

(51) International Patent Classification:
G01J 11/00 (2006.01) **G04F 13/02** (2006.01)Ltd., at The Weizmann Institute of Science, P.O. Box 95,
76100 Rehovot (IL).(21) International Application Number:
PCT/IL2011/000567(74) Agents: **PEARL COHEN ZEDEK LATZER** et al.;
Shenkar 5, PO Box 12704, 46733 Herzlia (IL).(22) International Filing Date:
18 July 2011 (18.07.2011)(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP,
KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD,
ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI,
NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD,
SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR,
TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/365,619 19 July 2010 (19.07.2010) US(71) Applicant (for all designated States except US): **YEDA
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Nirit** [IL/IL]; c/o Yeda Research and Development Co.(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG,
ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: LINEAR OPTICAL CHARACTERIZATION OF ULTRASHORT OPTICAL PULSES

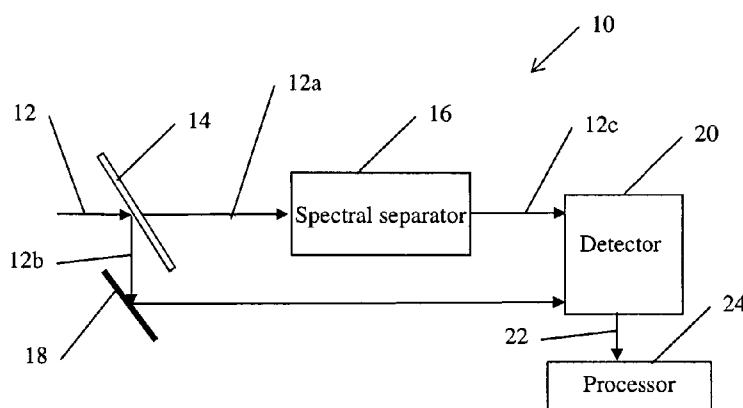


Fig. 1

(57) Abstract: A device (10) for characterization of an optical beam of at least one pulse includes a beam splitter (14) for splitting the optical beam (12) into at least a first beam (12a) and a second beam (12b), and a spectral separator (16) for spectrally separating at least one monochromatic wavelength component of the first beam. The device includes a photosensitive detector (20) for detecting the second beam and one of the monochromatic wavelength components (12c) of the first beam. The device further includes a processor (24) for determining a difference between the time of detection of the pulse of the second beam and the time of detection of the corresponding pulse of the monochromatic wavelength component of the first beam.

LINEAR OPTICAL CHARACTERIZATION OF ULTRASHORT OPTICAL PULSES

FIELD OF THE INVENTION

[0001] The present invention relates to optical pulses. More particularly, the present application relates to linear optical characterization of ultrashort optical pulses.

BACKGROUND OF THE INVENTION

[0002] Complete characterization of an optical pulse implies knowledge of its time profile, or, equivalently, its spectrum and the spectral phase. Although performance of detection electronics is progressing rapidly, a direct measurement of a sub-picosecond time profile has not yet been realized. For example, time resolution of electronic measurement devices has reached resolutions of several picoseconds. However, the duration of an ultrashort optical pulse may be only a few femtoseconds in the optical range and even shorter in the X-ray spectral range. Therefore, various indirect measurement techniques have been proposed for characterization of such ultrashort optical pulses.

[0003] For example, the pulse may be characterized by determining its Fourier components. For example, a pulse may be characterized as a series of functions of the form $E(\omega) = A(\omega)e^{i\varphi(\omega)}$, where $A(\omega)$ represents the amplitude of the component $E(\omega)$ with frequency ω , and $\varphi(\omega)$ represents the phase of the component. The amplitudes $A(\omega)$ of the components may be obtained using standard spectrometric techniques. For example, one or more pulses may be directed through a monochromator and the intensity of the output signal measured at each wavelength. However, limitations of electronic measurement devices may not enable direct determination of the phases $\varphi(\omega)$ of the components. Therefore, various techniques have been proposed to determine phases.

[0004] For example, the spectral phase of an ultrashort optical pulse can be reconstructed from analysis of interference of the pulse with a coherent synchronized reference pulse having an equivalent bandwidth. Often, however, such a reference pulse is not available.

[0005] In the absence of a reference pulse, the shape of an ultrashort optical pulse may be characterized using a self-referencing technique. For example, self-referenced characterization of an ultrashort pulse may be performed by analyzing the interaction of

the pulse with a replica of the pulse in a nonlinear optical medium. For example, nonlinear optical characterization techniques such as frequency-resolved optical gating (FROG) and spectral phase interferometry for direct electric-field reconstruction (SPIDER) have become standard tools ultrashort pulse analysis. Pulse analysis using techniques based on optical nonlinearity, however, may not be adequate in all situations. For example, the nonlinear optical medium may not create the required output signal when the input signals are weak. In addition, suitable nonlinear media may not be available for all wavelength ranges of interest (e.g. in the ultraviolet spectral range). Moreover, efficiency of the technique may not be sufficient when the bandwidth of the pulse is large. For example, accommodating a wide spectral bandwidth may entail reducing the dimensions of the nonlinear optical medium, further reducing the sensitivity of the technique to weak pulses.

[0006] Due to such difficulties, spectral phase retrieval methods have been proposed that employ linear optics only. For example, techniques have been described that utilize spectral shearing or time resolving interferometry to observe interference between adjacent spectral slices of the pulse. On the basis of the relative phase between the slices extracted from such measurements, the derivative of the spectral phase with respect to frequency may be calculated. When a spectral slice is sufficiently narrow such that the phase within it can be approximated by a linear function, the spectral phase derivative may also be measured directly as the time of arrival of the relevant spectral slice. For example, an optical system may split a beam of pulses such that part of the radiation passes directly to a detector, such as a photodiode, while another part passes through a monochromator on the way to a detector, such as a photodiode. The electronics connected to the detector may give the length of the time interval between detection of the direct and monochromator pulses. The measurement may be repeated with the monochromator set to transmit different wavelengths. The measured time differences at different wavelengths may yield a measurement of the derivative of the phase of the components of the pulse with respect to wavelength. The phase derivative may then be integrated to yield the phase as a function of wavelength. However, various factors, such as differences between the detectors, may prevent such a technique from being sufficiently accurate to characterize weak pulses.

[0007] It is an object of the present invention to provide a device and method for linear optical characterization of ultrashort optical pulses.

[0008] Other aims and advantages of the present invention will become apparent after reading the present invention and reviewing the accompanying drawings.

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SUMMARY OF THE INVENTION

[0009] There is thus provided, in accordance with some embodiments of the present invention, a device for characterization of an optical beam of at least one pulse. The device includes: a beam splitter for splitting the optical beam into at least a first beam and a second beam; a spectral separator for spectrally separating at least one monochromatic wavelength component of the first beam; a photosensitive detector for detecting the second beam and one of the monochromatic wavelength components of the first beam; and a processor for determining a difference between a time of detection of a pulse of the second beam and a time of detection of a corresponding pulse of the monochromatic wavelength components of the first beam.

[0010] Furthermore, in accordance with some embodiments of the present invention, the spectral separator includes a monochromator, and the monochromatic wavelength component includes a single monochromatic wavelength component.

[0011] Furthermore, in accordance with some embodiments of the present invention, the monochromator is adjustable so as to select a characteristic wavelength of the single monochromatic wavelength component.

[0012] Furthermore, in accordance with some embodiments of the present invention, the monochromator has a dispersionless configuration.

[0013] Furthermore, in accordance with some embodiments of the present invention, the monochromator has a 4f configuration.

[0014] Furthermore, in accordance with some embodiments of the present invention, the monochromatic wavelength component includes a plurality of spatially separated monochromatic wavelength components.

[0015] Furthermore, in accordance with some embodiments of the present invention, the photosensitive detector is a component detector of a detector array such that a plurality of component detectors of the detector array are configured to measure separate wavelength

components of the plurality of spatially separated monochromatic wavelength components.

[0016] Furthermore, in accordance with some embodiments of the present invention, the photosensitive detector includes a single-photon detector.

5 [0017] Furthermore, in accordance with some embodiments of the present invention, the single-photon detector includes a single photon avalanche photodiode.

[0018] Furthermore, in accordance with some embodiments of the present invention, the processor includes time-correlated single-photon counting (TCSPC) electronics.

10 [0019] Furthermore, in accordance with some embodiments of the present invention, the device includes a trigger detector for triggering a measurement by the TCSPC electronics.

[0020] Furthermore, in accordance with some embodiments of the present invention, the device includes a second beam splitter for splitting off a portion of the second beam for directing toward the trigger detector.

15 [0021] There is further provided, in accordance with some embodiments of the present invention, a method for characterization of a pulsed optical beam. The method includes: splitting the optical beam into at least a first beam and a second beam; spectrally separating a first monochromatic wavelength component of the first beam; detecting on a single photosensitive detector the second beam and the first monochromatic wavelength
20 component of the first beam; determining a difference between a time of detection of a pulse of the second beam and a time of detection of a corresponding pulse of the first monochromatic wavelength component of the first beam; spectrally separating a second monochromatic wavelength component of the first beam; detecting on a single photosensitive detector the second beam and the second monochromatic wavelength
25 component of the first beam; determining a difference between a time of detection of a pulse of the second beam and a time of detection of a corresponding pulse of the second monochromatic wavelength component of the first beam; determining a phase characterization of the pulsed optical beam from the time differences.

30 [0022] Furthermore, in accordance with some embodiments of the present invention, determining a phase characterization includes calculating a derivative of the time difference with respect to wavelength and as a function of wavelength.

[0023] Furthermore, in accordance with some embodiments of the present invention, the method includes spectrally separating the first monochromatic wavelength component and spectrally separating the second monochromatic wavelength sequentially.

5 [0024] Furthermore, in accordance with some embodiments of the present invention, the method includes spectrally separating the first monochromatic wavelength component and spectrally separating the second monochromatic wavelength concurrently.

[0025] Furthermore, in accordance with some embodiments of the present invention, the method includes repeating a plurality times detection of the second beam and the first monochromatic wavelength component of the first beam or detection of the second beam
10 and the second monochromatic wavelength component of the first beam.

[0026] Furthermore, in accordance with some embodiments of the present invention, the time of detection of a pulse of the second beam, the time of detection of a corresponding pulse of the first monochromatic wavelength component of the first beam, or the time of detection of a corresponding pulse of the second monochromatic wavelength component
15 of the first beam includes a calculated result of analysis of the repeated detections.

[0027] Furthermore, in accordance with some embodiments of the present invention, the calculated result includes a calculated centroid of a histogram of the times of detection of the repeated detections.

[0028] Furthermore, in accordance with some embodiments of the present invention, the
20 method includes splitting off from the second beam a trigger beam, and detecting the trigger beam with a trigger detector.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] In order to better understand the present invention, and appreciate its practical
25 applications, the following Figures are provided and referenced hereafter. It should be noted that the Figures are given as examples only and in no way limit the scope of the invention. Like components are denoted by like reference numerals.

[0030] Fig. 1 schematically shows a pulse characterization system suitable for
30 characterization of ultrashort pulses, in accordance with embodiments of the present invention.

[0031] Fig. 2 schematically shows a pulse characterization system suitable for characterization of weak ultrashort pulses, in accordance with some embodiments of the present invention.

[0032] Fig. 3 illustrates measurement of a time delay by the system shown in Fig. 2.

5 [0033] Fig. 4 shows results of measurement by the system shown in Fig. 2.

[0034] Fig. 5 schematically shows a pulse characterization system with a detectors array, in accordance with some embodiments of the present invention.

[0035] Fig. 6 shows flowchart of a method for characterization of a pulsed beam, in accordance with embodiments of the present invention.

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DETAILED DESCRIPTION OF EMBODIMENTS

[0036] In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be understood by those of ordinary skill in the art that the invention may be practiced without these specific details. In other instances, well-known methods, procedures, components, modules, units and/or circuits have not been described in detail so as not to obscure the invention.

20 [0037] Ultrashort optical pulse characterization in accordance with embodiments of the present invention uses linear optics to determine the phases of various wavelength components of the pulses. In a pulse characterization system, in accordance with embodiments of the present invention, a beam of optical pulses is divided by a beam splitter into at least two beams. A first beam is directed to a spectral separator, such as a
25 grating, that separates the beam into its various wavelength components. Each wavelength component may be characterized by an amplitude and phase. For example, each wavelength component may include a particular band of wavelengths. According to embodiments of the present invention, one monochromatic wavelength component, which includes a narrow band of wavelengths about a characteristic wavelength, is
30 directed toward a detector. Monochromatic should be understood as referring to a band of wavelengths that is characterized by a characteristic wavelength, the band being much

narrower than the spectral bandwidth of the entire beam spectrum. A second beam is also directed toward the detector.

[0038] Typically, corresponding pulses of the two beams arrive at the detector at different times. Thus, each of the pulses is typically detected at a different time.

5 Typically, due to the relatively slow response time of the detector electronics, the width of the detected pulse is much larger than the width of the actual pulse. A time of detection may therefore be assigned to a particular point of the detected pulse. For example, a time of detection may be assigned to the peak or centroid of the detected pulse. The pulse characterization system measures the time interval between the two
10 detection times. Measuring such a time interval may reduce the effects of systematic or slowly varying instrumental drift or measurement errors.

[0039] Time interval measurements may be made for different wavelength components of the pulse. By application of known numerical techniques, the time interval measurements at different wavelengths may be analyzed to yield a calculation of the
15 derivative of the time interval with respect to wavelength and as a function of wavelength. The derivative of the time interval with respect to wavelength is typically equivalent to the second derivative of the phase of a corresponding wavelength component of the pulsed beam with respect to wavelength. Through application of known numerical techniques, the derivatives at the various wavelengths may be integrated
20 to yield the phase of the wavelength components of the pulse as a function of wavelength.

[0040] Fig. 1 schematically shows a pulse characterization system suitable for characterization of ultrashort pulses, in accordance with embodiments of the present invention. An incident pulsed beam 12 may be directed to enter pulse characterization
25 system 10. Beam splitter 14 divides incident pulsed beam 12 into measurement pulsed beam 12a and reference pulsed beam 12b. Measurement pulsed beam 12a is directed into a spectral separation device 16. Spectral separation device 16 separates measurement pulsed beam 12a into one or more spectral component pulsed beams 12c. For example, spectral separation device 16 may include a monochromator that allows a single spectral
30 component pulsed beam 12c to emerge. For example, the monochromator may include one or more spectral separation components such as diffraction gratings, prisms, or filters for separating the measurement pulsed beam into spectral components on the basis of

wavelength. The monochromator may also include one or more selection elements, such as slits or collimators, for selecting a single spectral component to emerge. Typically, the relative positions or orientations of a spectral separation component and the selection elements are variable so as to enable selection of different spectral components at different times. For example, a monochromator may include a pulse shaper configuration. The emerging spectral component pulsed beam 12c is directed toward a detector 20.

[0041] Alternatively to a monochromator, a spectral separation device may separate measurement pulsed beam 12a into several emergent spectral component pulsed beams.

For example, the spectral separation device may include a component such as a grating or prism for directing separate spectral components of measurement pulsed beam 12a into different directions. In this case, several of the emergent spectral component beams may each be directed toward separate detectors, or toward separate detecting components of a detector array.

[0042] Reference pulsed beam 12b may be similarly directed toward detector 20. For example, pulse characterization system 10 may include beam directing optical components, represented by mirror 18, for directing reference pulsed beam 12b toward detector 20. In some embodiments of the present invention, the optical components may include an attenuator for attenuating reference pulsed beam 12b. In some embodiments of the present invention that include multiple detectors or a detector array, the optical components may include a beam expander for widening reference pulsed beam 12b. Thus, detector 20 may generate a detector output signal 22 when a pulse of reference pulsed beam 12b or of spectral component pulsed beam 12c impinges on a detecting surface of detector 20. For example, detector 20 may include a photodiode or photodiode array. Detector 20 may be selected to have a high sensitivity to weak signals. For example, detector 20 may be selected to be a single photon avalanche photodiode.

[0043] A detector output signal 22 generated by detector 20 may be transmitted to processor 24. For example, processor 24 may include an appropriate electronic circuit for determining the time delay between detection of the first optical pulse and detection of the second optical pulse. For example, processor 24 may include time correlated single photon counting (TCSPC) electronics to enable determination of the time delay in detection of weak pulses. Processor 24 may include further electronic circuitry, or a

programmable processor, to enable further processing. For example, processor 24 may include circuitry or programming to enable derivation of the phase of one or more spectral components of a pulse of incident pulsed beam 12.

[0044] Embodiments of a system for determining characteristics of a pulsed beam may include additional components, or may be configured for a particular type of beam. Fig. 2 schematically shows a pulse characterization system suitable for characterization of weak ultrashort pulses, in accordance with some embodiments of the present invention. An incident pulsed beam 12 may originate from a pulsed beam source 26. Incident pulsed beam 12 is divided by first beam splitter 14a into two beams. Measurement pulsed beam 12a is directed into monochromator 30. For example, monochromator 30 may include one or more spectral separation components, represented schematically by diffraction gratings 34, and one or more optical focusing components, represented schematically by concave mirrors 36. For example, monochromator 30 may have a dispersionless configuration, such as a 4f pulse shaper configuration. In a 4f configuration, each spectral separation component, such as a diffraction grating 34, is separated from a focusing component, such as a concave mirror 36, by a single focal length of the focusing component. Such a configuration may ensure that all spectral components travel approximately equal distances within monochromator 30, thus minimizing dispersion.

[0045] Alternatively to a dispersionless configuration, a monochromator 30 may introduce a known wavelength dependent dispersion, time delay, or phase shift. Analysis of measured results may then include a dispersion compensation calculation.

[0046] When measurement pulsed beam 12a enters monochromator 30, it is separated by a diffraction grating 34 (or other spectral separation component such as a prism) into spectral component beams 12a'. Each spectral component beam 12a' is characterized by a wavelength, and is angularly separated from other spectral component beams 12a'. Monochromator 30 may include at least one spectral selection component, such as moveable slit 32. For example, one or more optical components, such as concave mirrors 36, may cause at least some of spectral component beams 12a' to propagate parallel to one another (at the Fourier plane). For example, spectral component beams 12a' may be spatially separated from one another and approximately normal to the surface of moveable slit 32. Thus, moveable slit 32 may enable one spectral component beam 12a' to pass, while blocking all others. Moving moveable slit 32 to a different position may

enable a different spectral component beam 12a" to pass. For example, a motor for automatically moving moveable slit 32 may be controllable by a controller associated with processor 24. Alternatively, movement of moveable slit 32 may be controlled by an operator, either manually or via an electronic controller. For example, moveable slit 32 may be moved between measurements of a series of measurements.

[0047] Spectral component beam 12a" may emerge from monochromator 30, for example, after optically interacting with one or more additional components of monochromator 30, as spectral component pulsed beam 30c. Spectral component pulsed beam 30c, after emerging from monochromator 30, may impinge upon, or may be directed by optical components to impinge upon, single photon avalanche photodiode (APD) 28. For example, single photon APD 28 may be sensitive enough to detect a single photon of a pulse.

[0048] The second beam emerging from first beam splitter 14a is directed toward second beam splitter 14b. Second beam splitter 14b divides the incident beam into reference pulsed beam 12b and trigger pulsed beam 12d. Reference pulsed beam 12b is also directed toward single photon APD 28. Typically, a pulse of spectral component pulsed beam 12c and the corresponding pulse of reference pulsed beam 12b arrive at single photon APD 28 at different times. For example, in the example shown in Fig. 2, a pulse 13a of incident pulsed beam 12 enters pulse characterization system 10. The pulse impinges on single photon APD 28 as spectral component pulse 13c of spectral component pulsed beam 12c and as reference pulse 13b of reference pulsed beam 12b. In the example shown, reference pulse impinges on, and is detected by, single photon APD 28 ahead of spectral component pulse 13c. Output signals generated by single photon APD 28 are sent to TCSPC module 40 associated with processor 24. For example, TCSPC module 40 may be capable of measuring times of detection of reference pulse 13b and of spectral component pulse 13c at single photon APD 28. Typically, the order of detection is unimportant, i.e. the signal pulse can arrive either prior to or after the reference pulse.

[0049] Typically, it may be advantageous if both reference pulse 13b and spectral component pulse 13c have similar intensities. Therefore, second beam splitter 14b may be configured to split an incoming beam such that reference pulsed beam 12b receives less energy than trigger pulsed beam 12d. Alternatively, reference pulsed beam 12b may

be caused to pass through an attenuator so as to reduce the intensity of reference pulsed beam 12b.

[0050] Typically, TCSPC module 40 begins timing operation in response to an incident trigger signal 42. For example, trigger pulsed beam 12d may be directed onto trigger diode 38. For example, when trigger pulse 13d of trigger pulsed beam 12d impinges on trigger diode 38, trigger diode 38 (or an electronic circuit associated with trigger diode 38) generates trigger signal 42. Typically, the optical length of the path traversed by trigger pulsed beam 12d is smaller than the optical lengths of the optical paths traversed by the other beams. Alternatively, a trigger signal may be taken from another trigger source, such as, for example, another detector in the system, or from an appropriate circuit associated with pulsed beam source 26.

[0051] Further processing, either by processor 24 or by analysis external to processor 24 or pulse characterization system 10, may reduce the effects of random errors. For example, when incident pulsed beam 12 includes a train of approximately identical pulses 13a, measurements may be repeated on N pulses. Statistical analysis of the repeated measurements may then reduce the effects of random errors. Typically, repeating the measurement on N pulses increases the signal-to-noise ratio by a factor $\sqrt{N}$. For example, individual measurement results on the N pulses may be averaged. Alternatively, the measurement results may be arranged in the form of a histogram with respect to measured detection times. Typically, the histogram has two peaks related to the detection times of reference pulse 13b and spectral component pulse 13c. The time delay may be calculated from the time interval between the centroids of the two peaks.

[0052] Fig. 3 illustrates measurement of a time delay by the system shown in Fig. 2. Histogram peak centroid 22b at time t_1 corresponds to detection of reference pulses 13b by single photon APD 28. Histogram peak centroid 22c at time t_2 corresponds to detection of spectral component pulse 13c by single photon APD 28. The time delay, Δt , is equal to the difference t_2 minus t_1 .

[0053] Further analysis may also include derivation of pulse characteristics, in particular the relative phase shifts of spectral components of the pulse. For example, measurements may be repeated with moveable slit 32 in different positions. Thus, the measurements may be repeated for various spectral components of incident pulsed beam 12.

[0054] Fig. 4 shows results of measurement by the system shown in Fig. 2. In this case, measurements were made using an idQuantique id100 single photon APD and a PicoHarp 300 TCSPC module. The full width half maximum (FWHM) instrument response was about 70 ps. The monochromator was a dispersion-free 4f grating pulse shaper with moveable slit in the Fourier plane. Results curve 44a shows measured results (time delay versus wavelength) for 85 fs transform-limited laser output pulses from a Ti:sapphire mode-locked oscillator. The beam was attenuated to about one photon per pulse (approximately 10Pw), leading to about 10^6 detector counts per second. As expected, the curve shows the expected constant time delay for all spectral components.

Results curve 44b shows measured results for the chirped pulses formed by passing the same beam through a 6" slab of F3 glass. The curve shows the expected linear change in time delay with wavelength. The resolution of the measurements was estimated to be about 9.6 fs. Curve 46 shows the intensity spectrum in arbitrary units.

[0055] Alternatively to a monochromator and a single detector, a pulse characterization system in accordance with some embodiments of the present invention may include an array of detectors. Fig. 5 schematically shows a pulse characterization system with a detector array, in accordance with some embodiments of the present invention. As in previously described embodiments, detector array pulse characterization system 10' includes a first beam splitter 14a. First beam splitter 14a divides incident pulsed beam 12 into measurement pulsed beam 12a and a second beam. Measurement pulsed beam 12a is then separated into spectral component beams 12a' by a spectral separation device, represented by diffraction grating 34 and concave mirror 36. For example, the spectral separation device may separate measurement pulsed beam 12a into parallel spectral component beams 12a'. Each beam of spectral component beams 12a' may be characterized by a wavelength, and may be laterally displaced from one another. Spectral component beams 12a' are directed toward detector array 29. Detector array 29 includes a plurality of component single photon APD detectors 28'. For example, at least some spectral component beams 12a' may each be directed toward a component single photon APD detector 28' of detector array 29.

[0056] The second beam created by first beam splitter 14a is directed toward second beam splitter 14b. Second beam splitter 14b creates reference pulsed beam 12b and trigger pulsed beam 12d. Reference pulsed beam 12b is directed toward detector array

29. For example, reference pulsed beam 12b may pass through beam expander 48 to form expanded reference beam 12b'. Expanded reference beam 12b' may be directed toward detector array 29. For example, expanded reference beam 12b' may cover at some of component single photon APD detectors 28' of detector array 29. Thus, at least some of component single photon APD detectors 28' may detect a pulse of a spectral component beam 12a' and a pulse of expanded reference beam 12b'. A generated detector output signal 22 from each component single photon APD detectors 28' may be input to multi-channel TCSPC module 40'. Multi-channel TCSPC module 40' may then output detection times of the pulses detected by each component single photon APD detector 28'. In this manner, several wavelength ranges may be analyzed concurrently.

[0057] Detector array 29 may cover all spectral component beams 12a' of interest. Alternatively, detector array 29 may be spatially shifted across spectral component beams 12a' so as to detect signals from previously unmeasured spectral component beams 12a'.

[0058] Fig. 6 shows flowchart of a method for characterization of a pulsed beam, in accordance with embodiments of the present invention. It should be understood that division of the method into discrete steps is for illustration purposes only, and that the method could be otherwise divided into steps with equivalent results. Also, the order given for the steps is for illustration purposes only, and the order of steps of the method, unless otherwise indicated, may be altered, or steps may be performed concurrently, with equivalent results. All such equivalent alternative divisions and rearrangements should be considered as within the scope of the present invention.

[0059] An incident pulsed beam is separated into a measurement beam and a reference beam (step 50), for example, by passing through a beam splitter. The measurement beam is then separated into separate spectral component beams (step 52), for example, by a spectral separation component. Each spectral component beam may be characterized by a wavelength. A pulse of a spectral component beam is incident on a detector. Typically at a different time, a corresponding pulse of the reference beam (e.g. both pulses resulting from separation of a single incident pulse) is incident on the same detector (step 54). The time of detection of each of the two pulses may be determined, typically with reference to a trigger event. In order to reduce the effect of random measurement errors, step 54 may be repeated and the separate results combined to form a result with improved signal-to-noise ratio. The difference between the times of arrival of the two pulses may then be

calculated (step 56). For example, a processor of a system implementing the method may include an electronic logic circuit for performing the calculation.

5 [0060] Typically, in order to obtain a characterization of the incident pulse, the measurement is performed for more than one spectral component beam. For example, the measured spectral component beam may be selected by a monochromator with adjustable output spectral range. Alternatively, a detector array with multiple component detectors may concurrently detect pulses of several spectral component beams. If measurements have not yet been made on all required spectral components (step 58), another spectral component beam, or set of spectral component beams, may be selected (step 60). For
10 example, a monochromator may be adjusted to change the characteristic wavelength of a spectral component beam output by the monochromator. Alternatively, the position of a detector array may be adjusted so as to measure a different set of spectral component beams. Steps 54-58 may then be repeated with the newly selected spectral component beams.

15 [0061] When measurements have been performed for all required spectral component beams, the results may be analyzed to yield a pulse characterization (step 62). For example, a derivative of the measured time interval with respect to wavelength or frequency may be numerically calculated. Alternatively, the time interval results may be fit to a function that describes an expected form of the result.

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CLAIMS

What we claim is:

1. A device for characterization of an optical beam of at least one pulse, the device
5 comprising:
a beam splitter for splitting the optical beam into at least a first beam and a second beam;
a spectral separator for spectrally separating at least one monochromatic wavelength
component of the first beam;
a photosensitive detector for detecting the second beam and one of said at least one
10 monochromatic wavelength component of the first beam; and
a processor for determining a difference between a time of detection of a pulse of the
second beam and a time of detection of a corresponding pulse of said one of said
at least one monochromatic wavelength component of the first beam.
- 15 2. A device as claimed in claim 1, wherein the spectral separator comprises a
monochromator, and said at least one monochromatic wavelength component comprises
a single monochromatic wavelength component.
3. A device as claimed in claim 2, wherein the monochromator is adjustable so as to
20 select a characteristic wavelength of said single monochromatic wavelength component.
4. A device as claimed in claim 2, wherein the monochromator has a dispersionless
configuration.
- 25 5. A device as claimed in claim 4, wherein the monochromator has a 4f
configuration.
6. A device as claimed in claim 1, wherein said at least one monochromatic
wavelength component comprises a plurality of spatially separated monochromatic
30 wavelength components.
7. A device as claimed in claim 6, wherein the photosensitive detector is a
component detector of a detector array such that a plurality of component detectors of the

detector array are configured to measure separate wavelength components said plurality of spatially separated monochromatic wavelength components.

8. A device as claimed in claim 1, wherein the photosensitive detector comprises a
5 single-photon detector.

9. A device as claimed in claim 8, wherein the single photon detector comprises a single-photon avalanche photodiode.

10. A device as claimed in claim 1, wherein the processor comprises time-correlated
10 single-photon counting (TCSPC) electronics.

11. A device as claimed in claim 10, comprising a trigger detector for triggering a measurement by the TCSPC electronics.

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12. A device as claimed in claim 11, comprising a second beam splitter for splitting off a portion of the second beam for directing toward the trigger detector.

13. A method for characterization of a pulsed optical beam, the method comprising:
20 splitting the optical beam into at least a first beam and a second beam;
spectrally separating a first monochromatic wavelength component of the first beam;
detecting on a single photosensitive detector the second beam and the first
monochromatic wavelength component of the first beam;
determining a difference between a time of detection of a pulse of the second beam and a
25 time of detection of a corresponding pulse of the first monochromatic wavelength
component of the first beam;
spectrally separating a second monochromatic wavelength component of the first beam;
detecting on a single photosensitive detector the second beam and the second
monochromatic wavelength component of the first beam;
30 determining a difference between a time of detection of a pulse of the second beam and a
time of detection of a corresponding pulse of the second monochromatic
wavelength component of the first beam;

determining a phase characterization of the pulsed optical beam from the time differences.

14. A method as claimed in claim 13, wherein determining a phase characterization
5 comprises calculating a derivative of the time difference with respect to wavelength and as a function of wavelength.

15. A method as claimed in claim 13, comprising spectrally separating the first
monochromatic wavelength component and spectrally separating the second
10 monochromatic wavelength sequentially.

16. A method as claimed in claim 13, comprising spectrally separating the first
monochromatic wavelength component and spectrally separating the second
monochromatic wavelength concurrently.

17. A method as claimed in claim 13 comprising repeating a plurality times detection
of the second beam and the first monochromatic wavelength component of the first beam
or detection of the second beam and the second monochromatic wavelength component
of the first beam.

18. A method as claimed in claim 17, wherein said time of detection of a pulse of the
second beam, said time of detection of a corresponding pulse of the first monochromatic
wavelength component of the first beam, or said time of detection of a corresponding
pulse of the second monochromatic wavelength component of the first beam comprises a
20 calculated result of analysis of the repeated detections.

19. A method as claimed in claim 18, wherein the calculated result comprises a
calculated centroid of a histogram of the times of detection of the repeated detections.

20. A method as claimed in claim 13, comprising splitting off from the second beam
a trigger beam, and detecting the trigger beam with a trigger detector.

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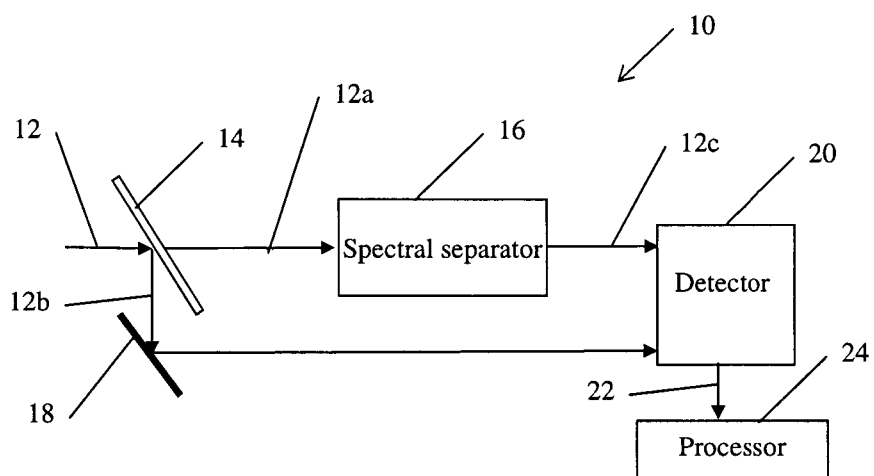


Fig. 1

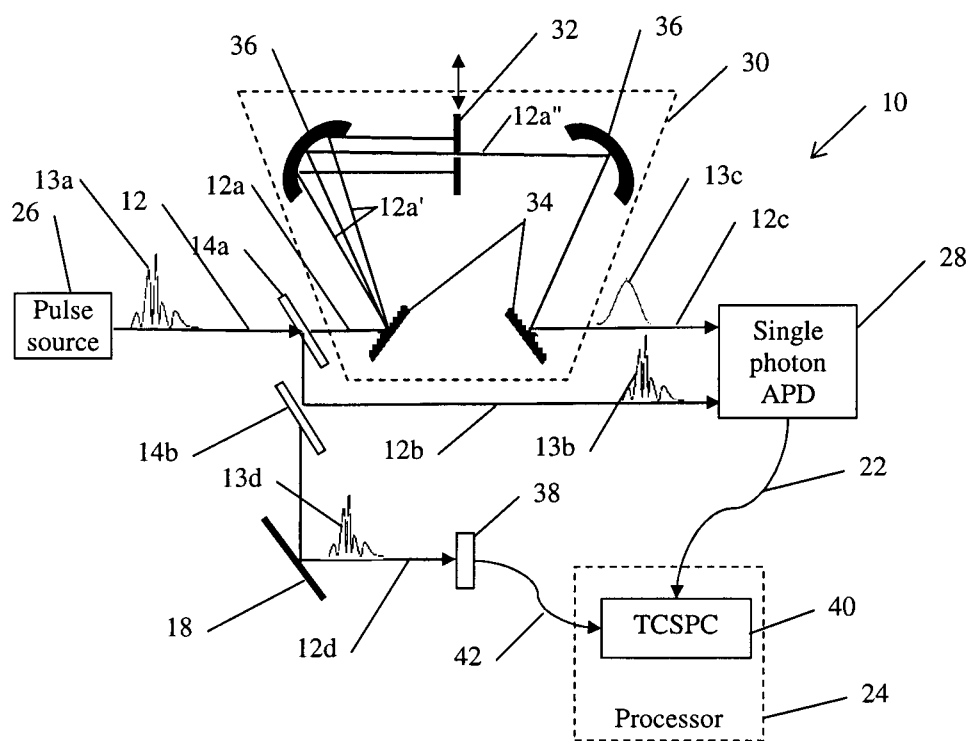


Fig. 2

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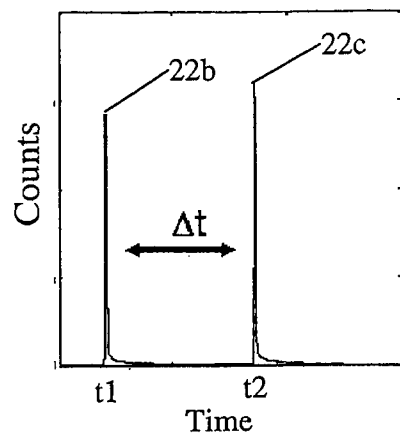


Fig. 3

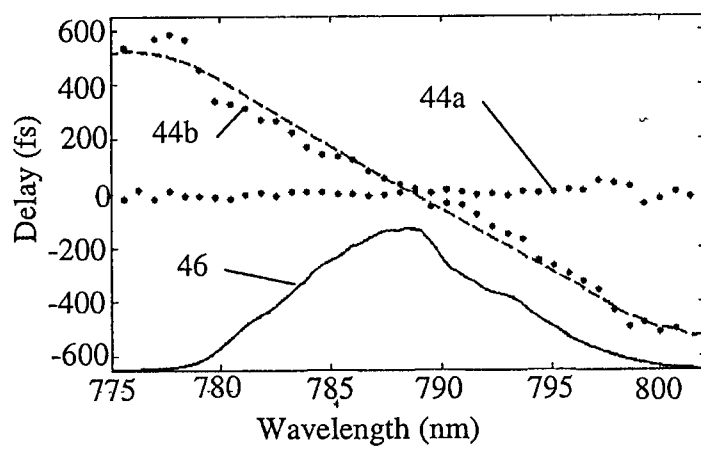


Fig. 4

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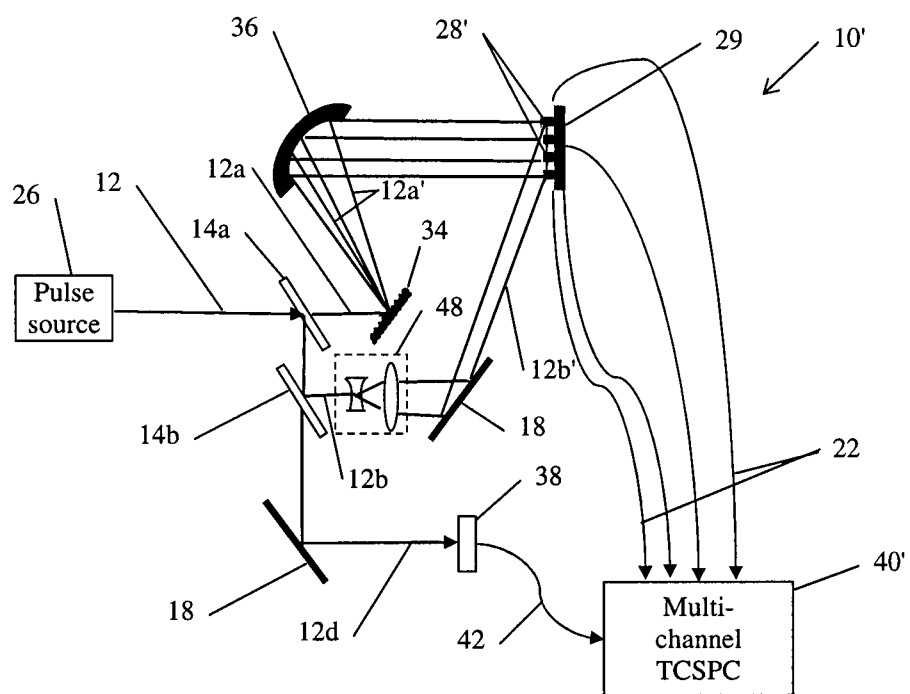


Fig. 5

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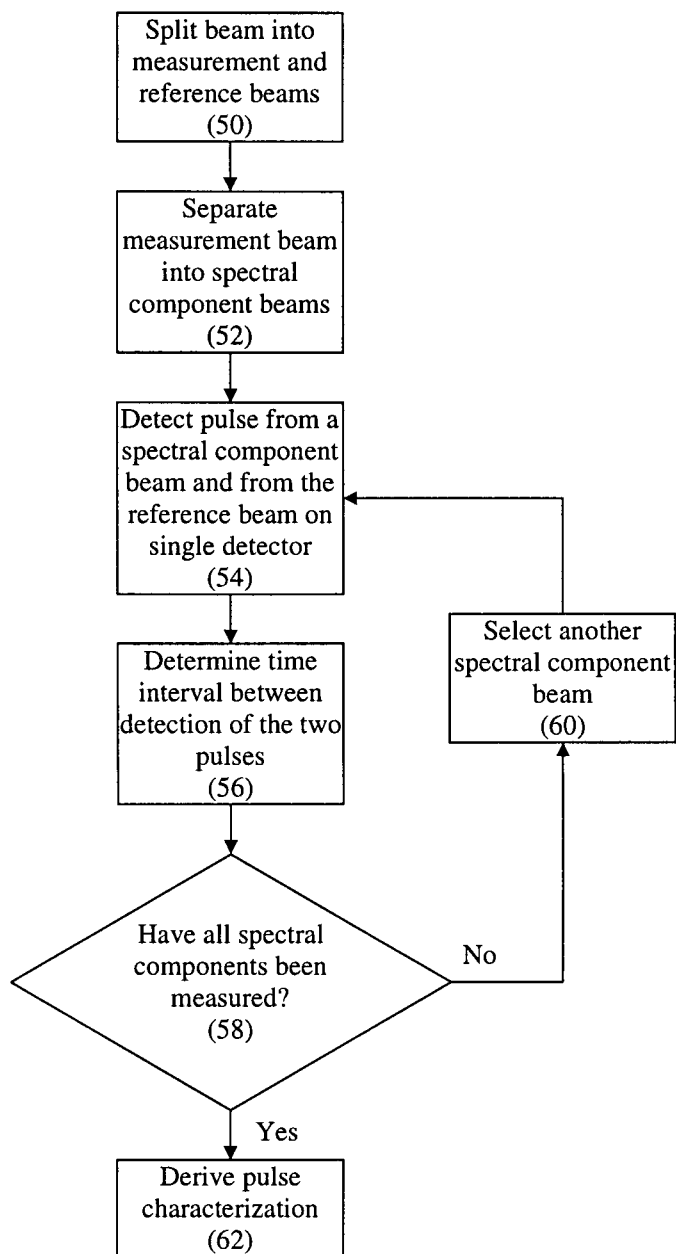


Fig. 6

INTERNATIONAL SEARCH REPORT

International application No

PCT/IL2011/000567

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01J11/00 G04F13/02
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01J G04F

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	O. SCHWARTZ, O. RAZ, O. KATZ, N. DUDOVICH, AND D. ORON: "Measuring Time Profiles of Ultraweak Ultrashort Pulses by Time Domain", INTERNATIONAL CONFERENCE ON ULTRAFast PHENOMENA, OSA TECHNICAL DIGEST (CD) (OPTICAL SOCIETY OF AMERICA, 2010), PAPER TUE25, 18 July 2010 (2010-07-18), XP002661847, the whole document ----- -/--	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not
considered to be of particular relevance

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or priority date and not in conflict with the application but
cited to understand the principle or theory underlying the
invention

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cannot be considered novel or cannot be considered to
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"Y" document of particular relevance; the claimed invention
cannot be considered to involve an inventive step when the
document is combined with one or more other such docu-
ments, such combination being obvious to a person skilled
in the art.

"&" document member of the same patent family

Date of the actual completion of the international search

21 October 2011

Date of mailing of the international search report

08/11/2011

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Rödig, Christoph

INTERNATIONAL SEARCH REPORT

International application No

PCT/IL2011/000567

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	TREBINO R ET AL: "MEASURING ULTRASHORT LASER PULSES IN THE TIME-FREQUENCY DOMAIN USING FREQUENCY-RESOLVED OPTICAL GATING", REVIEW OF SCIENTIFIC INSTRUMENTS, AIP, MELVILLE, NY, US, vol. 68, no. 9, 1 September 1997 (1997-09-01), pages 3277-3295, XP000723527, ISSN: 0034-6748, DOI: 10.1063/1.1148286 paragraph [VIII] -----	1-20