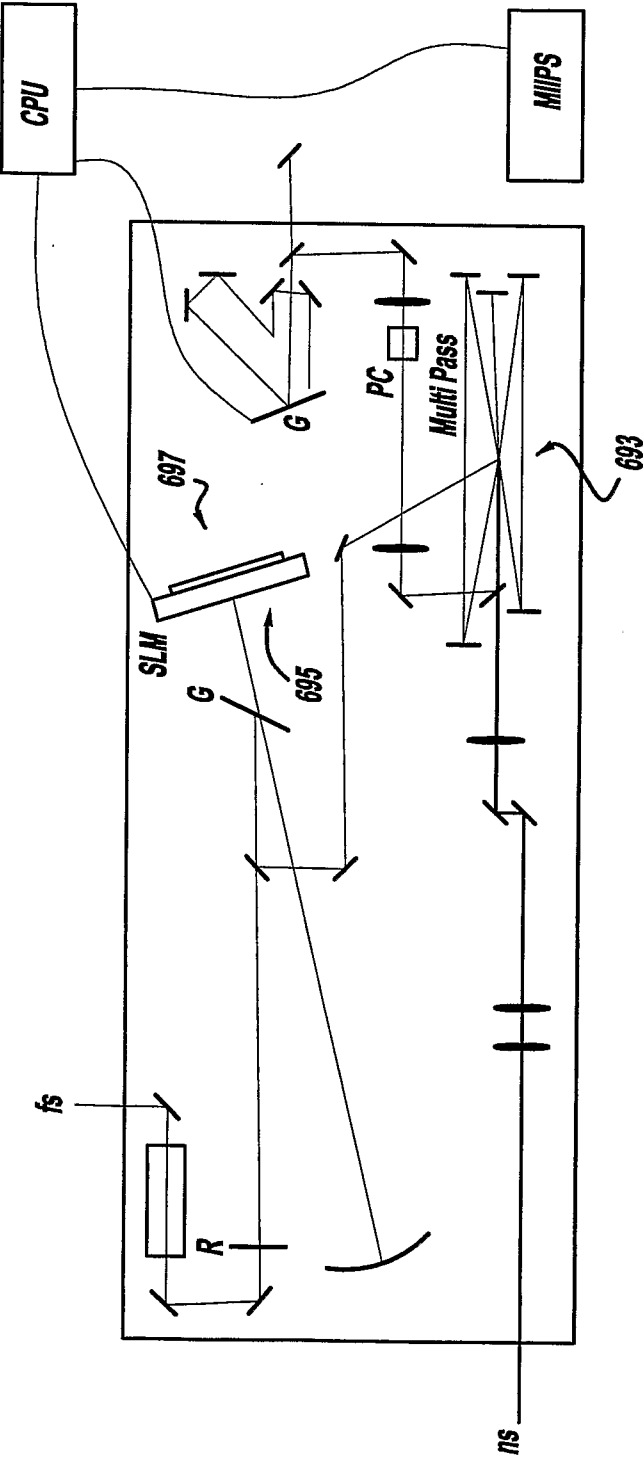
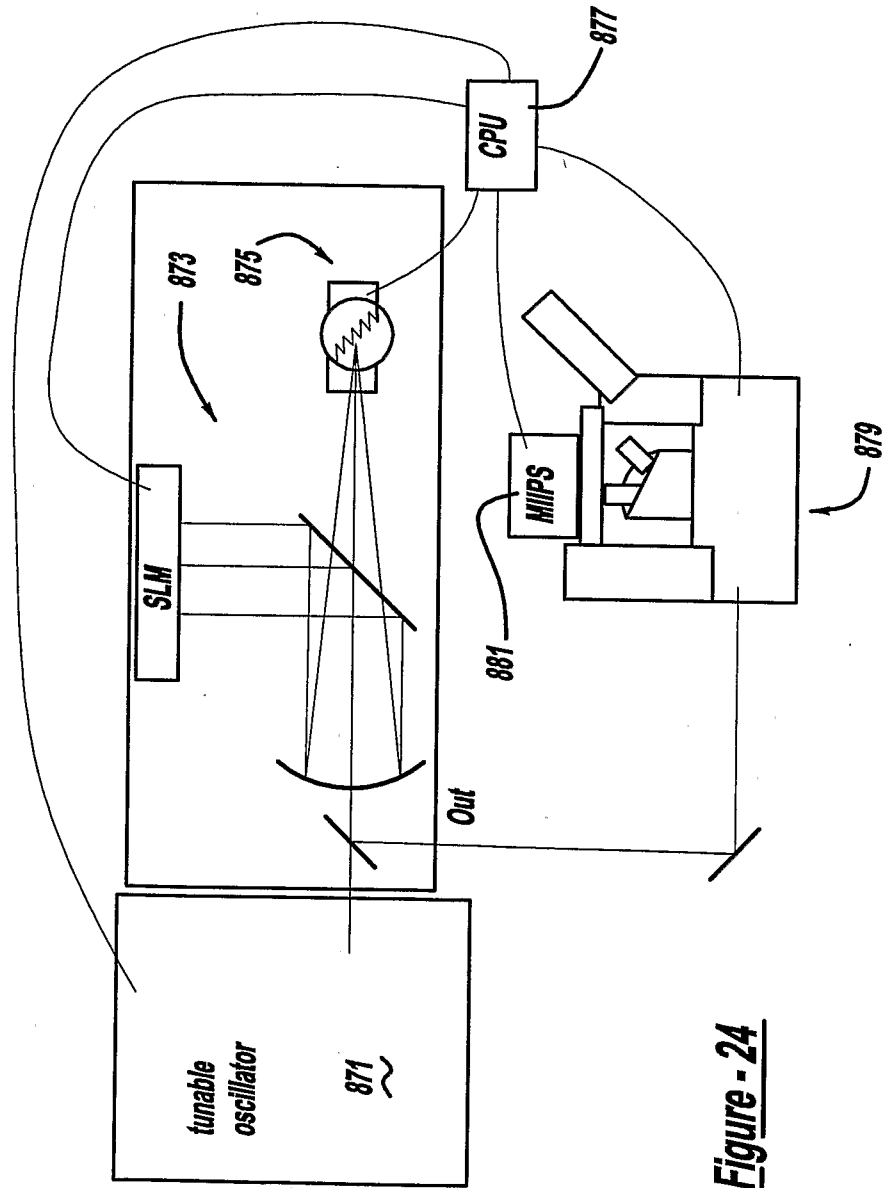
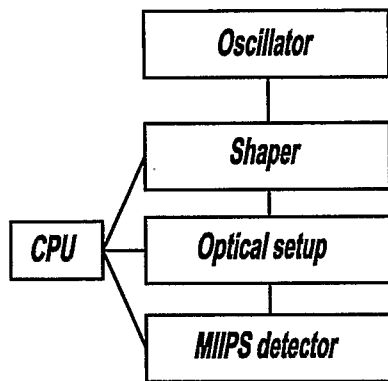


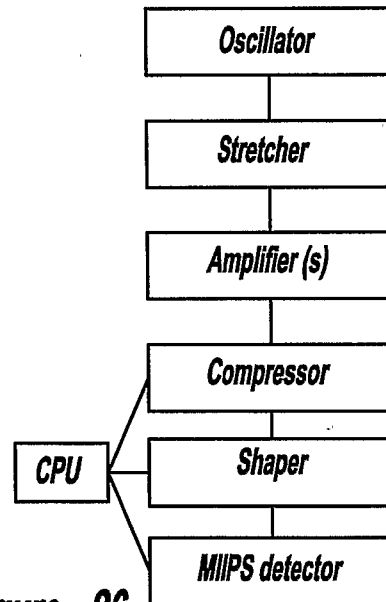
Figure - 23



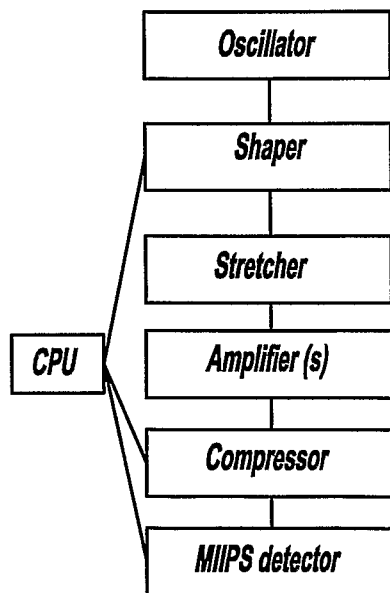
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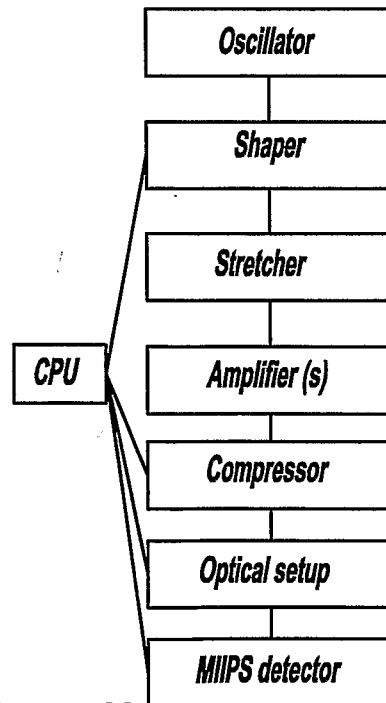
**Figure - 25**



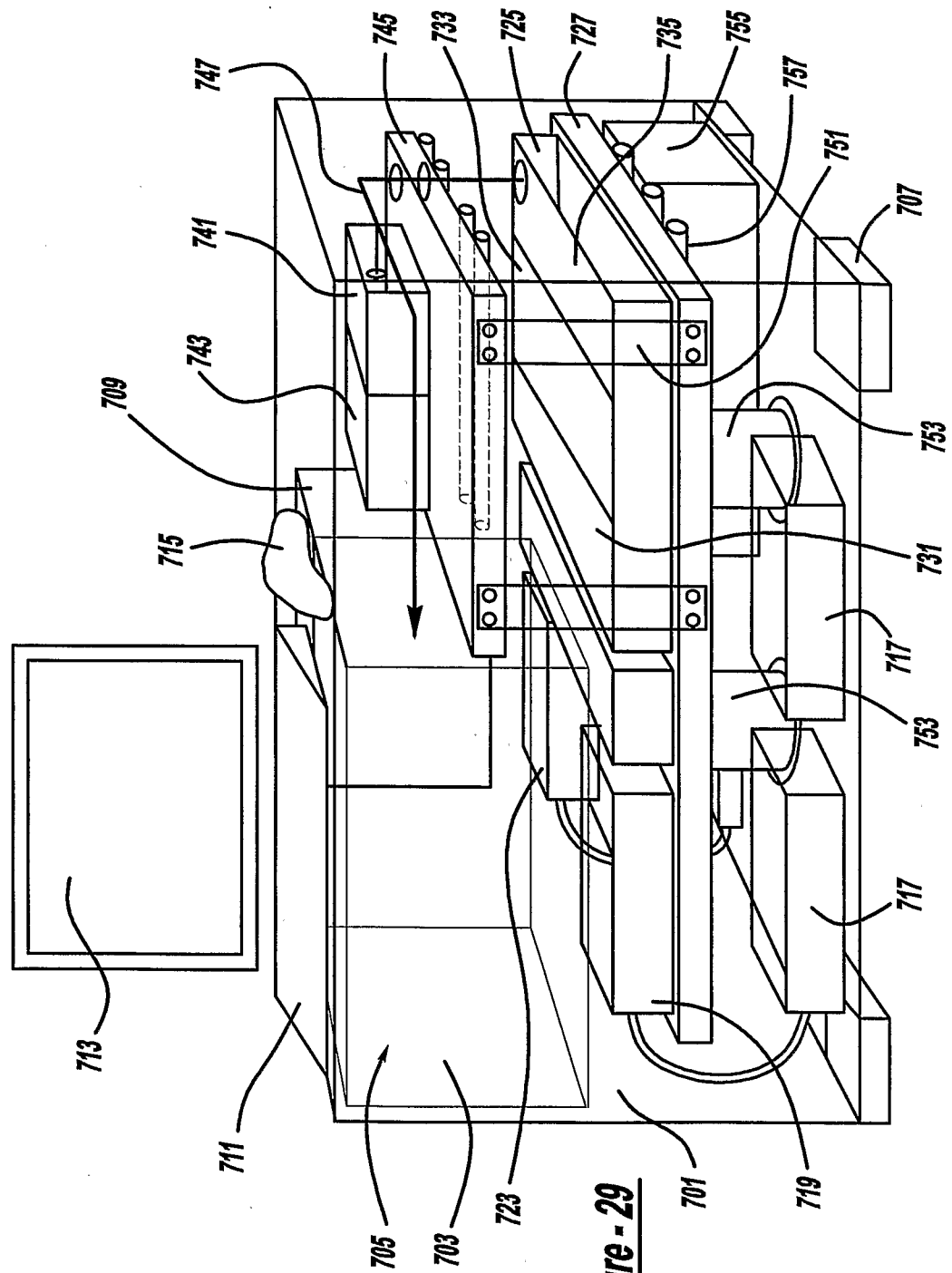
**Figure - 26**



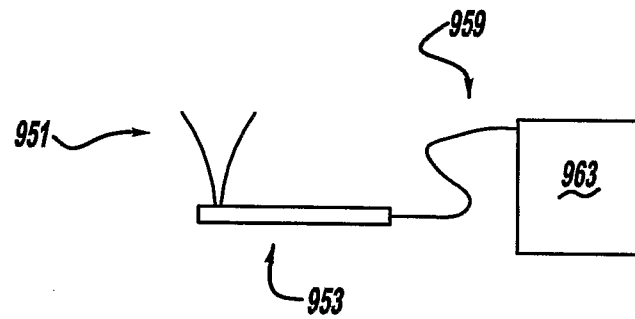
**Figure - 27**



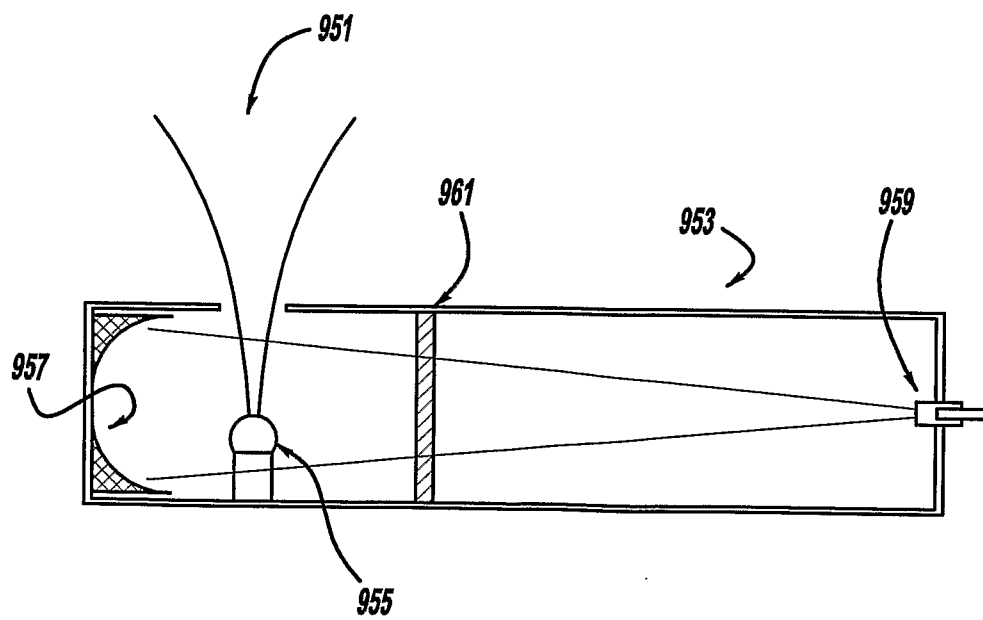
**Figure - 28**



**Figure - 29**



**Figure - 30**



**Figure - 31**