(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
30 March 2023 (30.03.2023)

WIPO | PCT

(10) **International Publication Number**
WO 2023/049758 A2

(51) **International Patent Classification:**
G01J 1/42 (2006.01)

(21) **International Application Number:**
PCT/US2022/076795

(22) **International Filing Date:**
21 September 2022 (21.09.2022)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
63/246,504 21 September 2021 (21.09.2021) US
63/247,453 23 September 2021 (23.09.2021) US

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(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, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

WO 2023/049758 A2

(54) **Title:** SYSTEMS AND METHODS FOR RECORDING OF TERAHERTZ WAVEFORMS

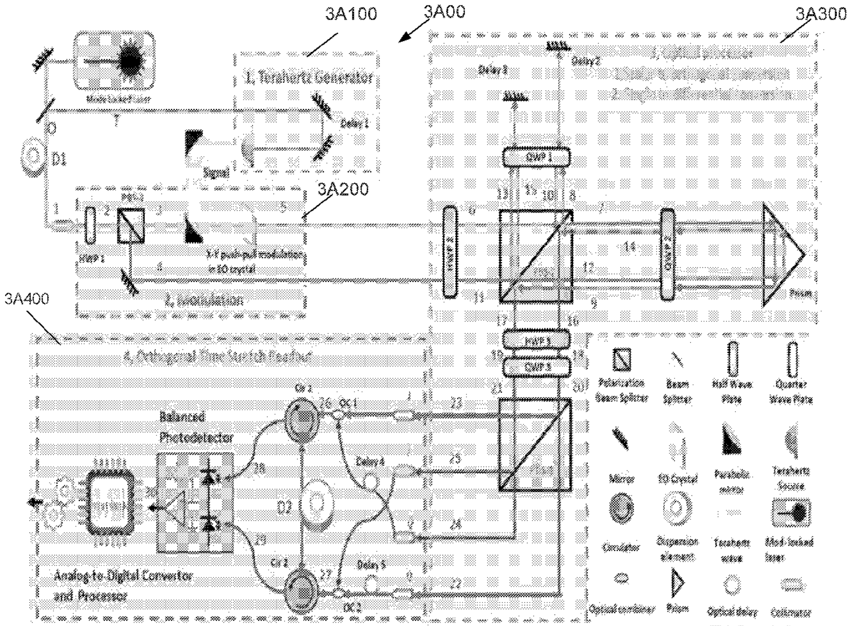


FIG. 3A

(57) **Abstract:** Systems and methods for single-shot detection and characterization of pulsed Terahertz waveforms in accordance with embodiments of the invention are described. A terahertz detection system can include orthogonal time stretch data acquisition to provide single¬ shot detection in a data acquisition backend. The system can include an orthogonal camera-based data acquisition back end to provide single-shot detection. Certain embodiments can map temporal information onto the spectrum of a broadband optical pulse via pulse chip modulation. Data acquisition can be performed in a back-end using single-shot orthogonal time stretch data acquisition processes. Phase diversity can be used to overcome frequency fading and provide broadband operation.

[Continued on next page]

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, 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, KM, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

SYSTEMS AND METHODS FOR RECORDING OF TERAHERTZ WAVEFORMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit of and priority under 35 U.S.C. 119(e) to U.S. Provisional Patent Application No. 63/246,504, entitled “Method for Recording of Terahertz Waveforms”, by Jalali et al., filed September 21, 2021, and to U.S. Provisional Patent Application No. 63/247,453, entitled “Systems and Methods for Recording of Terahertz Waveforms”, by Jalali et al., filed September 23, 2021, the disclosures of which are hereby incorporated by reference in their entirety for all purposes.

FIELD OF THE INVENTION

[0002] The present invention generally relates to systems and methods for recording of terahertz waveforms, in particular systems for detecting single-shot Terahertz waveforms and characterization of pulsed Terahertz waveforms.

BACKGROUND

[0003] Electromagnetic signals in the terahertz spectrum have many applications in sensing and communication. However, measuring terahertz signals can be difficult as bandwidth of a system can be a significant factor in the ability to measure these signals. Conventional techniques can use equivalent time sampling and can achieve sufficient effective bandwidth; however, there applications are limited.

SUMMARY OF THE INVENTION

[0004] Systems and methods for single-shot detection and characterization of pulsed Terahertz waveforms in accordance with embodiments of the invention are described. Terahertz detection systems in accordance with many embodiments can include orthogonal time stretch data acquisition back end to provide single-shot detection. Terahertz detection systems in accordance with several embodiments of the system can include an orthogonal camera-based data acquisition back end to provide single-shot detection.

[0005] An embodiment includes a system of characterizing terahertz signals that includes: a broadband optical pulse source that generates broadband pulses; an optical power splitter that receives broadband pulses from the broadband optical pulse source and produces a plurality of channels including optical O channel (channel O) and terahertz T channel (channel T); a dispersion element D1 that receives a same pulsed optical source from channel O and chirps an optical pulse and produces a signal 1; a device that receives an optical pulse from the channel T and generates a burst of terahertz radiation in response; and a delay stage that receives the same pulsed optical source from channel O and provides a delay to the chirped optical pulse so that the generated burst of terahertz radiation response and the chirped optical pulse overlap in time; a device under test (DUT) that receives the burst of terahertz radiation to produce a terahertz response signal that includes characteristics of the DUT; a half wave plate (HWP-1) with its fast axis rotated by 22.5 degrees compared to a horizontal component of light polarization that receives the chirped optical pulse from the dispersion element D1; an optical polarization beam splitter (PBS-2) that receives the chirped optical pulse from the HWP-1 and splits the chirped optical pulse into two orthogonal polarized signals, signal 3 and signal 4; a pair of parabolic mirrors that combines the burst of terahertz radiation with the optical pulse and the signal 3, and directs them into an electro-optic crystal (EO); an electro-optic (EO) crystal that modulates a light polarization in response to an electric field of the burst of terahertz radiation producing signal 5; a half wave plate (HWP-2) with a fast axis rotated by 22.5 degrees compared to a horizontal polarization that receives input signal 4 and signal 5 and produces output signals 6 and 11; a polarization beam splitter cube (PBS-2) with fast axis aligned to a horizontal polarization state of light that receives the signal 6 and produces orthogonal polarization signals 7 and 8; a quarter wave plate (QWP-1) with a fast axis rotated by 45 degrees compared to a horizontal polarization of light, that receives the signal 8 and generates an output that is reflected by a mirror and passes QWP-1 again producing signal 10; a quarter wave plate (QWP-2) with a fast axis rotated by 45 degrees compared to a horizontal polarization of light, that receives the signal 7 and generates an output that is reflected by a reflector, and passes QWP-2 again producing signal 9; wherein the HWP-2, PBS-2, QWP-2, QWP-2 and reflector perform functions on reference signal 4 and add the reference signal 4 with correct polarization to the output signals 17 and 18; a half wave plate (HWP-3) with its fast axis rotated by 22.5 degrees compared to a horizontal polarization of light that receives the signals 16 and 17 and outputs signals 18 and 19; a quarter wave plate (QWP-3) with its fast axis aligned to the horizontal polarization of light that receives the signals 18 and 19 and outputs signals 20 and 21; and a polarization beam splitter cubic (PBS-3) with its fast axis aligned to a horizontal polarization state of light that receives signals 20 and 21 and outputs two pairs of differential signals, signals 22 and 24, and 23 and 25, that are orthogonal in both polarization and temporal phase.

[0006] In a further embodiment, the system further includes: a pair of optical delay lines and couplers that combine signal 23 with 24, and signal 22 with 25, producing a differential in-phase signal 26, and a differential quadrature signal 27, where signals 26 and 27 are time interleaved; a pair of optical circulators and a second dispersion element (D2) that stretch the signals in time and direct them to output signals 28 and 29; a balanced photodetector with a differential amplifier that produces output 30 containing time interleaved in-phase and quadrature analog signals in the electrical domain; an analog-to-digital converter; a digital signal processor configured for processing a digitized signal using a maximum ratio combining process that eliminates a dispersion penalty; and a computer that analyzes the digital signal and provides a visualization of results.

[0007] In still a further embodiment, starting from signals 22-25, the four signals 22-25 are delayed and interleaved in time such that they can be captured using a single spectrometer, optical delay stages Delay4, Delay5 and beam combiners OC1 and OC2 combine signal 23 with 24, and signals 22 with 25, producing differential in-phase signal 26, and differential quadrature signal 27; an optical delay stage delay6 that interleaves signal 27 relative to signal 26; an optical combiner (OC3) that combines signal 26 and signal 27 together and produces time interleaved signal 28; an optical diffractive grating that maps wavelength into space and produces signal 29; a camera that records the diffracted optical beam and quantizes the signals into the digital domain and produces signal 30; a digital signal processor configured for processing the digitized signal using a maximum ratio combining process to eliminate dispersion penalty; and a computer that analyzes the digitized signal and provides a visualization of results.

[0008] In still a further embodiment, the pulsed optical source is configured with a supercontinuum source.

[0009] In still a further embodiment again, the dispersion element (2) includes a dispersive optical fiber that is selected from the group consisting of a fiber Bragg grating (FBG), a chromo-modal dispersion (CMD) device, a single-mode fiber (SMF), a dispersive compensating fiber (DCF), a Raman optical fiber with internal Raman amplification providing high dispersion combined with a net gain, and an arrayed wave-guide grating (AWG).

[0010] In still a further embodiment again, an analog-to-digital converter (ADC) is configured to convert an electrical equivalent of a stretched optical source and which operates at a lower frequency than an input signal being captured.

[0011] In yet a further embodiment, the system further includes programming executable on a processing device that performs high-speed time-domain analysis of terahertz signals.

[0012] In a further embodiment again, a machine learning process is trained and used to perform the signal processing.

[0013] In a further embodiment still, the system further includes programming executable on a processing device for performing high-speed spectroscopy of the terahertz signals.

[0014] In a further embodiment still, the system further includes programming executable on a processing device for performing high-speed inspection and quality testing of industrial materials.

[0015] In a further embodiment still, the system further includes programming executable on a processing device for performing high-speed quality inspection of pharmaceutical products.

[0016] In a further embodiment still, the system further includes programming executable on a processing device for performing high-speed inspection of packaged integrated circuits to spot counterfeit products.

[0017] In a further embodiment still, the system further includes programming executable on a processing device for performing high-speed imaging of biological tissues.

[0018] In a further embodiment still, the system further includes programming executable on a processing device for performing high-speed analysis of communication signals for terahertz burst-mode communications.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The description and claims will be more fully understood with reference to the following figures and data graphs, which are presented as exemplary embodiments of the invention and should not be construed as a complete recitation of the scope of the invention.

[0020] FIG. 1A illustrates a terahertz detection system with orthogonal time stretching in accordance with an embodiment of the invention.

[0021] FIG. 1B illustrates a terahertz detection system with orthogonal camera data acquisition in accordance with an embodiment of the invention.

[0022] FIG. 2 illustrates an architecture of an optical processor in accordance with an embodiment of the invention.

[0023] FIG. 3A illustrates an architecture of a terahertz detection system in accordance with an embodiment of the invention.

[0024] FIG. 3B illustrates an architecture of an orthogonal camera data acquisition backend of a terahertz detection system in accordance with an embodiment of the invention.

[0025] FIG. 4A illustrates metadata used in a simulation of a terahertz detection system in accordance with an embodiment of the invention.

[0026] FIGS. 4B-4C illustrate graphs of simulated results of a terahertz detection system with orthogonal time stretching in accordance with an embodiment of the invention.

[0027] FIG. 5A-5B illustrate graphs of simulated results of a terahertz detection system with orthogonal time stretching in accordance with an embodiment of the invention.

[0028] FIG. 6A-6B illustrate graphs of simulated results of a terahertz detection system with orthogonal camera readout in accordance with an embodiment of the invention.

[0029] FIG. 7A-7B illustrate graphs of simulated results of a terahertz detection system with orthogonal camera readout in accordance with an embodiment of the invention.

[0030] FIG. 8 illustrates graphs of the impact of analog-to-digital converter (ADC) quantization noise on an accuracy of a measured terahertz pulse in accordance with an embodiment of the invention.

[0031] FIG. 9 illustrates graphs of the impact of optical nonlinearity in the frequency domain in accordance with an embodiment of the invention.

[0032] FIG. 10 illustrates graphs of the impact of nonlinearity on the time domain reconstruction in accordance with an embodiment of the invention.

[0033] FIG. 11 illustrates a graph of the impact of laser bandwidth in accordance with an embodiment of the invention.

DETAILED DESCRIPTION OF THE DRAWINGS

[0034] Systems and methods for single-shot detection and characterization of pulsed Terahertz waveforms in accordance with embodiments of the invention are described. Terahertz detection systems in accordance with many embodiments can include orthogonal time stretch data acquisition back end to provide single-shot detection. Terahertz detection systems in accordance with several embodiments of the system can include an orthogonal camera-based data acquisition back end to provide single-shot detection. Certain embodiments can map temporal information onto the spectrum of a broadband optical pulse via pulse chip modulation. Readout can be performed in a back-end using single-shot orthogonal time stretch data acquisition processes. In certain embodiments, readout and/or data acquisition can be obtained using at least one single shot spectrometers and/or processes. In many embodiments, phase diversity can be used to overcome frequency fading and provide broadband operation.

[0035] Terahertz detection systems in accordance with many embodiments can provide simultaneous differential detection for high sensitivity and phase diversity for wideband operation among other applications. Wideband operations can overcome a frequency fading phenomenon and/or dispersion penalty, described in detail below, that can be inherent in many time stretch systems. Many embodiments provide for applications in Terahertz spectroscopy of material, including biological specimens, the characterization of electron beam X-ray sources, and data communication, among many other applications that utilize detectors.

[0036] Prior systems include techniques that may use equivalent time sampling and that can achieve sufficient effective bandwidth; however these prior systems can be limited as they may generally work when a signal is repetitive. As such, terahertz detection systems in accordance with many embodiments can provide single-shot measurements of Terahertz signals. In particular, many embodiments of the detection systems can operate in single-shot and can capture single-shot events and can provide single-shot measurement of Terahertz signals (among other frequency spectrums).

[0037] Terahertz detection systems in accordance with many embodiments can modulate a terahertz signal onto a chirped laser pulse, and then the composite signal can be subjected to an optical signal processing module. An optical signal processing module can perform several operations, including a first operation that can convert from a scalar (e.g., single-phase) to a vector (e.g., in-phase and quadrature orthogonal components) and a second operation that can provide simultaneous conversion from single-ended to differential. The signals can then enter a backend module. The signals may then be stretched in time in a dispersive element such that the signal bandwidth can be reduced for capture by a single photodiode followed by a real-time digitizer. Many embodiments of the system can use an optical processor to simultaneously implement phase-diversity and differential-detection.

[0038] Terahertz detection systems in accordance with several embodiments can include different backend data acquisition configurations, including orthogonal time stretch data acquisition and orthogonal camera-based data acquisition back end to provide single-shot detection, among other back end configurations as appropriate to the requirements of specific applications in accordance with embodiments of the invention.

[0039] Terahertz detection system in accordance with several embodiments can include an orthogonal time stretch processes that includes a composite signal after an optical processor, and signals can be stretched in time in a dispersive element such that the signal's bandwidth can be reduced for capture by a single photodiode followed by a real-time digitizer, which can be referred to as orthogonal time stretching.

[0040] Terahertz detection systems in accordance with certain embodiments of the invention can include at least one orthogonal camera and related processing that can capture composite signals after an optical processor using an orthogonal camera based optical spectrometer.

[0041] Terahertz detection systems that can be used to record the terahertz electric field evolution in single shot can be beneficial in many applications including terahertz spectroscopy of irreversible processes as well as for data communication applications in the terahertz portion of the spectrum where there can be an abundance of untapped bandwidth. Terahertz detection systems in accordance with many embodiments can be used to characterize electron beams in accelerators such as those used to create X-rays for biological and scientific applications, among various other applications that may benefit from incorporating detection systems.

[0042] Terahertz detection systems in accordance with many embodiments of the invention can include orthogonal time stretch data acquisition that can provide simultaneous phase diversity and differential operation. In particular, detection systems in accordance with many embodiments of the invention can simultaneously provide differential detection with sufficient bandwidth. Many embodiments of the detection systems can provide differential (e.g., balanced) detection, which can be an important feature for the detection of weak Terahertz signals.

[0043] In many embodiments of the Terahertz detection systems, a phase diversity can extend a system bandwidth by removing the dispersion penalty, and differential operation can offer high sensitivity by eliminating common-mode noise and distortion. Many embodiments of the detection system can provide real-time analog to digital conversion of signals with Terahertz bandwidth. As noted, detection systems in accordance with many embodiments can be used for many applications, including in electron beam X-ray sources, data communication, and security, among numerous other applications. Described are issues related to dispersion penalty and techniques that address these issues.

[0044] An important phenomenon that can limit a temporal resolution of terahertz detection systems is a dispersion penalty phenomenon. The phenomenon can occur when chirped optical pulses that have been modulated with data undergo a Fourier transform. In terahertz detections systems that use orthogonal time stretch configurations in accordance with many embodiments, a Fourier transform can occur when the spectrum is mapped into time in a dispersive fiber (e.g., in the far-field regime). In terahertz detection systems that use camera-based configurations in accordance with many embodiments, a Fourier transform can occur when the spectrum is mapped into space by a diffraction grating (e.g., in the far-field regime). Described herein are details for detection system with orthogonal time stretch configurations in accordance with several embodiments of the invention. A dispersion penalty can occur when modulation is a conventional double sideband. The dispersion penalty can create frequency fading in the form of nulls in the transfer function. Because certain frequencies (e.g., those near the nulls) can be lost, the reconstructed time domain may not be accurate. This problem can get progressively worse with the increase in the bandwidth of a terahertz waveform.

[0045] In many embodiments of the terahertz detection systems, double-sideband modulation (DSB) can be used to modulate a radio frequency (RF) signals onto the optical pre-chirped carrier. In many embodiments, for terahertz applications, modulation can occur in several stages (e.g., two stages). In a first stage, an input terahertz source can modulate the polarization of a laser pulse. In a second stage, the polarization can be converted into intensity modulation in a prism (e.g., a Walston prism). The resulting intensity modulation can be double sideband. As has been shown in prior art, this problem can be mitigated with single sideband modulation processes, which may not be appropriate when an input signal has wide, e.g., terahertz, bandwidth. Accordingly, terahertz detection systems in accordance with many embodiments can include phase diversity processes.

[0046] A dispersion penalty may occur due to a modulated chirped optical pulse undergoing a Fourier transform operation. Terahertz detection system in accordance with many embodiments can include a backend data acquisition configuration that can perform transform operations. Terahertz detection systems in accordance with many embodiments that include orthogonal time stretch configurations can include at least one dispersive fiber. Terahertz detection systems in accordance with several embodiments that include orthogonal camera configurations can include at least one diffractive element.

[0047] Terahertz detection systems can improve issues related to detection sensitivity. Terahertz detection systems in accordance with many embodiments can modulate a terahertz signal on the spectrum of a chirped optical pulse. The resulting signal may have a large envelope and a small modulation of the envelop representing the terahertz waveform. A small terahertz signal can be extracted from this large envelope. While this can be a challenging signal processing problem by itself, it can be made more difficult by complex (non-uniform) nonuniformity of the spectrum of typical laser pulses. These nonuniformities are often larger than the terahertz modulation and can mask the terahertz signal. Accordingly, terahertz detection systems in accordance with many embodiments can use differential detection architectures to improve detection sensitivity issues. In particular, both the pulse envelope and the spectral nonuniformities can appear as common-mode and can be canceled when the two outputs of a differential detector are subtracted, and may leave only the terahertz signal of interest. Terahertz detection systems in accordance with many embodiments can provide differential detection. Terahertz detection system in accordance with many embodiments can perform phase diversity (e.g., for maximum time resolution) and differential detection (e.g., for high detection sensitivity).

[0048] Many embodiments of the terahertz detection systems can provide single-shot terahertz detection. Detection systems in accordance with many embodiments can use different backend configurations for data acquisition, including orthogonal time stretching, orthogonal cameras, among others. A terahertz detection system with orthogonal time stretching configuration in accordance with an embodiment of the invention is illustrated in Fig. 1A. A terahertz detection system with orthogonal camera-based configuration in accordance with an embodiment of the invention is illustrated in Fig. 1B.

[0049] Terahertz Detection systems in accordance with many embodiments can include several processing phases. In many embodiments, detection systems can include five processing phases. As illustrated in Fig. 1A, chirped source module 1A05 can include a mode locked laser that can be pre-stretched by a dispersion element so that the time information is mapped into optical wavelength. Modulation module 1A10 can modulate a terahertz pulse on an optical pulse by electrical optical sampling (EO sampling). Optical processing module 1A15 can send modulated pulses to an optical processor to generate a phase diversity and differential signals. In certain embodiments, the optical processor can be unique optical processor. Optical processors in accordance with many embodiments of the system can provide important functionality for the systems (e.g., optical processors such as optical processor illustrated in Fig. 2 and described below in accordance with an embodiment of the invention). An orthogonal stretch by dispersion fiber module (1A20) (e.g., a second dispersion element) can stretch a differential in_phase and quadrature signals in order to slow down a frequency of terahertz pulse. Wavelength information can be mapped back to time domain by a spool of dispersion fiber. Analog differential detection and DSP module (1A25) can provide differential detection using a balanced photodetector. In many embodiments, a digital processing process can be utilized to reconstruct the terahertz pulse from the in_phase and quadrature signals. Although Fig. 1A illustrates a particular architecture of a single shot terahertz detection system with orthogonal time stretching, any of a variety of architectures can be utilized as appropriate to the requirements of specific applications in accordance with embodiments of the invention.

[0050] Fig. 1B illustrates a terahertz detection system with an orthogonal camera backend configuration in accordance with an embodiment of the invention. As illustrated in Fig. 1B, chirped source module 1B05 can include a mode locked laser that can be pre-stretched by a dispersion element so that the time information is mapped into optical wavelength. Modulation module 1B10 can modulate a terahertz pulse on an optical pulse by electrical optical sampling (EO sampling). Optical processing module 1B15 can send modulated pulses to an optical processor to generate a phase diversity and differential signals. In certain embodiments, the optical processor can be unique optical processor. Optical processors in accordance with many embodiments of the terahertz detection systems can provide important functionality (e.g., optical processors such as optical processor described below and illustrated in Fig. 2 in accordance with an embodiment of the invention).

[0051] As illustrated in Fig. 1B, an orthogonal stretch by diffraction grating and camera module (1B20) (a second dispersion element) can stretch differential in_phase and quadrature signals in order to slow down a frequency of terahertz pulse. Diffraction grating can be utilized to map the wavelength information into spatial domain.

[0052] Digital differential detection and DSP module (1B25) can provide differential detection using digital subtraction. In many embodiments, a digital processing process can be utilized to reconstruct the terahertz pulse from the in_phase and quadrature signals. Although Fig. 1B illustrates a particular configuration of terahertz detection system with orthogonal camera-based data acquisition backend configuration, any of a variety of configurations, including configurations with different backend data acquisition configurations can be utilized as appropriate to the requirements of specific applications in accordance with embodiments of the invention.

[0053] Terahertz detection systems in accordance with many embodiments can include at least one optical processor that can provide important functionalities. An architecture of an optical processor in accordance with an embodiment of the invention is illustrated in Fig. 2. A polarization decomposition and single differential conversion block (205) can accept a polarization modulated chirped optical pulse as well as a reference (unmodulated) pulse. The polarization decomposition and single differential conversion block (205) can convert the single-ended modulated pulse into a differential pair that can also be orthogonally polarized. In many embodiments, a reference pulse can also be a converter to two orthogonal polarizations. A polarization superposition block (210) can consolidate these four signals into two, each including the common reference and the differential signals. A polarization to intensity conversion and phase decomposition block (215) can convert the polarization modulated signals to differential intensity modulated signals where the modulation phase can also be decomposed to the I (in-phase) and the Q (quadrature) components. Although Fig. 2 illustrates a particular architecture of an optical processor, any of a variety of architectures may be utilized for optical processors as appropriate to the requirements of specific applications in accordance with embodiments of the invention.

[0054] Terahertz detection systems in accordance with many embodiments of the invention can simultaneously provide differential detection for high sensitivity and phase diversity (orthogonal) operation for broadband operation. An architecture of terahertz detection system that simultaneously provides differential detection for high sensitivity and phase diversity (orthogonal) operation for broadband operation in accordance with an embodiment of the invention is illustrated in Figs. 3A. In particular, Fig. 3A illustrates a terahertz detection system that includes an orthogonal time stretching configuration data acquisition backend 3A400. Many embodiments of the terahertz detection systems can use different data acquisition backends, including orthogonal time stretching (e.g., as illustrated in Fig. 3) or orthogonal camera data acquisition backend. Fig. 3B illustrates an orthogonal camera data acquisition backend that can be utilized in terahertz detection systems in accordance with many embodiments of the invention.

[0055] As illustrated in Fig. 3A in accordance with an embodiment of the invention, terahertz generator 3A100 can be a terahertz source, modulation element 3A200 can be a modulation element, optical processor 3A300 can be an optical processor, and orthogonal time stretch readout 3A400 can be a data acquisition backend readout. Symbol definitions have been provided in the lower right corner of Fig. 3A for various symbols, including polarization beam splitter, beam splitter, half wave plate, quarter wave plate, mirror, EO crystal, parabolic mirror, terahertz source, circulator, dispersion element, terahertz wave, mode-locked laser, optical combiner, prism, optical delay, and collimator. A key component to detection systems can be optical processors. Figs. 3A illustrates a terahertz detection system 3A00 that can include an optical processor 3A300 in accordance with an embodiment of the invention. Components 3A100, 3A200 and 3A300 can be common to different terahertz detection systems with different data acquisition backends, including terahertz detection systems that include orthogonal time stretching in accordance with many embodiments and terahertz detection systems that include orthogonal camera configurations in accordance with many embodiments. Fig. 3A illustrates a detection system architecture with orthogonal time stretch data acquisition 3A400 for orthogonal time stretching in accordance an embodiment of the invention. Fig. 3B illustrates an architecture of an orthogonal camera readout data acquisition backend 3B400 that can be used in terahertz detection systems in accordance with an embodiment of the invention.

[0056] A terahertz detection system with orthogonal time stretch readout in accordance with an embodiment of the invention is illustrated in Fig. 3A. The system 3A00 can include an orthogonal time stretch readout module 3A400 which can perform orthogonal time stretch producing differential outputs for both in-phase (I) and quadrature (Q) channels. In many embodiments, inputs to the readout can be 4 signals: the I and its inverted (differential) copy, and the Q and its inverted (differential) copy. The I and Q channels can be time interleaved using delay lines. The interleaving can reduce a number of components that may be needed. In many embodiments, interleaving can reduce by half the number of components that may be needed. In addition to reducing the cost and complexity, interleaving can eliminate mismatch between the I and Q channels caused by mismatches in dispersive fibers, photodiodes, and/or ADCs. Free space optical beams can be collected by four collimators and coupled into optical fibers. The in-phase differential channels $(I, \bar{I})$, can be sent to a second dispersion fiber (D2) in the opposite directions via a pair of circulators. Then, I and $\bar{I}$ can be sent to a balanced photodetector for differential detection. The quadrature channels $(Q, \bar{Q})$ can be interleaved with the in-phase channels by undergoing a pair of optical time delays. The interleaving can allow both I and Q channels to use a same circulators, dispersion fiber, and balanced detector and ADC. In the balanced photodetector, the optical pulse envelope and the common-mode noise can be canceled.

[0057] In particular, Figs. 3A-3B illustrate the detection system 3A00 can characterize terahertz signals, that includes a broadband optical pulse source that can generate broadband pulses, an optical power splitter that can receive broadband pulses from a broadband optical source and can produces several channels including optical O channel (channel O) and terahertz T channel (channel T), a dispersion element (D1) that can receive a same pulsed optical source from channel (O) and can chirp an optical pulse and can produce a first signal (1), a device (e.g., a photoconductive antenna, among other) that can receive the optical pulse from the channel (T) and can generate a burst of terahertz radiation in response, and a delay stage (Delay 1) that can receive the same pulsed optical source from channel (O) and provides a delay to the chirped optical pulse so that the generated burst of terahertz radiation response and the chirped optical pulse overlap in time. In several embodiments, the system can include a device under test (DUT) that receives the burst of terahertz radiation to produce a terahertz response signal that includes characteristics of the DUT; a half wave plate (HWP-1) with its fast axis rotated by 22.5 degrees compared to a horizontal component of light polarization that can receive the chirped optical pulse from the dispersion element (D1); an optical polarization beam splitter (PBS-2) that can receive the chirped optical pulse from the half wave plate (HWP-1) and can split the chirped optical pulse into two orthogonal polarized signals, signal (3) and signal (4); a pair of parabolic mirrors that can combine the burst of terahertz radiation with the optical pulse and the signal (3), and can direct them into an electro-optic crystal (EO); an electro-optic (EO) crystal that modulates a light polarization in response to an electric field of the burst of terahertz radiation producing signal (5); a half wave plate (HWP-2) with a fast axis rotated by a certain degrees (e.g., 22.5 degrees) compared to a horizontal polarization that receives inputs (4) and (5) and produces output signals (6) and (11); a polarization beam splitter cube (PBS-2) with fast axis aligned to a horizontal polarization state of light that receives the signal (6) and produces orthogonal polarization signals (7) and (8); a quarter wave plate (QWP-1) with a fast axis rotated by a certain degrees (e.g., 45 degrees) compared to a horizontal polarization of light, that receives the signal (8) and generates an output that is reflected by a mirror and passes quarter wave plat (QWP-1) again producing signal (10); a quarter wave plate (QWP-2) with a fast axis rotated by a certain degrees (e.g., 45 degrees) compared to a horizontal polarization of light, that receives the signal (7) and generates an output that is reflected by a reflector, and passes quarter wave plate (QWP-2) again producing signal (9); where the HWP-2, PBS-2, QWP-2, QWP-2 and reflector can perform the functions on the reference signal (4) and add the reference signal (4) with correct polarization to the output signals (17) and (18); a half wave plate (HWP-3) with its fast axis rotated by a certain degrees (e.g., 22.5 degrees) compared to a horizontal polarization of light that receives the signals (16) and (17) and outputs signals (18) and (19); a quarter wave plate (QWP-3) with its fast axis aligned to the horizontal polarization of light that receives the signals (18) and (19) and outputs signals (20) and (21); a polarization beam splitter cubic (PBS-3) with its fast axis aligned to a horizontal polarization state of light that receives signals (20) and (21) and outputs two pairs of differential signals, signals (22) and (24), and (23) and (25), that are orthogonal in both polarization and temporal phase. The system can further include a pair of optical delay lines and couplers that combine signal (23) with (24), and signal (22) with (25), producing a differential in-phase signal (26), and a differential quadrature signal (27), where signals (26) and (27) can be time interleaved, a pair of optical circulators and a second dispersion element (D2) that can stretch the signals in time and direct them to output signals (28) and (29), a balanced photodetector with a differential amplifier that can produce output (30) including time interleaved in-phase and quadrature analog signals in the electrical domain, an analog-to-digital converter, a digital signal processor configured that processes a digitized signal using a maximum ratio combining process that eliminates a dispersion penalty, and a computer that analyzes the digital signal and provides a visualization of results.

[0058] As illustrated in Fig. 3A, starting from signals (22-25), the four signals (22-25) can be delayed and interleaved in time such that they can be captured using a single spectrometer, optical delay stages (Delay 4), (Delay 5) and beam combiners (OC1) and (OC2) can combine signal (23) with (24), and signals (22) with (25), producing the differential in-phase signal (26), and the differential quadrature signal (27). In several embodiments, an optical delay stage (Delay 6) can interleave signal (27) relative to signal (26), an optical combiner (OC3) can combine signal (26) and signal (27) together and can produce time interleaved signal (28); and an optical diffractive grating that can map wavelength into space and can produce signal (29).

[0059] Detection system in accordance with many embodiments can include a camera that can record a diffracted optical beam and can quantize the signals into the digital domain and produces signal 30, and can include a digital signal processor configured to process the digitized signal using a maximum ratio combining process to eliminate dispersion penalty.

[0060] Terahertz detection systems in accordance with many embodiments can include at least one computer that can analyze a digitized signal and provide a visualization of results.

[0061] In many embodiments of the terahertz detection systems, a pulsed optical source can be configured with a supercontinuum source. In several embodiments, a dispersion element can include a dispersive optical fiber that can be a fiber Bragg grating (FBG), a chromo-modal dispersion (CMD) device, a single-mode fiber (SMF), a dispersive compensating fiber (DCF), a Raman optical fiber with internal Raman amplification providing high dispersion combined with a net gain, and/or an arrayed wave-guide grating (AWG), among other types of dispersive optical fibers. An analog-to-digital converter (ADC) can be configured to convert the electrical equivalent of the stretched optical source and can operate at a lower frequency than the input signal being captured.

[0062] Many embodiments of the terahertz detection systems can include programming executable on said processing device that performs high-speed time-domain analysis of terahertz signals. In many embodiments, a machine learning process can be trained and used to perform signal processing. Terahertz detection systems in accordance with many embodiments can include programming executable on a processing device for performing high-speed spectroscopy of the terahertz signals.

[0063] Terahertz detection systems in accordance with several embodiments can include programming executable on a processing device for performing high-speed inspection and quality testing of industrial materials.

[0064] Terahertz detection systems in accordance with several embodiments can include executable code on for execution on a processing device for performing high-speed quality inspection of pharmaceutical products. Several embodiments of detection systems can include programming executable code on a device that performs high-speed inspection of packaged integrated circuits to spot counterfeit products. Systems in accordance with several embodiments can include programming executable code on a processing device that can perform high-speed imaging of biological tissues. Systems in accordance with many embodiments can include executable on a processing device that can perform high-speed analysis of communication signals for terahertz burst-mode communications.

[0065] Although Fig. 3A illustrates a particular terahertz detection system architecture that includes an orthogonal time stretch backend data acquisition architecture, any of a variety of architectures, including architectures that use different backend data acquisition architectures including orthogonal camera data acquisition architectures as illustrated in for example, Fig. 3B, can be utilized as appropriate to the requirements of specific applications in accordance with embodiments of the invention. Although Fig. 3B illustrates an architecture of an orthogonal camera readout data acquisition backend that can be utilized as a backend in terahertz detection systems, including, for example, the terahertz detection system illustrated in Fig. 3A, any of a variety of architectures may be utilized for orthogonal camera data acquisition backends as appropriate to the requirements of specific applications in accordance with embodiments of the invention.

Modulations

[0066] Terahertz detection systems in accordance with many embodiments can use modulation processes. In many embodiments, a terahertz waveform modulates a polarization of an optical pulse in an EO crystal. The polarizations of the light and the terahertz can be aligned and enter the EO crystal at a particular degree (e.g., 45 degree) with respect to its fast axis. In many embodiments, the reference arm may not be modulated; its polarization can be orthogonal to that of the modulated arm. The signal and the reference can then enter an optical processor.

Optical processors

[0067] Terahertz detection systems in accordance with many embodiments can include at least one optical processor. A purpose of an optical processor in accordance with several embodiments can be to generate in-phase and quadrature phase modulated differential outputs. As described, Fig. 3A illustrates an optical processor 3A300 in accordance with an embodiment of the invention. In many embodiments, first, a polarization modulated signal and a reference can be sent to a half wave plate (HWP-

1), whose fast axis can be rotated by a certain degree compared to a horizontal polarization state (X polarization). In several embodiments, a fast axis can be rotated by 22.5 degree compared to a horizontal polarization state (X polarization). Therefore, the HWP-1 can rotate the polarization states of both signal and reference can be rotated by 45 degrees (2x22.5 degrees), which can align with 45 degrees to the optical axis of (PBS-2). In many embodiments, the (PBS-2) can then split the orthogonal polarization beams with equal power. In this way, the polarization modulated signal can be separated into a pair of differential phase modulated pulse with orthogonal (X and Y) polarizations.

[0068] In many embodiments, Y polarization component can travel in the vertical direction and can be reflected by a mirror but its polarization state can be rotated by 90 degree and become X polarization by passing a 22.5-degree rotated quarter wave plate (QWP-1) twice. In the meantime, X polarization beams that travel horizontally can be reflected by a prism (e.g., corner cube reflector) and pass a quarter wave plate (QWP-2) twice and become Y polarization beams. The reference can be processed in the same way. In this way, X polarization part of signal and reference optical pulses can be exchanged. After adjusting the mirror delays, a pair of differential single arm polarization modulated signal can be created after the PBS-2 combine signals and reference together.

[0069] In many embodiments, the combination of the HWP-2, QWP-3 and the PBS-3 can be used to convert the polarization modulation to intensity modulation. The HWP-3 with a rotated angle of 22.5 degree compare to the horizontal polarization state can rotate the polarization by 45 degree (22.5*2 degree). The fast axis of QWP-3 can be aligned with the horizontal polarization of light to induce a 90-degree phase shift between the X- and Y-polarizations producing the in-phase (I) and quadrature (Q) components. In many embodiments, PBS-3 can produce four outputs: the I/Q pair and their differential.

[0070] Terahertz detection systems in accordance with many embodiments can include a readout stage that can follow the optical processor. There can be several options for the readout stage. In many embodiments, an orthogonal time stretch readout may use dispersive time stretch followed by a real-time analog to digital converter

(ADC). As described, a terahertz detection system that includes orthogonal time stretch backend configuration in accordance with an embodiment of the invention is illustrated in Fig. 3A. Terahertz detection systems in accordance with many embodiments can include a camera based grating spectrometer (e.g., an optical spectrum analyzer) data acquisition backend. A camera based grating spectrometer can be, for example, an optical spectrum analyzer, among various types of spectrometers. As described, a terahertz detection system that includes a camera based grating spectrometer data acquisition backend in accordance with an embodiment of the invention is illustrated in Fig. 3B.

[0071] Detections systems in accordance with many embodiments that include orthogonal camera data acquisition can interleave all four signals into one channel. Inputs to a readout can be the four signals: the I and its inverted (differential) copy, and the Q and its inverted (differential) copy. Two sequential interleaving stages can combine these four into a signal channel so they can be captured using a single spectrometer. First, optical delay stages (Delay 4), (Delay 5) and beam combiners (OC1) and (OC2) can interleave the I channels together, and the Q channels together, producing the differential in-phase and differential quadrature signals. Then an optical delay stage (Delay6) and optical combiner (OC3) can combine them together and produce a single channel that includes four time interleaved signals. The four signals can be sequentially captured by an orthogonal camera based diffraction grating spectrometer, which can produce a digital output.

[0072] Detection systems in accordance with many embodiments and include digital signal processing module (DSP). Detection systems in accordance with several embodiments that include orthogonal camera data acquisition can include at least one DSP module. Detection systems in accordance with many embodiments that include orthogonal time stretch data acquisition processes can include at least one DSP module. An automated DSP for calibration can be designed to (a) segment the time sequences into individual frames and align the frames in time, (b) identify the impulse and the proper frame length from the time-domain data sequence, (c) apply asymmetrical windowing and zero-padding (to improve the performance and resolution in the frequency domain), and (d) a fast Fourier transform (FFT) and an MRC can be used to recover signal in the frequency domain, (e) the frequency domain signal can be converted back to time domain waveform by an inverse fast Fourier transform (IFFT) converter. In many embodiments, digital signal processing can be performed using machine learning.

[0073] Terahertz detection systems in accordance with many embodiments can include modulation and/or optical processors. Fig. 3A illustrates a detection system that includes a modulation module 3A200 and an optical processor module 3A300 in accordance with an embodiment of the invention. Described now are the mathematical description of a modulation (e.g., modulation module 3A200) and optical processor (e.g., optical processor 3A300 of Fig. 3A) components in a detection system in accordance with several embodiments, which can be important components. For other components, the mathematical frameworks can be similar to that in previous techniques. As described, the equation numbers below correspond to the node numbers in the figures, in particular Fig. 3A and Fig. 3B, written using parenthesis, e.g., node 2 appears as “(2)”. Also, the following notation is used to describe the horizontal, X and the vertical, Y polarization of light $\begin{pmatrix}E_X\\E_Y\end{pmatrix}$. The equations below utilize the Jones matrices for quarter wave plate (QWP), half wave plate (HWP) and polarization beam splitter (PBS). These matrices are described below.

HWP-1 and PBS-1

[0074] The optical electric field in time domain after the HWP-1 which is rotated by 22.5 degree compare to the horizontal polarization state (at node 2) can be written as

[0075]
$$E_2(t) = \frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}1 & 1\\1 & -1\end{pmatrix}(E_X)=\frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}E_X\\E_Y\end{pmatrix}, \tag{2}$$

[0076] In which $E_1(t)$ is the optical field after first dispersion element (D1).

[0077] The horizontal and vertical polarization are separated by the PBS-1 into:

[0078]
$$E_3(t) = E_2(t)\begin{pmatrix}1 & 0\\0 & 0\end{pmatrix}=\frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}1 & 0\\0 & 0\end{pmatrix}\begin{pmatrix}E_X\\E_Y\end{pmatrix} = \frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{2}}(E_X), \tag{3}$$

[0079]
$$E_4(t) = E_2(t)\begin{pmatrix}0 & 0\\0 & 1\end{pmatrix}=\frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}0 & 0\\0 & 1\end{pmatrix}\begin{pmatrix}E_X\\E_Y\end{pmatrix} = \frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{2}}(E_Y). \tag{4}$$

Modulation

[0080] Next, these X-component of the light electric field is modulated by Terahertz wave using a GaAs crystal, whereas the Y-component serves as the reference. The polarization coordinate can be rotated of light, E_x, to align it at $-45°$ with respect to the fast axis of the crystal. In this case, the polarization state of light can be modulated by the Terahertz wave and push-pull modulation is achieved in terms of the projection of the light electric field onto the axis of the crystal, $E_{X'}$ and $E_{Y'}$. Then consider the components of the new electric field in the original X and Y coordinates. These operations are mathematically described as

[0081]
$$E_5(t) = E_3(t)\begin{pmatrix}1 & -1\\ 1 & 1\end{pmatrix}\begin{pmatrix}e^{jm} & e^{-jm}\end{pmatrix}\begin{pmatrix}1 & 1\\ -1 & 1\end{pmatrix} = \frac{1}{2}E_1(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}1 & 1\\ -1 & 1\end{pmatrix}\begin{pmatrix}E_{X'}e^{jm}\\ E_{Y'}e^{-jm}\end{pmatrix} = \frac{1}{2}E_1(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}E_X(e^{jm}+e^{-jm})\\ E_Y(e^{jm}-e^{-jm})\end{pmatrix}. \quad (5)$$

[0082] Where $E_{X'}$ and $E_{Y'}$ represent the fast and slow axis of the crystal. The first 2x2 matrix rotates the light polarization onto the fast and slow axis of the crystal. The 1x2 matrix describes the phase modulation by the crystal. The parameter, m, includes the modulation caused by the Terahertz wave. It is the time-dependent Terahertz voltage across the crystal normalized to the half-wave voltage of the crystal. The second 2x2 matrix rotates the polarization back to the original coordinates.

HWP-2 for Signal

[0083] Next, the light passes through the HWP-2. Here the fast axis is aligned at 22.5° with respect to the X-polarization of light, producing:

[0084]
$$E_6(t) = \frac{1}{2}e^{-i\frac{\pi}{2}}E_5(t)\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} = \frac{1}{2}E_1(t)e^{-j\pi}\begin{pmatrix}E_X e^{jm}\\ -E_Y e^{-jm}\end{pmatrix} \quad (6)$$

PBS-2, QWP-1 and QWP-2 for Signal

[0085] The PBS-2 splits the horizontal and vertical polarization states provide the pair of push-pull phase modulation fields:

[0086]
$$E_7(t) = \frac{1}{2}e^{-j\pi}E_1(t)E_X e^{jm} \quad (7)$$

[0087]
$$E_8(t) = -\frac{1}{2}e^{-j\pi}E_1(t)E_Y e^{-jm}. \quad (8)$$

[0088] The next operation is to mix the signal and the reference. These can be achieved by a PBS-2 and double pass through QWP-1 or QWP-2 with their fast axis rotated by 45° compare to the horizontal polarization state of light. So, when the optical field is reflected and then arrives back to PBS-2, the polarization state is converted to:

[0089] $$E_9(t) = E_7(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix} = \frac{1}{2}e^{-j\frac{3\pi}{2}}E_1(t)E_Y e^{jm}, \qquad (9)$$

[0090] $$E_{10}(t) = E_8(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix} = -\frac{1}{2}e^{-j\frac{3\pi}{2}}E_1(t)E_X e^{-jm}. \qquad (10)$$

HWP-2 for Reference

[0091] Now, consider Eq. (4), which is the Y polarization component, and which constitutes the reference signal. After passing the HWP-2 with its fast axis rotated by 22.5° compare to the horizontal polarization, this provides

[0092] $$E_{11}(t) = E_4(t)\frac{\sqrt{2}}{2}e^{-j\frac{\pi}{2}}\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} = \frac{1}{2}E_1(t)e^{-j\pi}\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}(E_Y) = \frac{1}{2}E_1(t)e^{-j\pi}\begin{pmatrix}E_X\\ -E_Y\end{pmatrix}.$$

(11)

[0093] The PBS-2 then splits the horizontal and vertical polarization components into,

[0094] $$E_{12}(t) = \frac{1}{2}E_{12}(t)\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix} = \frac{1}{2}E_1(t)e^{-j\pi}E_X, \qquad (12)$$

[0095] $$E_{13}(t) = \frac{1}{2}E_{12}(t)\begin{pmatrix}0 & 0\\ 0 & 1\end{pmatrix} = -\frac{1}{2}E_1(t)e^{-j\pi}E_Y. \qquad (13)$$

[0096] After double pass through QWP-1 or QWP-2 with their fast axis rotated by 45° compare to the horizontal polarization, the electric fields returning to PBS-2 are given by,

[0097] $$E_{14}(t) = E_{12}(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix} = \frac{1}{2}E_1(t)e^{-j\frac{3\pi}{2}}E_Y, \qquad (14)$$

[0098] $$E_{15}(t) = E_{13}(t)e^{-j\frac{\pi}{2}}\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix} = -\frac{1}{2}E_1(t)e^{-j\frac{3\pi}{2}}E_X. \qquad (15)$$

[0099] After exiting the PBS-2, the modulated signals in Eq. (9) and (10) are mixed with unmodulated references of Eq. (14) and (15) producing the signals at nodes 16 and 17:

[0100] $$E_{16}(t) = \frac{1}{2}E_1(t)e^{-j\frac{3\pi}{2}}\begin{pmatrix}-e^{-jm}E_X\\ E_Y\end{pmatrix}, \qquad (16)$$

[0101] $E_{17}(t) = \frac{1}{2}E_1(t)e^{-j\frac{3\pi}{2}}\begin{pmatrix} -E_X \\ e^{jm}E_Y \end{pmatrix}$. (17)

HWP-3 and QWP-3

[0102] After HWP-3 with its fast axis rotated by 22.5° compare to the horizontal polarization state, expressions should be:

[0103] $E_{18}(t) = \frac{\sqrt{2}}{4}E_1(t)e^{-j\frac{3\pi}{2}}e^{-j\frac{\pi}{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} -e^{-jm}E_X \\ E_Y \end{pmatrix} = -\frac{\sqrt{2}}{4}E_1(t)\begin{pmatrix} (e^{-jm} - 1)E_X \\ (e^{-jm} + 1)E_Y \end{pmatrix}$,

(18)

[0104] $E_{19}(t) = \frac{\sqrt{2}}{4}E_1(t)e^{-j\frac{3\pi}{2}}e^{-j\frac{\pi}{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} -E_X \\ e^{jm}E_Y \end{pmatrix} = -\frac{\sqrt{2}}{4}E_1(t)\begin{pmatrix} (1 - e^{jm})E_X \\ (e^{jm} + 1)E_Y \end{pmatrix}$. (19)

[0105] These signals enter QWP-3 with its fast axis aligned with horizontally polarization states. This converts the linear polarization states into circular polarization states:

[0106] $E_{20}(t) = E_{18}(t)e^{-i\frac{\pi}{4}}\begin{pmatrix} 1 & 0 \\ 0 & j \end{pmatrix} = -\frac{\sqrt{2}}{4}E_1(t)e^{-j\frac{\pi}{4}}\begin{pmatrix} \left(e^{-jm} - 1\right)E_X \\ j\left(e^{-jm} + 1\right)E_Y \end{pmatrix}$ (20)

[0107] $E_{21}(t) = E_{19}(t)e^{-i\frac{\pi}{4}}\begin{pmatrix} 1 & 0 \\ 0 & j \end{pmatrix} = -\frac{\sqrt{2}}{4}E_1(t)e^{-j\frac{\pi}{4}}\begin{pmatrix} (1 - e^{jm})E_X \\ j(e^{jm} + 1)E_Y \end{pmatrix}$ (21)

[0108] PBS-3

[0109] At last, PBS-3 splits the two polarizations for each beam. Thus, polarization modulations are converted into two differential intensity modulated I and Q pairs:

[0110] $E_{22}(t) = -\frac{\sqrt{2}}{4}E_1(t)e^{-j\frac{\pi}{4}}\left(e^{-jm} - 1\right) = -j\frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{4}}e^{j\frac{m}{2}}\sin\left(\frac{m}{2}\right) = \bar{Q}$ (22)

[0111] $E_{23}(t) = -\frac{\sqrt{2}}{4}E_1(t)e^{-i\frac{\pi}{4}}j\left(e^{-jm} + 1\right) = j\frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{4}}e^{j\frac{m}{2}}\cos\left(\frac{m}{2}\right) = I$ (23)

[0112] $E_{24}(t) = -\frac{\sqrt{2}}{4}E_1(t)e^{-i\frac{\pi}{4}}\left(1 - e^{jm}\right) = j\frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{4}}e^{j\frac{m}{2}}\sin\left(\frac{m}{2}\right) = Q$ (24)

[0113] $E_{25}(t) = -\frac{\sqrt{2}}{4}E_1(t)e^{-i\frac{\pi}{4}}j(e^{jm} + 1) = -j\frac{\sqrt{2}}{2}E_1(t)e^{-j\frac{\pi}{4}}e^{j\frac{m}{2}}\cos\left(\frac{m}{2}\right) = \bar{I}$ (25)

[0114] All these outputs can include both the amplitude and the phase modulation through the parameter, m. A key observation is that the quadrature components Eq. (22) and Eq. (24) have opposite amplitudes allowing differential detection for high sensitivity detection. The same is true for in-phase components, Eq. (23) and Eq. (25). The phase modulation can be converted to amplitude modulation after dispersion in the fiber. This is the dispersion penalty effect that causes nulls in the frequency response and limits the bandwidth of detections system in accordance with many embodiments. However, the electric fields for the I and Q differ by 90° phase. After photodetection, the corresponding signals are 180° out of phase, causing their null locations to be complementary. This property, known as phase diversity, allows for the removal of the nulls using a digital signal processing process, for example, the Maximum Ratio Combining (MRC). While phase diversity is a known technique, it may only be achieved for single-ended signals. Accordingly, detection systems in accordance with many embodiments provide that phase diversity is not achieved with differential signals.

[0115] Jones Matrixes. The polarization rotation operations of QWP, HWP and PBS can be mathematically described by their so-called Jones matrices. Described herein are Jones matrices that can be used in many embodiments.

[0116] The Half-wave plate with the fast axis at an angle of θ to the horizontal polarization of the optical field has a Jones matrix:

[0117] $$e^{-i\frac{\pi}{2}}\begin{pmatrix}\cos^2\theta-\sin^2\theta & 2\cos\theta\sin\theta\\ 2\cos\theta\sin\theta & \sin^2\theta-\cos^2\theta\end{pmatrix}$$

[0118] If $\theta = 22.5°$, the transfer matrix will be:

[0119] $$e^{-i\frac{\pi}{2}} = \frac{\sqrt{2}}{2}e^{-i\frac{\pi}{2}}\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}$$

[0120] And if $\theta = 45°$:

[0121] $$e^{-i\frac{\pi}{2}}\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}.$$

[0122] The quarter-wave plate (QWP) with the fast axis at an angle of θ:

[0123] $$e^{-i\frac{\pi}{4}}\begin{pmatrix}\cos^2\theta+i\sin^2\theta & (1-i)\cos\theta\sin\theta\\ (1-i)\cos\theta\sin\theta & \sin^2\theta+i\cos^2\theta\end{pmatrix}$$

[0124] If $\theta = 0\ with\ fast$ axis to the horizontal:

[0125] $$e^{-i\frac{\pi}{4}}\begin{pmatrix}1 & 0\\ 0 & i\end{pmatrix}$$

[0126] The polarization rotation matrix is:

[0127] $$\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}$$

[0128] If $\theta = -45°$, the Jones matrix should be $\begin{pmatrix}1 & -1\\ 1 & 1\end{pmatrix}$;

[0129] If $\theta = 45°$, the Jones matrix should be $\begin{pmatrix}1 & 1\\ -1 & 1\end{pmatrix}$;

[0130] PBS is a dual output orthogonal linear polarizer. For a linear polarizer with an angle of θ the Jones matrix is

[0131] $\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

[0132] So, if $\theta = 0°$, the Jones matrix should be $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$;

RESULTS

[0133] Fig. 4A illustrates a table of Metadata in the simulation in accordance with an embodiment of the invention.

[0134] Fig. 1B provides simulated results for the Orthogonal Time Stretch technique in accordance with several embodiments of the invention. Here an ideal Gaussian Terahertz pulse was used to show the basic operation of the system. (a) The input pulse that is to be measured (dashed) along with the output of the conventional time stretch. Because of the dispersion penalty, the measured pulse is completely distorted. (b) Input pulse and the output of the system. It can be seen that the system faithfully reproduces the Terahertz pulse using phase diversity. (c) The two orthogonal (in-phase and quadrature) channels of the system. (d) The frequency spectrum of the input Terahertz pulse (dashed) and the conventional time stretch showing frequency nulls. (e) The frequency spectrum of the input Terahertz pulse (dashed) and the phase diversity Orthogonal Time Stretch system showing good agreement. (f) The frequency spectrum of the two orthogonal (in-phase and quadrature) channels of the system.

[0135] In many embodiments, a simulation based on Orthogonal Time Stretch and Orthogonal Camera technique is conducted by using VPI Photonics Transmission Maker 11.0 software. The metadata is listed in Table 1 illustrated in Fig. 4A in accordance with an embodiment of the invention. In the simulation, a mode locked laser generates a serial of 48.8 fs optical pulse with a repetition rate of 19.8 MHz is sent into a 10-meter standard single mode fiber with a dispersion of 18 ps/(nm*km). And then, the pre-stretched optical pulse is amplified by an EDFA. The output power is set to be 25 mw. In the modulation component the modulation index is set to be 0.15 rad, which is the same as prior experimental results. After passing through an optical processor, the signals are stretched by a 2 km single mode fiber in detection system with an

Orthogonal Time Stretch system in accordance with an embodiment of the invention. In a detection system with an Orthogonal Camera system, an optical spectrum analyzer with a resolution of 1.25 GHz can be used to stretch the signals in accordance with an embodiment of the invention. Fig 4B illustrates the results of a detection system with Orthogonal Time Stretch when an ideal Gaussian terahertz pulse is imported. As illustrated in Fig. 4B item (a) and Fig. 4C item (d), in the conventional receiver, signals suffer from distortion in the time domain and null point in frequency domain due to the dispersion penalty. Fig. 4B item (b) and Fig. 4C item (e) show that Terahertz pulse can be well recovered, and the null point in the frequency domain is eliminated because of the differential and phase diversity design. The I and Q channel performance is shown in Fig. 4B item (c) and Fig. 4C item (f), it can find a 90-degree phase difference in the time domain between in-phase and quadrature channels as well as the complimentary null point in the frequency domain. Fig. 5A and Fig. 5b are the result in the same setup, but a real terahertz pulse is imported, which is extracted from the previous experiment. As illustrated, the design in accordance with many embodiments can totally retrieve the terahertz pulse very precisely; even the second peak can be recovered.

[0136] Fig. 6A-6B and Fig. 7A-7B illustrate a result of a detection system with an orthogonal camera process in accordance with several embodiments of the invention, when the idea Gaussian pulse and real pulse imported, respectively. Different from a detection system with an orthogonal time stretch process, the digital mapping function from the wavelength information into the time domain should be calculated by considering the dispersion slope in D1. The results agree with the theory, as well.

[0137] Fig. 5A-5B illustrate simulated results for a detection system with orthogonal time stretch in accordance with several embodiments of the invention. Here a real terahertz pulse can be used. The terahertz pulse can be an experimentally produced pulse. Item (a) of Fig. 5A illustrates the input pulse that is to be measured (dashed) along with the output of the conventional time stretch. Because of a dispersion penalty, the measured pulse can be completely distorted. Fig. 5A item (b) illustrates input pulse and the output of a system in accordance with an embodiment. It can be seen that the system in accordance with an embodiment faithfully reproduces the terahertz pulse using phase diversity. Fig. 5A item (c) illustrates the two orthogonal (in-phase and quadrature) channels of a system. Fig. 5B item (d) illustrates the frequency spectrum of the input terahertz pulse (dashed) and the conventional time stretch showing frequency nulls. Fig. 5B item (e) illustrates the frequency spectrum of the input terahertz pulse (dashed) and a phase diversity orthogonal time stretch system showing good agreement. Fig. 5B item (f) illustrates the frequency spectrum of the two orthogonal (in-phase and quadrature) channels of our system.

[0138] Fig. 6A-6B illustrate simulated results for a detection system that includes orthogonal camera processes in accordance with an embodiment of the invention. Here an ideal Gaussian terahertz pulse can be used to show the basic operation of the system. Item (a) illustrates an input pulse that is to be measured (dashed) along with the output of a system that includes orthogonal camera. Because of the dispersion penalty, the measured pulse is completely distorted. Item (b) illustrates input pulse and the output of a system. A system faithfully reproduces a terahertz pulse using phase diversity. Item (c) illustrates the two orthogonal (in-phase and quadrature) channels of a system. Item (d) illustrates the frequency spectrum of the input Terahertz pulse (dashed) and the orthogonal camera based processes showing frequency nulls. Item (e) illustrates a frequency spectrum of the input Terahertz pulse (dashed) and a system with phase diversity orthogonal time stretching showing good agreement. Item (f) illustrates a frequency spectrum of two orthogonal (in-phase and quadrature) channels of a system.

[0139] Fig. 7A-7B illustrate simulated results for a detection system that includes orthogonal camera in accordance with several embodiments of the invention. Here a real terahertz pulse can be used. The terahertz pulse can be the experimentally produced pulse. Item (a) illustrates an input pulse that is to be measured (dashed) along with the output a conventional camera based process. Because of the dispersion penalty, the measured pulse can be completely distorted. Item (b) illustrates an input pulse and the output of a system. It can be seen that a system can faithfully reproduce a terahertz pulse using phase diversity. Item (c) illustrates two orthogonal (in-phase and quadrature) channels of a system. Item (d) illustrates a frequency spectrum of a input terahertz pulse (dashed) and a system with a camera based process showing frequency nulls. Item (e) illustrates a frequency spectrum of an input terahertz pulse (dashed) and a phase diversity orthogonal time stretch system showing good agreement. Item (f) illustrates a frequency spectrum of two orthogonal (in-phase and quadrature) channels of a system.

[0140] Compare with detection systems that include orthogonal time stretch and detection systems that include orthogonal camera, a frame rate of a detection system with orthogonal time stretch system can go up to 1 GHz, which is approximately 1000 times higher than that of a detection system with orthogonal camera in accordance with several embodiments of the invention. A detection system with orthogonal time stretch system in accordance with several embodiments of the invention can sacrifice quantization bits due to trade-off in high-speed analog to digital converter. Fig. 8 illustrates recovered terahertz pulse using a detection system with orthogonal time stretch with different quantization bits in accordance with several embodiments of the invention. Fig. 8 illustrates that fully recovered if quantization bits more than 6 bits. Detection systems with orthogonal time stretch in accordance with several embodiments of the invention can potentially have issues of nonlinearity of optical fiber. Nonlinearity in the optical dispersion fiber can shift the null point in the frequency domain and then break the complementary relation between in-phase and quadrature channels. However, the length of the second dispersion fiber can be much shorter than that in a traditional time stretch system. So, the nonlinear phenomenon may not be as strong as that in a traditional time stretch system. Fig. 9 and Fig. 10 illustrate an impact of nonlinearity in an optical fiber in accordance with several embodiments of the invention. Detection systems in accordance with many embodiments, a peak power before D2 can typically be around 10 W. So, nonlinearity should issues should be minimized. Fig 11 illustrates a relation between terahertz bandwidth and optical bandwidth when an idea Gaussian pulse with 3 dB bandwidth of 1.2 THz is imported into a detection system with orthogonal time stretch in accordance with several embodiments of the invention. In many embodiments, an optical bandwidth may need to be larger than 50 nm to avoid the roll-off at high frequency.

[0141] Fig. 8 illustrates an impact of analog-to-digital converter (ADC) quantization noise on the accuracy of a measured terahertz pulse in accordance with several embodiments of the invention. Item (a) illustrates reconstructed pulse for ADC resolutions of 10, 8, and 6 bits, showing that a system in accordance with an embodiment can work well even with a modest resolution of 6 bits. Item (b) illustrates a same with ADC resolutions of 6, 4 and 2bits. A degradation can be clearly observed for resolutions below 6 bits.

[0142] Fig. 9 illustrates an impact of optical nonlinearity in the frequency domain in accordance with several embodiments of the invention. Item (a) illustrates a frequency spectrum of a conventional single channel time stretch system for optical power levels of 15W, 63W and 243W. The power can correspond to the peak pulse power entering the second dispersive fiber. Optical nonlinearity can shift the position of the nulls. Item (b) illustrates a frequency spectrum of orthogonal (in-phase and quadrature) channels at low power (15W). Item (c) illustrates same at 63W and (d) at 253W. At high power, optical nonlinearity disturbs the ideal complementary behavior of the two channels.

[0143] Fig. 10 illustrates an impact of optical nonlinearity on the time domain reconstruction in accordance with several embodiments of the invention. Item (a) illustrates input pulse (dashed) and the reconstructed pulse at three different power levels. Item (b) illustrates frequency spectrum of an input and a reconstructed pulse. High optical powers degrade the reconstructed pulse.

[0144] Fig. 11 illustrates an impact of laser bandwidth in accordance with several embodiments of the invention. The frequency response of the input (black dash line) reconstructed terahertz pulse at three different optical bandwidths. The bandwidth of the reconstructed terahertz pulse can degrade when optical bandwidth lower than 50 nm.

[0145] Although specific implementations of terahertz detection systems are discussed above with respect to Figs. 1-11, any of a variety of implementations utilizing the above discussed techniques can be utilized for terahertz detection systems in accordance with embodiments of the invention. While the above description contains many specific embodiments of the invention, these should not be construed as limitations on the scope of the invention, but rather as an example of one embodiment thereof. It is therefore to be understood that the present invention may be practice otherwise than specifically described, without departing from the scope and spirit of the present invention. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive.

WHAT IS CLAIMED IS:

1. A system of characterizing terahertz signals, comprising:

a broadband optical pulse source that generates broadband pulses;

an optical power splitter that receives broadband pulses from the broadband optical pulse source and produces a plurality of channels including optical O channel (channel O) and terahertz T channel (channel T);

a dispersion element D1 that receives a same pulsed optical source from channel O and chirps an optical pulse and produces a signal 1;

a device that receives an optical pulse from the channel T and generates a burst of terahertz radiation in response;

a delay stage that receives the same pulsed optical source from channel O and provides a delay to the chirped optical pulse so that the generated burst of terahertz radiation response and the chirped optical pulse overlap in time;

a device under test (DUT) that receives the burst of terahertz radiation to produce a terahertz response signal that includes characteristics of the DUT;

a half wave plate (HWP-1) with its fast axis rotated by 22.5 degrees compared to a horizontal component of light polarization that receives the chirped optical pulse from the dispersion element D1;

an optical polarization beam splitter (PBS-2) that receives the chirped optical pulse from the HWP-1 and splits the chirped optical pulse into two orthogonal polarized signals, signal 3 and signal 4;

a pair of parabolic mirrors that combines the burst of terahertz radiation with the optical pulse and the signal 3, and directs them into an electro-optic crystal (EO);

an electro-optic (EO) crystal that modulates a light polarization in response to an electric field of the burst of terahertz radiation producing signal 5;

a half wave plate (HWP-2) with a fast axis rotated by 22.5 degrees compared to a horizontal polarization that receives input signal 4 and signal 5 and produces output signals 6 and 11;

a polarization beam splitter cube (PBS-2) with fast axis aligned to a horizontal polarization state of light that receives the signal 6 and produces orthogonal polarization signals 7 and 8;

a quarter wave plate (QWP-1) with a fast axis rotated by 45 degrees compared to a horizontal polarization of light, that receives the signal 8 and generates an output that is reflected by a mirror and passes QWP-1 again producing signal 10;

a quarter wave plate (QWP-2) with a fast axis rotated by 45 degrees compared to a horizontal polarization of light, that receives the signal 7 and generates an output that is reflected by a reflector, and passes QWP-2 again producing signal 9;

wherein the HWP-2, PBS-2, QWP-2, QWP-2 and reflector perform functions on reference signal 4 and add the reference signal 4 with correct polarization to the output signals 17 and 18;

a half wave plate (HWP-3) with its fast axis rotated by 22.5 degrees compared to a horizontal polarization of light that receives the signals 16 and 17 and outputs signals 18 and 19;

a quarter wave plate (QWP-3) with its fast axis aligned to the horizontal polarization of light that receives the signals 18 and 19 and outputs signals 20 and 21; and

a polarization beam splitter cubic (PBS-3) with its fast axis aligned to a horizontal polarization state of light that receives signals 20 and 21 and outputs two pairs of differential signals, signals 22 and 24, and 23 and 25, that are orthogonal in both polarization and temporal phase.

2. The system of claim 1, further comprising:

a pair of optical delay lines and couplers that combine signal 23 with 24, and signal 22 with 25, producing a differential in-phase signal 26, and a differential quadrature signal 27, where signals 26 and 27 are time interleaved;

a pair of optical circulators and a second dispersion element (D2) that stretch the signals in time and direct them to output signals 28 and 29;

a balanced photodetector with a differential amplifier that produces output 30 containing time interleaved in-phase and quadrature analog signals in the electrical domain;

an analog-to-digital converter;

a digital signal processor configured for processing a digitized signal using a maximum ratio combining process that eliminates a dispersion penalty; and

a computer that analyzes the digital signal and provides a visualization of results.

3. The system of claim 1, wherein, starting from signals 22-25, the four signals 22-25 are delayed and interleaved in time such that they can be captured using a single spectrometer, optical delay stages Delay4, Delay5 and beam combiners OC1 and OC2 combine signal 23 with 24, and signals 22 with 25, producing differential in-phase signal 26, and differential quadrature signal 27;

wherein the system further comprises:

an optical delay stage delay6 that interleaves signal 27 relative to signal 26;

an optical combiner (OC3) that combines signal 26 and signal 27 together and produces time interleaved signal 28;

an optical diffractive grating that maps wavelength into space and produces signal 29;

a camera that records the diffracted optical beam and quantizes the signals into the digital domain and produces signal 30;

a digital signal processor configured for processing the digitized signal using a maximum ratio combining process to eliminate dispersion penalty; and

a computer that analyzes the digitized signal and provides a visualization of results.

4. The system of claim 1, wherein the pulsed optical source is configured with a supercontinuum source.

5. The system of claim 1, wherein the dispersion element (2) comprises a dispersive optical fiber that is selected from the group consisting of a fiber Bragg grating (FBG), a chromo-modal dispersion (CMD) device, a single-mode fiber (SMF), a dispersive compensating fiber (DCF), a Raman optical fiber with internal Raman amplification providing high dispersion combined with a net gain, and an arrayed wave-guide grating (AWG).

6. The system of claim 1, wherein an analog-to-digital converter (ADC) is configured to convert an electrical equivalent of a stretched optical source and which operates at a lower frequency than an input signal being captured.

7. The system of claim 1, further comprising programming executable on a processing device that performs high-speed time-domain analysis of terahertz signals.

8. The system of claim 1, wherein a machine learning process is trained and used to perform the signal processing.

9. The system of claim 1, further comprising programming executable on a processing device for performing high-speed spectroscopy of the terahertz signals.

10. The system of claim 1, further comprising programming executable on a processing device for performing high-speed inspection and quality testing of industrial materials.

11. The system of claim 1, further comprising programming executable on a processing device for performing high-speed quality inspection of pharmaceutical products.

12. The system of claim 1, further comprising programming executable on a processing device for performing high-speed inspection of packaged integrated circuits to spot counterfeit products.

13. The system of claim 1, further comprising programming executable on a processing device for performing high-speed imaging of biological tissues.

14. The system of claim 1, further comprising programming executable on a processing device for performing high-speed analysis of communication signals for terahertz burst-mode communications.

15. An apparatus for characterizing terahertz signals employing both differential detection for high sensitivity and, simultaneously, phase diversity for overcoming dispersion penalty, comprising:

a broadband optical pulse source that generates broadband pulses;

an optical power splitter that receives the broadband pulses from the said optical source and produces two channels: optical “O” (channel O) and terahertz “T” (channel T);

a dispersion element D1 that receives a same pulsed optical source from channel O to chirp an optical pulse and producing signal 1;

an antenna device that receives the optical pulse from the channel T and generates a burst of terahertz radiation in response;

a delay stage that receives the same pulsed optical source from channel O and provides a delay to the chirped optical pulse producing signal 1 so that the burst of terahertz radiation response and the chirped optical pulse overlap in time;

a device under test (DUT) that receives the burst of terahertz radiation response to produce a terahertz response signal that includes characteristics of the DUT;

a half wave plate (HWP-1) with a fast axis rotated by 22.5 degrees compared to a horizontal component of light polarization that receives the chirped optical pulse from the dispersive element D1;

an optical polarization beam splitter (PBS-2) that receives the chirped optical pulse from the HWP-1 and splits the chirped optical pulse into two orthogonal polarized signals, signal 3 and signal 4;

a pair of parabolic mirrors that combines the burst of terahertz radiation with the optical pulse, the signal 3, and directs them into an electro-optic crystal;

an electro-optic (EO) crystal that modulates light polarization in response to the electric field of the terahertz response signal producing signal 5;

a half wave plate (HWP-2) with a fast axis rotated by 22.5 degrees compared to a horizontal polarization that receives as inputs signal 4 and signal 5 and produces output signal 6 and signal 11;

a polarization beam splitter cube (PBS-2) with a fast axis aligned to a horizontal polarization state of light that receives the signal 6 and produces orthogonal polarization signals, signals 7 and signal 8;

a quarter wave plate (QWP-1) with a fast axis rotated by 45 degrees compared to a horizontal polarization of light that receives the signal 8 and generates an output that is reflected by a mirror and passes QWP-1 again producing signal 10;

a quarter wave plate (QWP-2) with a fast axis rotated by 45 degrees compared to a horizontal polarization of light that receives the signal 7 and generates an output that is reflected by a reflector and passes QWP-2 again producing signal 9;

wherein the HWP-2, PBS-2, QWP-2, QWP-2 and reflector perform functions on the signal 4 and add the signal 4 with correct polarization to the output signals 17 and 18;

a half wave plate (HWP-3) with its fast axis rotated by 22.5 degrees compared to a horizontal polarization of light that receives the signals 16 and 17 and outputs signals 18 and 19;

a quarter wave plate (QWP-3) with its fast axis aligned to a horizontal polarization of light that receives signals 18 and 19 and outputs signals 20 and 21; and

a polarization beam splitter cubic (PBS-3) with a fast axis aligned to a horizontal polarization state of light that receives signals 20 and 21 and outputs two pairs of differential signals that are orthogonal in both polarization and temporal phase: signal 22 and signal 24, and signal 23 and signal 25.

16. The apparatus of claim 15, further comprising:

a pair of optical delay lines and couplers that combine signal 23 with signal 24, and signal 22 with signal 25, producing a differential in-phase signal 26, and a differential quadrature signal 27, where signal 26 and signal 27 are time interleaved;

a pair of optical circulators and a second dispersion element D2 that stretch the signals in time and direct them to output signal 28 and signal 29;

a balanced photodetector with a differential amplifier that produces output signal 30 comprising time interleaved in-phase and quadrature analog signals in the electrical domain;

an analog-to-digital converter that generates a digitized signal;

a digital signal processor configured to process the digitized signal using a maximum ratio combining process to eliminate dispersion penalty; and

at least one computer that analyzes the digitized signal and provides a visualization of results.

17. The apparatus of claim 15, wherein, starting from signals 22-25, the four signals 22-25 are delayed and interleaved in time such and captured using a spectrometer, wherein optical delay stages Delay4, Delay5 and beam combiners OC1 and OC2 combine signal 23 with signal 24, and signal 22 with signal 25, producing a differential in-phase signal 26, and a differential quadrature signal 27;

wherein the system further comprises:

an optical delay stage (delay6) that interleaves signal 27 relative to signal 26;

an optical combiner (OC3) that combines signal 26 and signal 27 together and produces time interleaved signal 28;

an optical diffractive grating that maps the wavelength into space and produces signal 29;

a camera that records the diffracted optical beam and quantizes the signals into the digital domain and generates signal 30;

a digital signal processor processes the digitized signal using a maximum ratio combining process to eliminate dispersion penalty; and

at least one computer processes the digitized signal and provides a visualization of results.

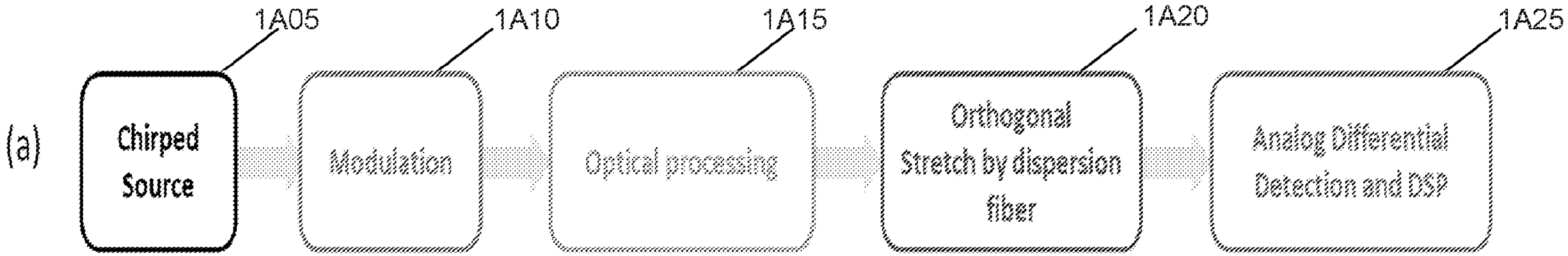

(a)
1A05
Chirped Source
1A10
Modulation
1A15
Optical processing
1A20
Orthogonal Stretch by dispersion fiber
1A25
Analog Differential Detection and DSP

FIG. 1A

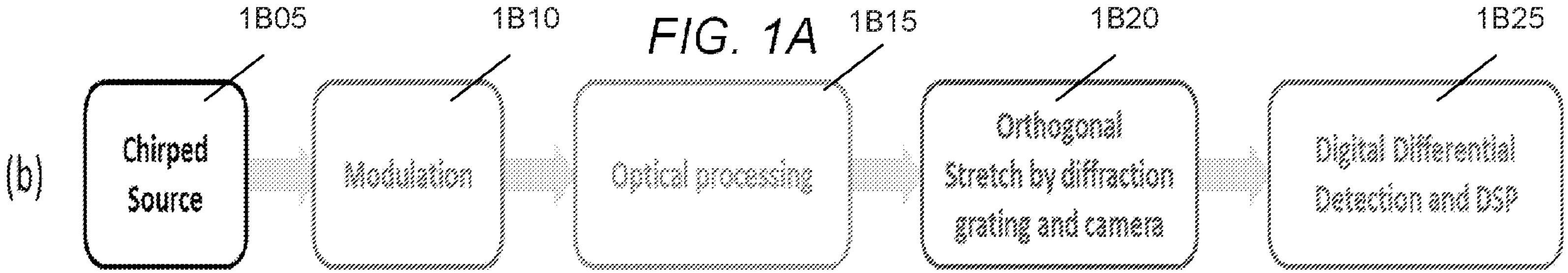

(b)
1B05
Chirped Source
1B10
Modulation
1B15
Optical processing
1B20
Orthogonal Stretch by diffraction grating and camera
1B25
Digital Differential Detection and DSP

FIG. 1B

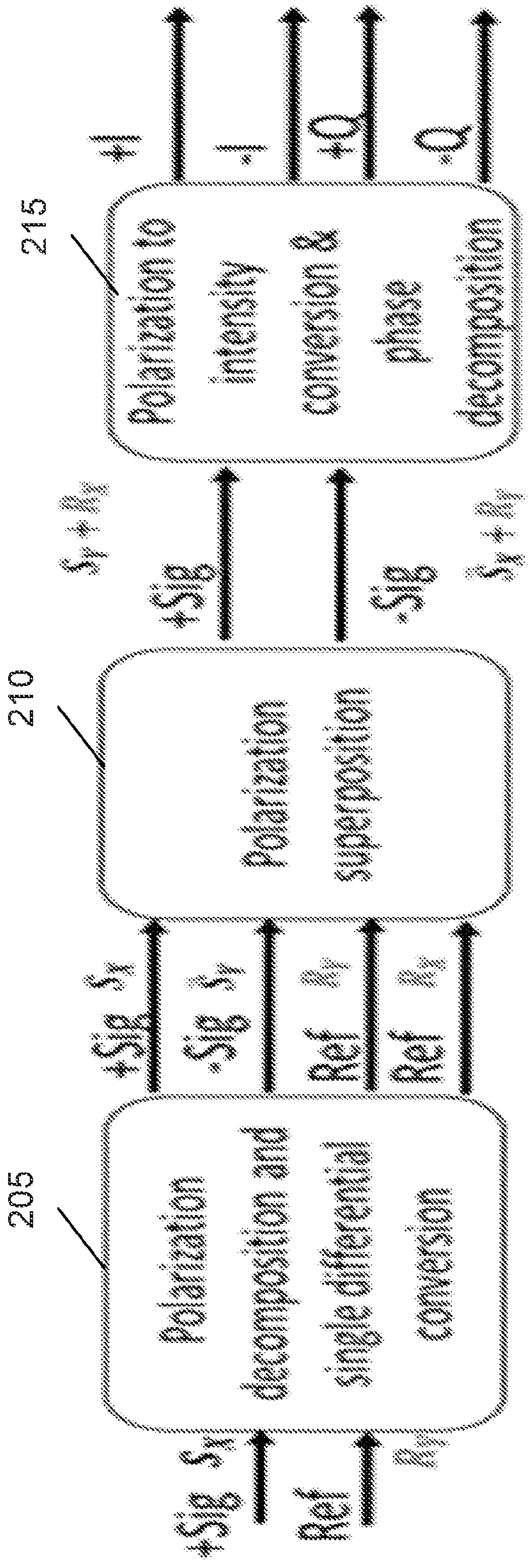
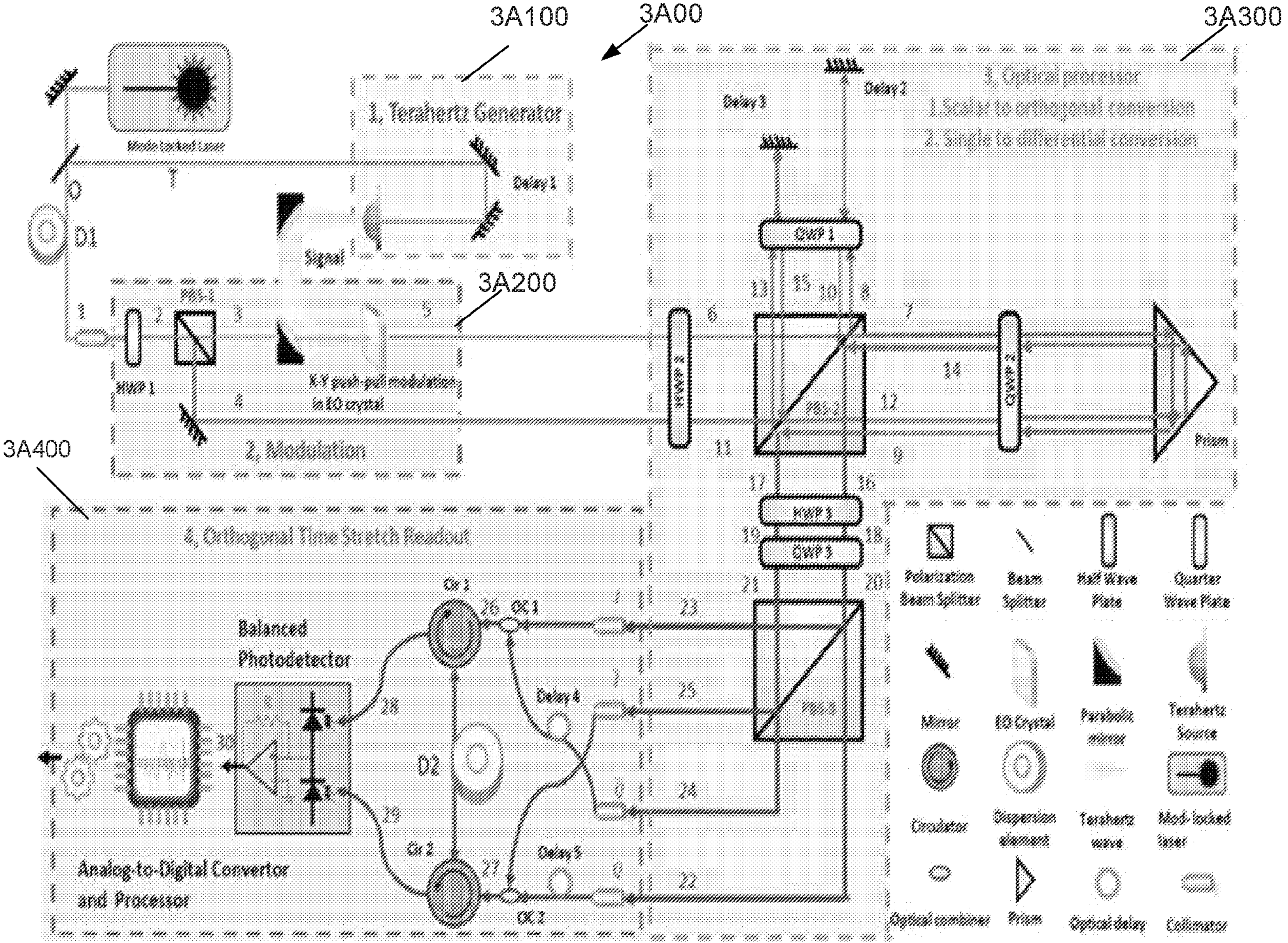

205
Polarization decomposition and single differential conversion
210
Polarization superposition
215
Polarization to intensity conversion & phase decomposition
+Sig S_x
Ref R_y
+Sig S_x
-Sig S_y
Ref R_y
Ref R_x
+Sig $S_y + R_y$
-Sig $S_x + R_x$
+I
-I
+Q
-Q

FIG. 2



3A100
3A00
3A300
3A200
3A400
Mode Locked Laser
1, Terahertz Generator
Delay 1
Signal
D1
0
1
2
3
4
5
HWP 1
PBS 1
X-Y push-pull modulation in EO crystal
2, Modulation
3, Optical processor
1.Scalar to orthogonal conversion
2. Single to differential conversion
Delay 3
Delay 2
QWP 1
HWP 2
QWP 2
PBS 2
PBS 3
HWP 3
QWP 3
Prism
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
4, Orthogonal Time Stretch Readout
Balanced Photodetector
Cir 1
Cir 2
OC 1
OC 2
Delay 4
Delay 5
D2
26
27
28
29
30
Analog-to-Digital Convertor and Processor
Polarization Beam Splitter
Beam Splitter
Half Wave Plate
Quarter Wave Plate
Mirror
EO Crystal
Parabolic mirror
Terahertz Source
Circulator
Dispersion element
Terahertz wave
Mod-locked laser
Optical combiner
Prism
Optical delay
Collimator

FIG. 3A

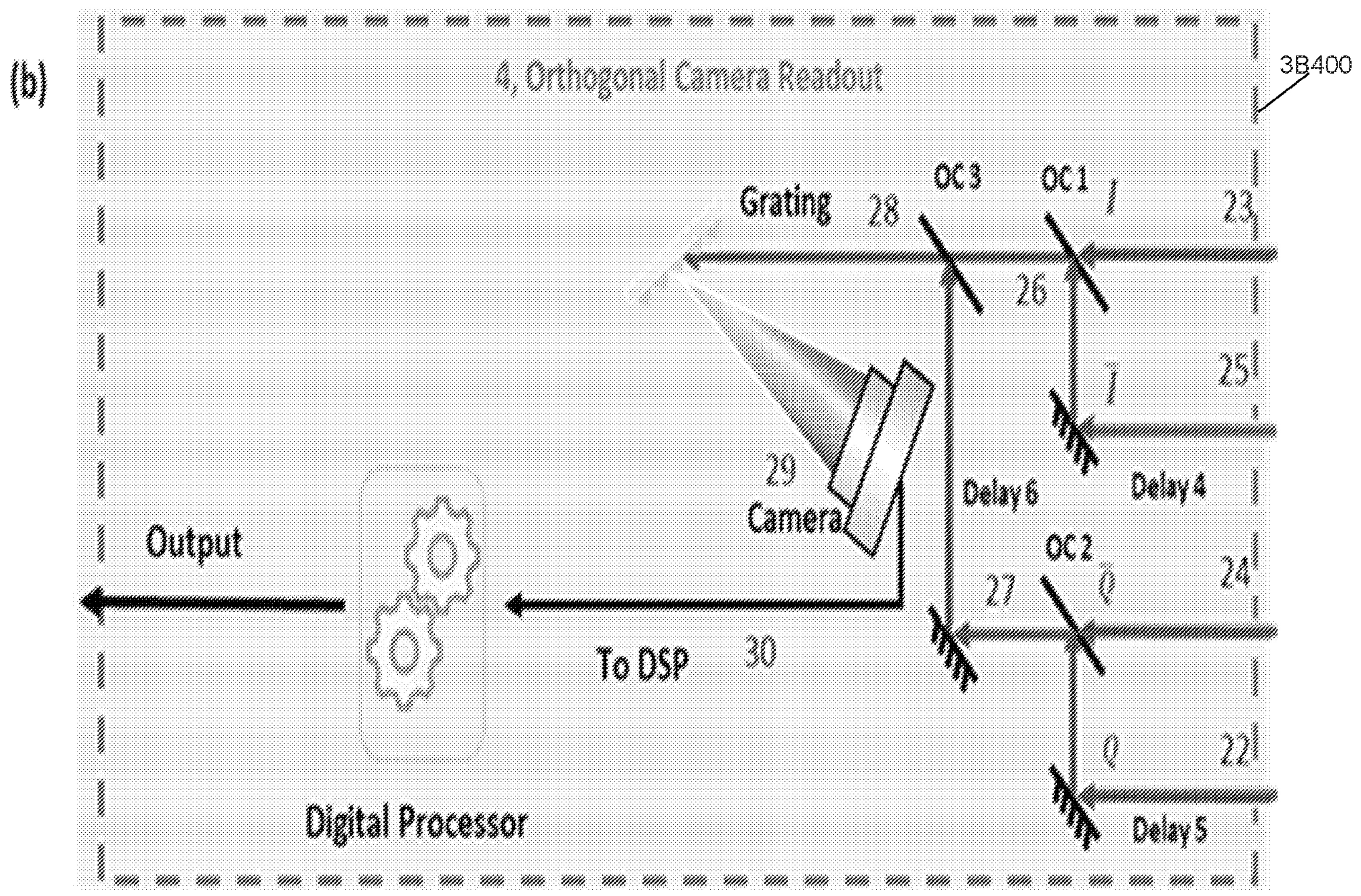

(b)
4, Orthogonal Camera Readout
3B400
Grating
28
OC 3
OC 1
1
23
26
25
1
29
Camera
Delay 6
Delay 4
OC 2
0
24
27
Output
To DSP
30
0
22
Digital Processor
Delay 5

FIG. 3B

Parameter Name	Value	Unit
Optical center wavelength	193.1	THz
Optical pulse width	48.83	fs
Peak optical power	1.5e4	W
Repetition rate	19.53	MHz
Average optical power after D1	25	mw
Length of dispersion fiber D1	0.01	km
Length of dispersion fiber D2	2	km
Nonlinear Coefficient	0.79	W/km
Dispersion of fibers	18	s/m^2
Dispersion slope of fibers	0.092e3	s/m^3
Bandwidth of optical filter	100	nm
Responsivity of photodetectors	0.6	A/W
Transimpedance gain	2000	Ohms
Resolution of ADC	8	bit
Sampling rate of ADC	100	GS/s

FIG. 4A

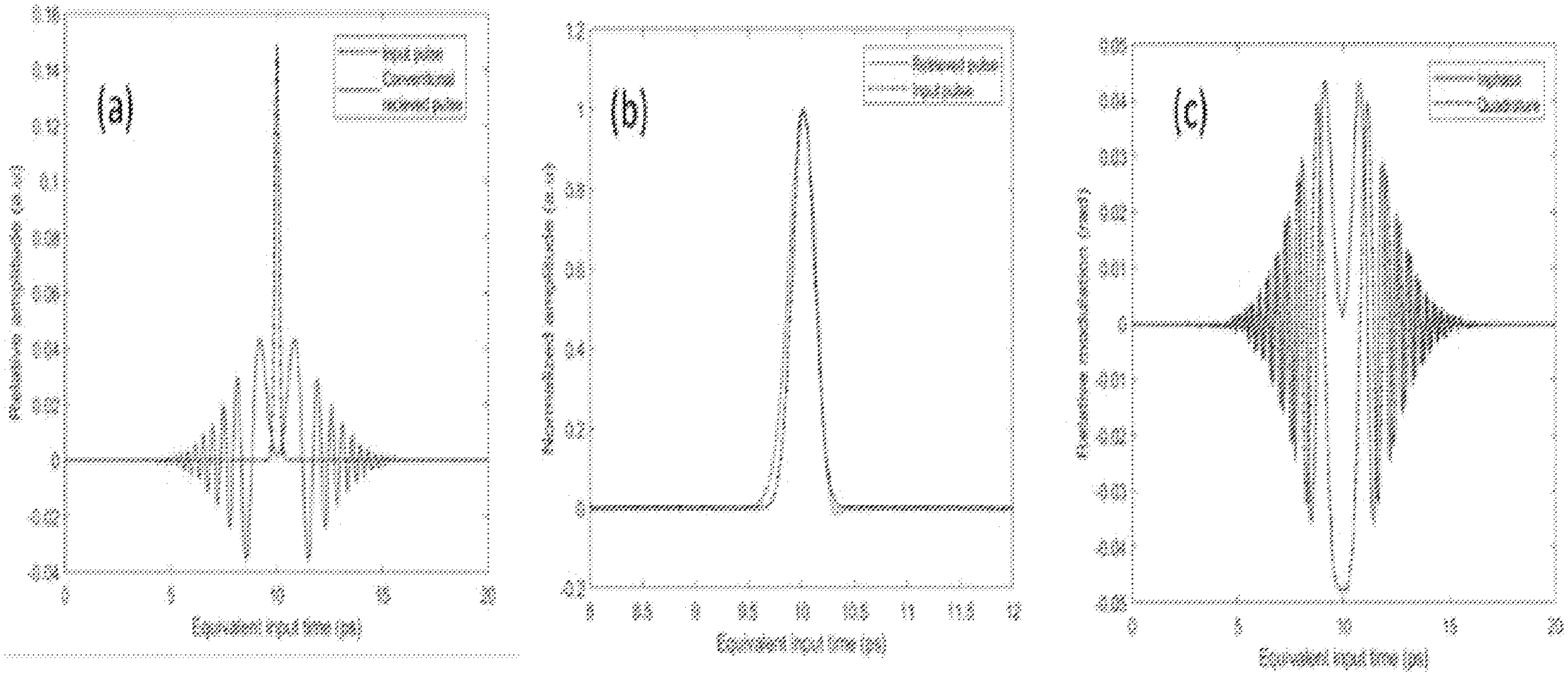

(a)
Input pulse
Conventional
Tailored pulse
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
5
10
15
20
Equivalent input time (ps)
(b)
Tailored pulse
Input pulse
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
9
9.5
10
10.5
11
11.5
12
Equivalent input time (ps)
(c)
Inphase
Quadrature
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
0
5
10
15
20
Equivalent input time (ps)

FIG. 4B

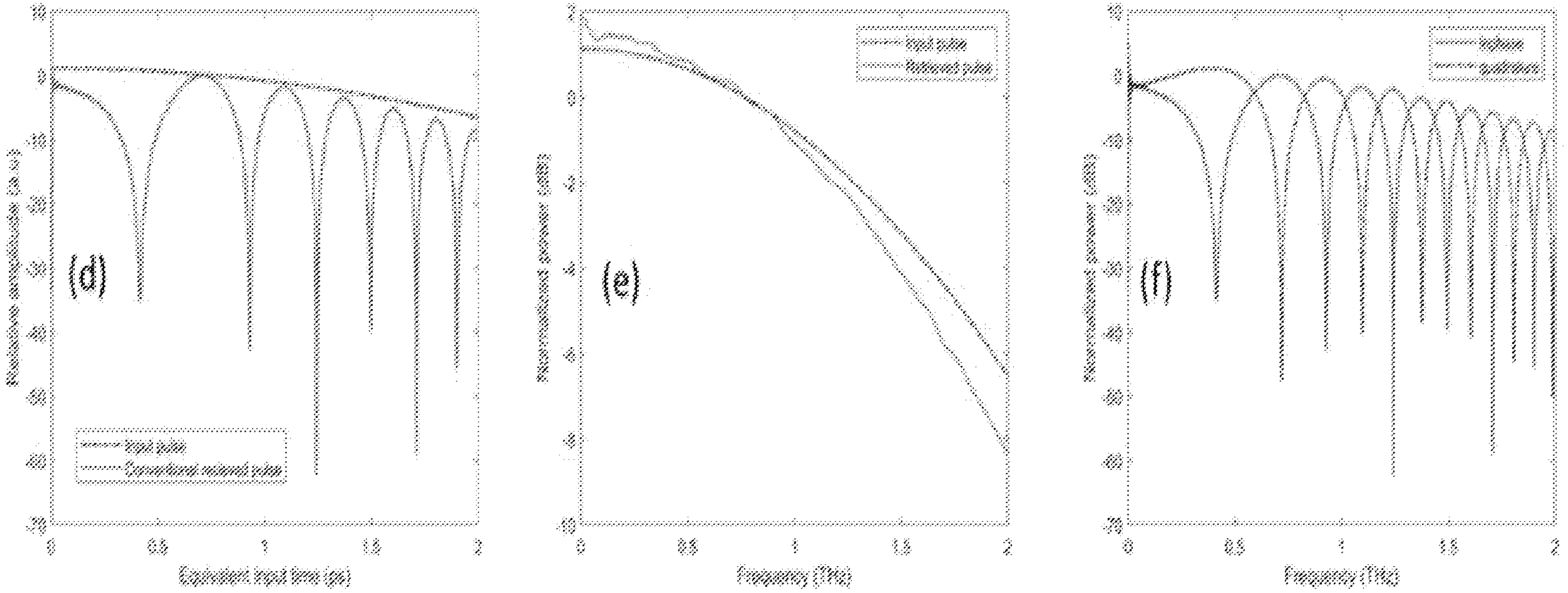

(d)
10
0
-10
-20
-30
-40
-50
-60
-70
0
0.5
1
1.5
2
Input pulse
Equivalent input time (ps)
(e)
2
0
-2
-4
-6
-8
-10
0
0.5
1
1.5
2
Input pulse
Reflected pulse
Normalized power (dB)
Frequency (THz)
(f)
10
0
-10
-20
-30
-40
-50
-60
-70
0
0.5
1
1.5
2
Normalized power (dB)
Frequency (THz)

FIG. 4C

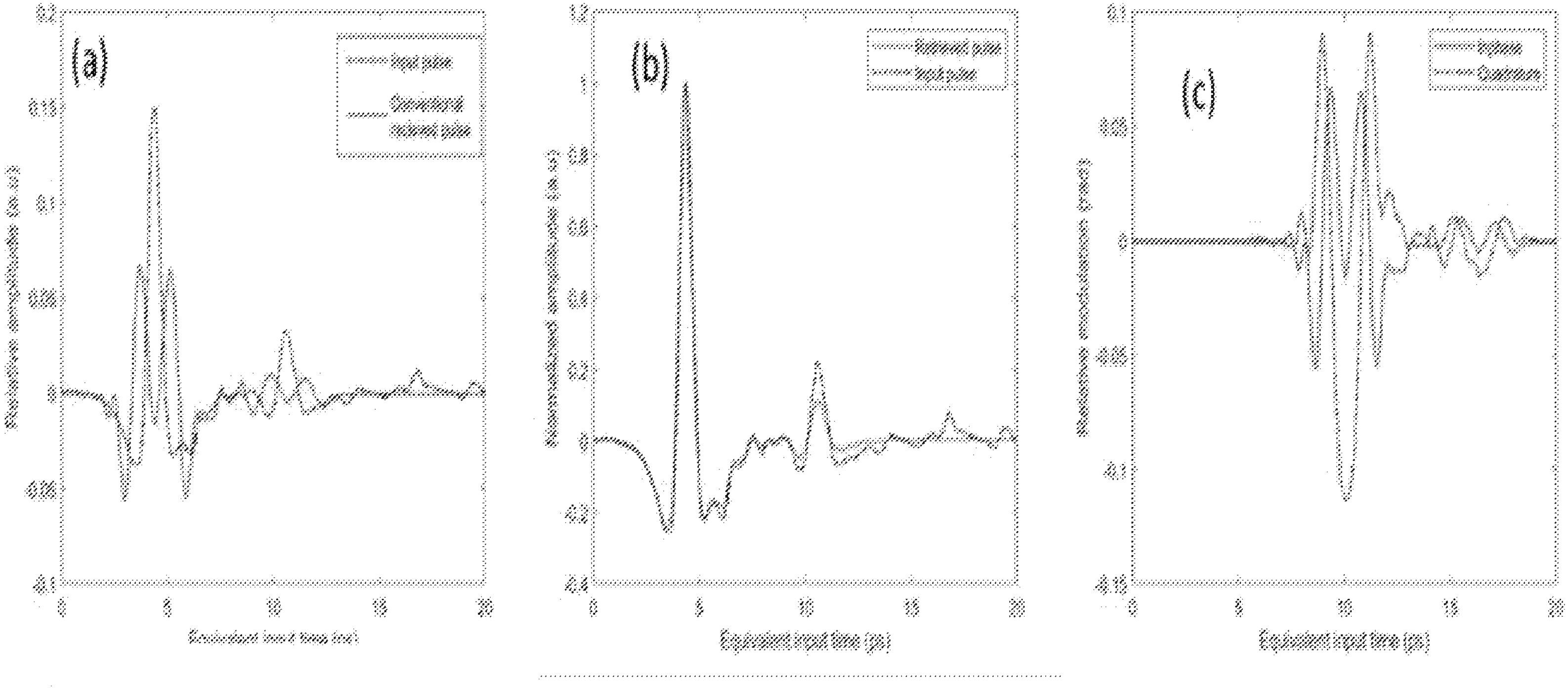

(a)
Input pulse
Conventional received pulse
Relative amplitude (a.u)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
Equivalent input time (ps)
(b)
Retrieved pulse
Input pulse
Normalized amplitude (a.u)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
Equivalent input time (ps)
(c)
Inphase
Quadrature
Relative modulation (rad)
0.1
0.05
0
-0.05
-0.1
-0.15
0
5
10
15
20
Equivalent input time (ps)

FIG. 5A

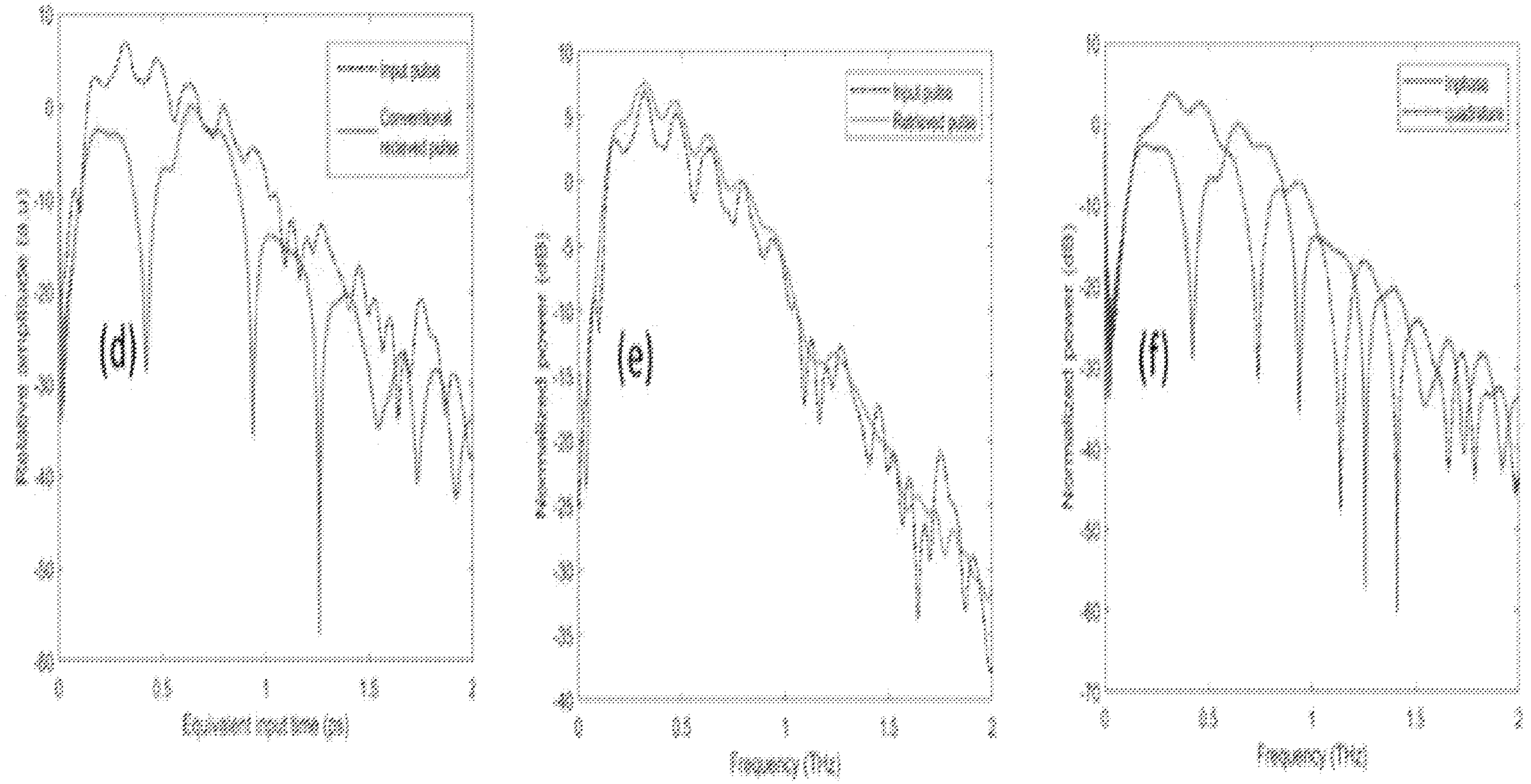

(d)
Input pulse
Conventional recieved pulse
Relative amplitude (a.u.)
Equivalent input time (ps)
0
0.5
1
1.5
2
(e)
Input pulse
Retrieved pulse
Normalized power (dB)
Frequency (THz)
(f)
Inphase
quadrature
Normalized power (dB)
Frequency (THz)

FIG. 5B

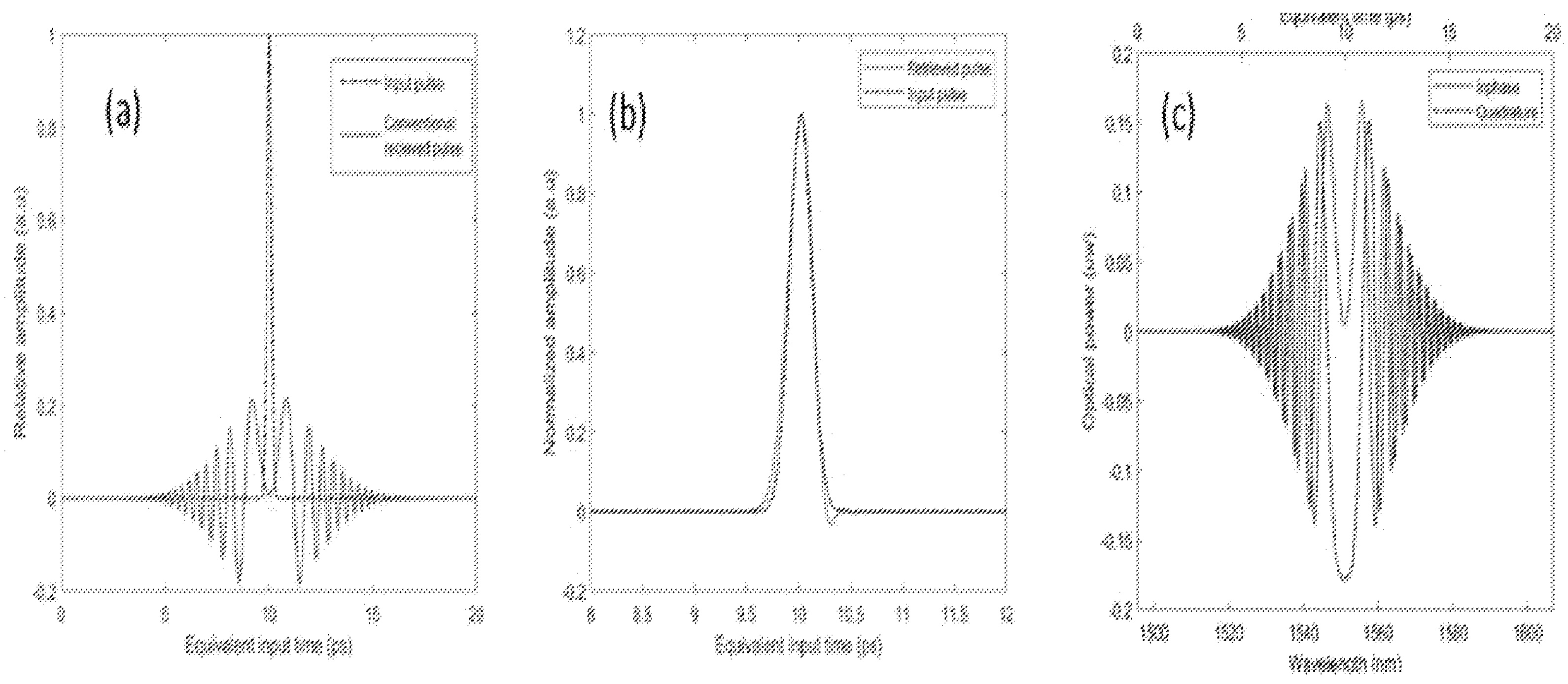

(a)
Input pulse
Conventional stretched pulse
Photodiode amplitude (a.u.)
Equivalent input time (ps)
1
0.8
0.6
0.4
0.2
0
-0.2
0
5
10
15
20
(b)
Retrieved pulse
Input pulse
Normalized amplitude (a.u.)
Equivalent input time (ps)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
8
8.5
9
9.5
10
10.5
11
11.5
12
(c)
In-phase
Quadrature
Optical power (mW)
Equivalent time (ps)
Wavelength (nm)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
5
10
15
20
1500
1520
1540
1560
1580
1600

FIG. 6A

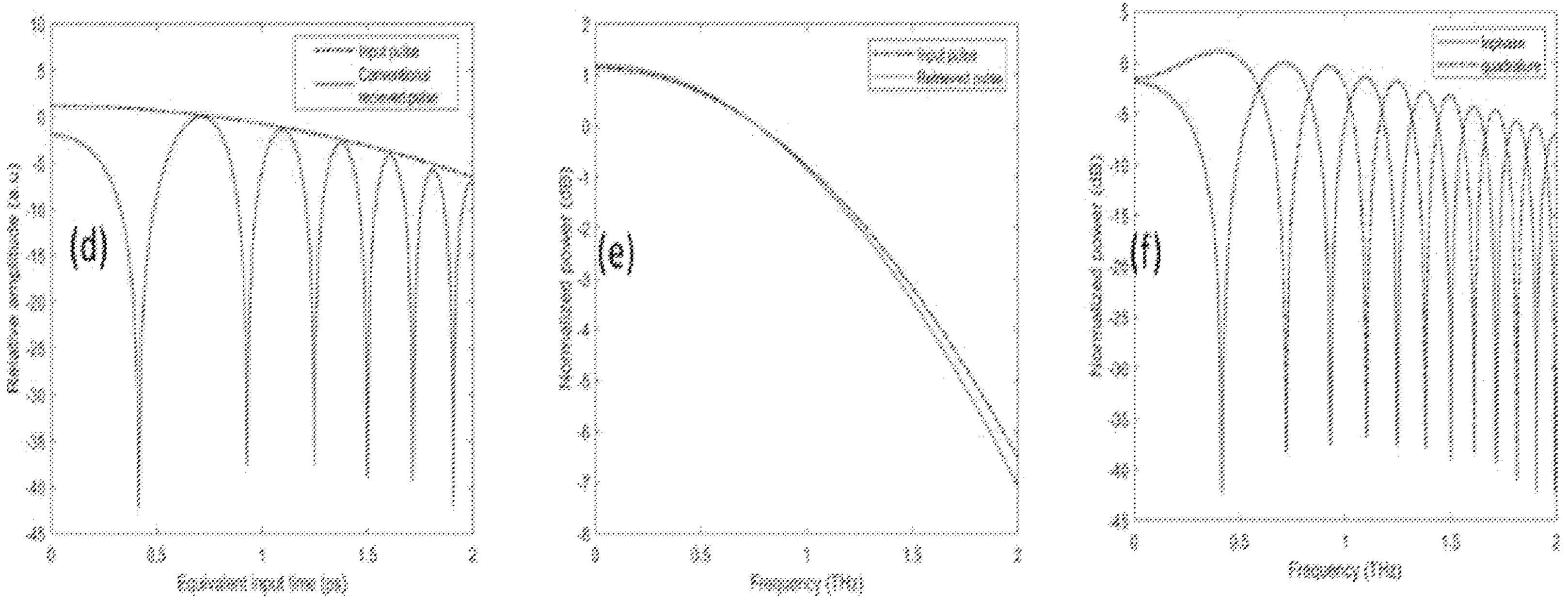

(d)
Relative amplitude (a.u.)
Equivalent input time (ps)
Input pulse
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
0
0.5
1
1.5
2
(e)
Normalized power (dB)
Frequency (THz)
Input pulse
Retrieved pulse
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0
0.5
1
1.5
2
(f)
Normalized power (dB)
Frequency (THz)
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
0
0.5
1
1.5
2

FIG. 6B

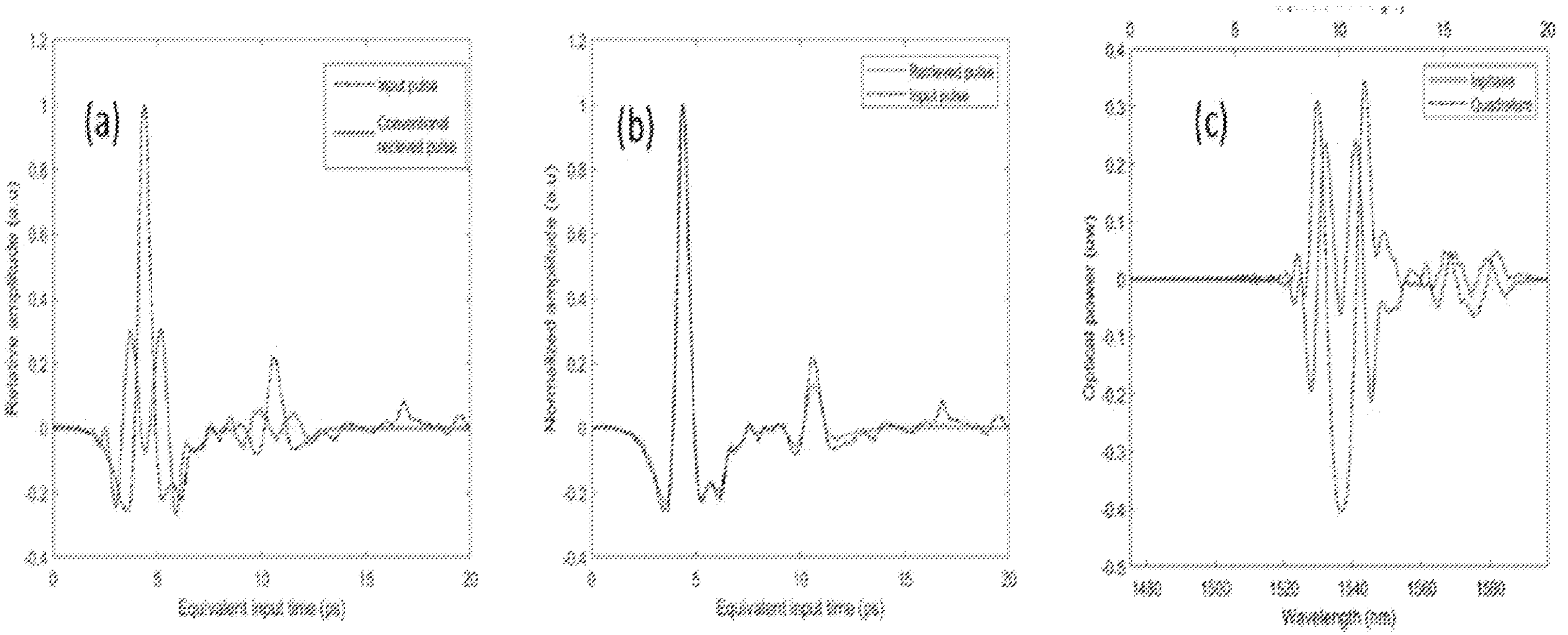

(a)
Input pulse
Convolved output pulse
Relative amplitude (a.u.)
Equivalent input time (ps)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
(b)
Retrieved pulse
Input pulse
Normalized amplitude (a.u.)
Equivalent input time (ps)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
(c)
In-phase
Quadrature
Optical power (a.u.)
Wavelength (nm)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
1480
1500
1520
1540
1560
1580
0
5
10
15
20

FIG. 7A

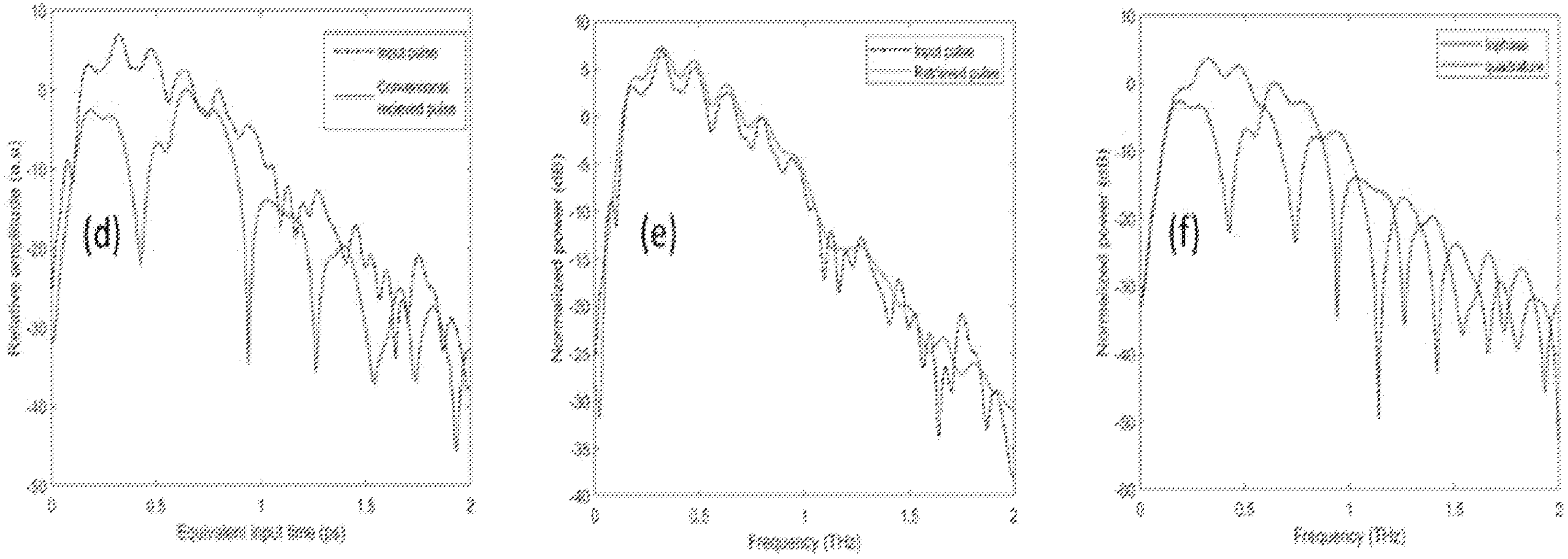

(d)
Relative amplitude (a.u)
Equivalent input time (ps)
Input pulse
Conventional relaxed pulse
10
0
-10
-20
-30
-40
-50
0
0.5
1
1.5
2
(e)
Normalized power (dB)
Frequency (THz)
Input pulse
Retrieved pulse
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
0
0.5
1
1.5
2
(f)
Normalized power (dB)
Frequency (THz)
Inphase
quadrature
10
0
-10
-20
-30
-40
-50
-60
0
0.5
1
1.5
2

FIG. 7B

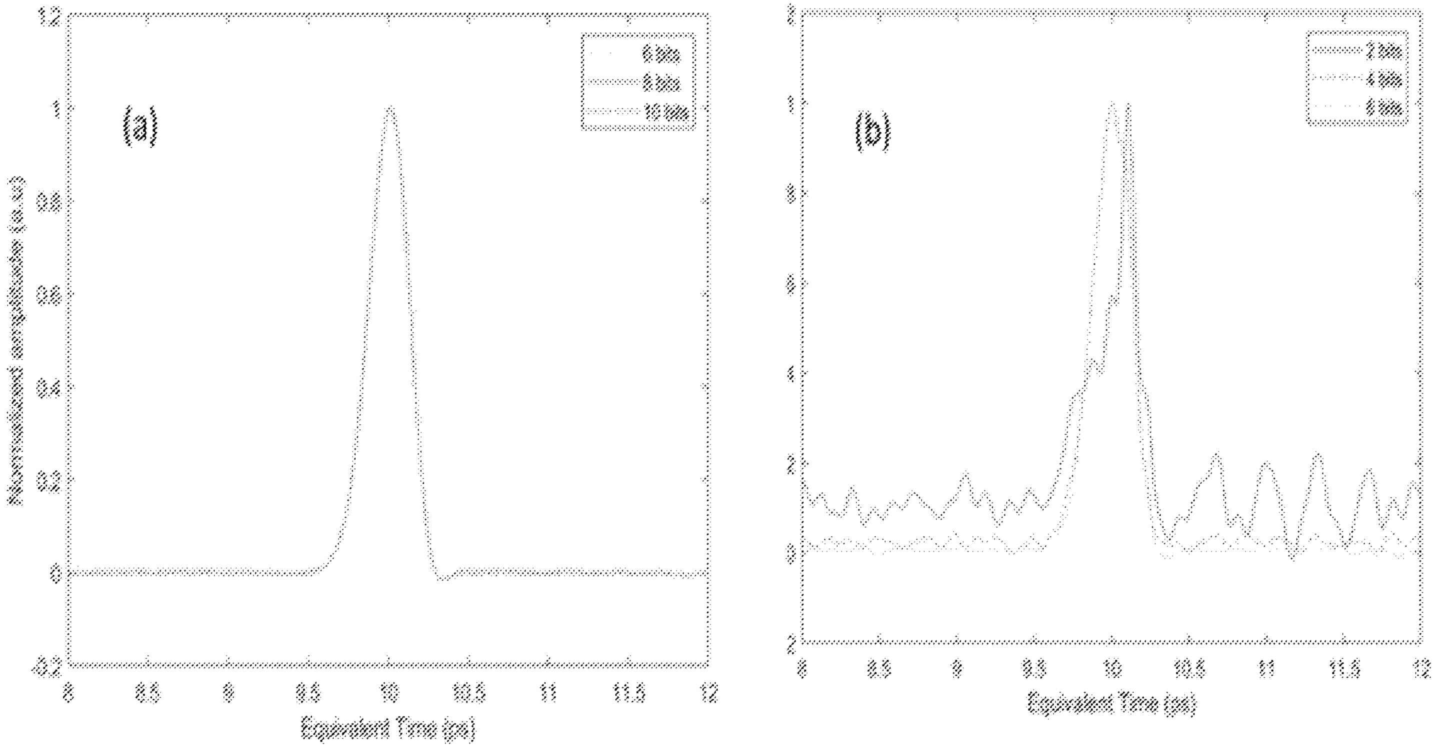

(a)
6 bits
8 bits
10 bits
Normalized amplitude (a.u.)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
8
8.5
9
9.5
10
10.5
11
11.5
12
Equivalent Time (ps)
(b)
2 bits
4 bits
6 bits
2
1
8
6
4
2
0
2
8
8.5
9
9.5
10
10.5
11
11.5
12
Equivalent Time (ps)

FIG. 8

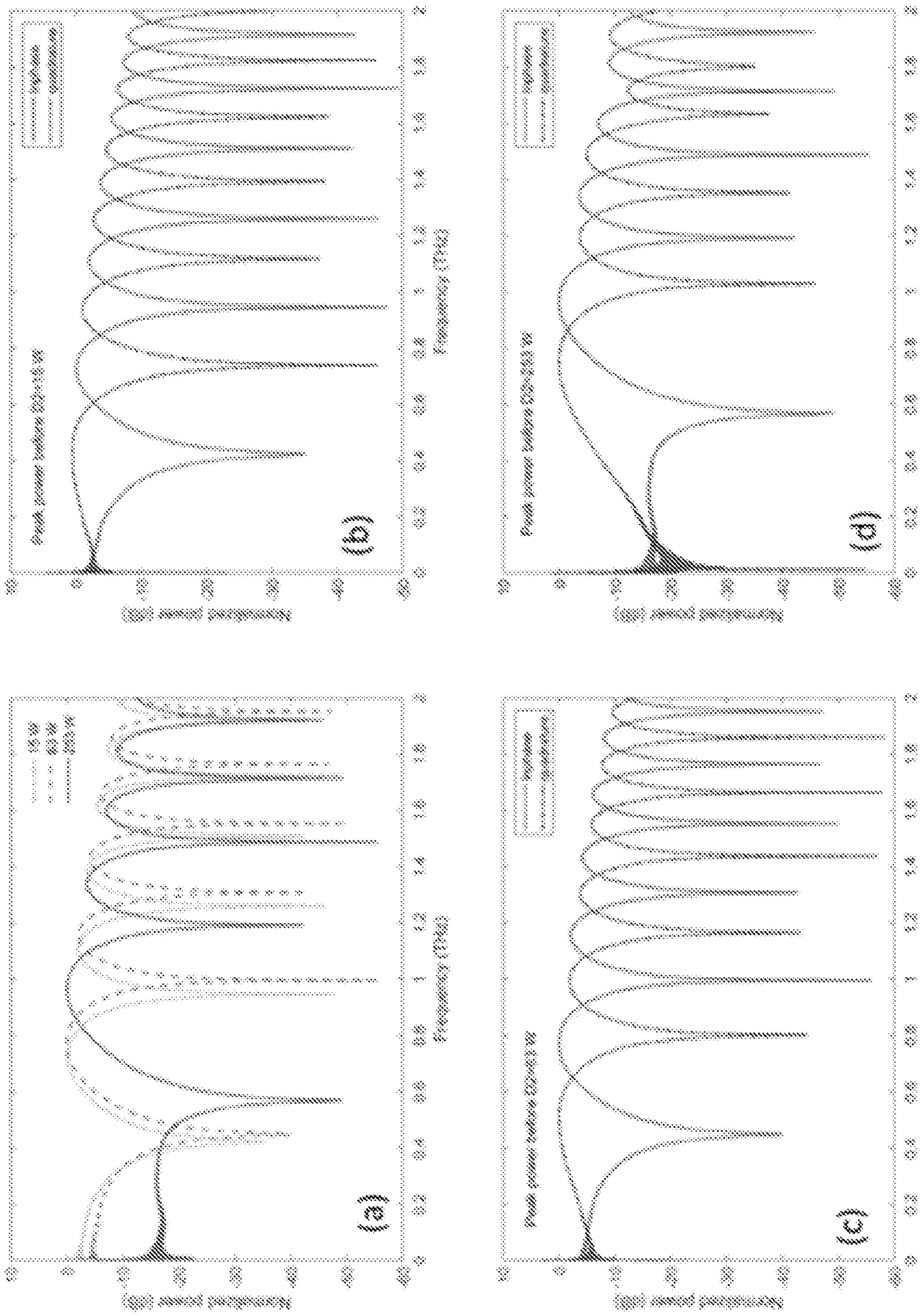

(a)
(b)
(c)
(d)
Frequency (THz)
Normalized power (dB)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

FIG. 9

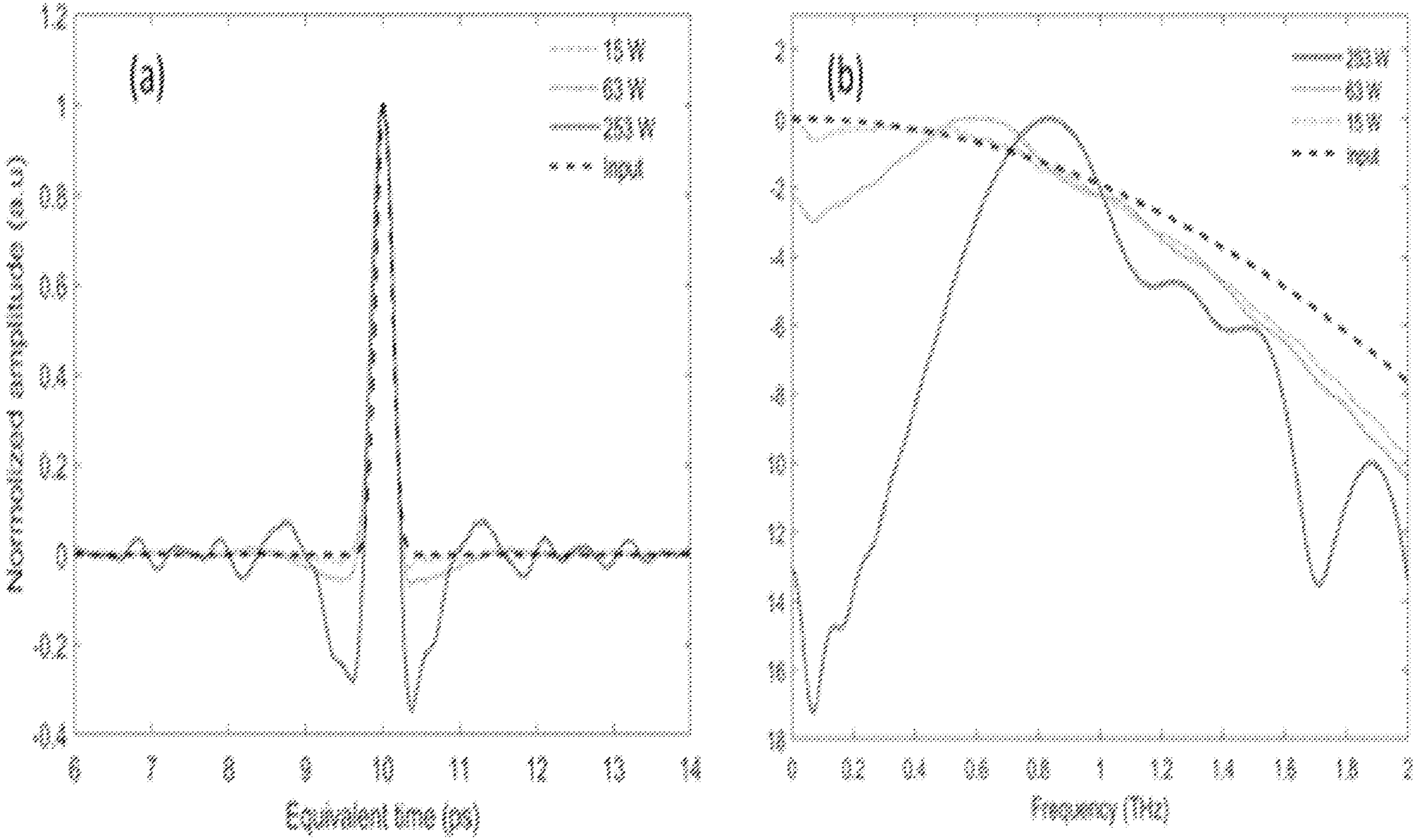

(a)
Normalized amplitude (a.u)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
6
7
8
9
10
11
12
13
14
Equivalent time (ps)
15 W
63 W
253 W
Input
(b)
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Frequency (THz)
253 W
63 W
15 W
Input

FIG. 10

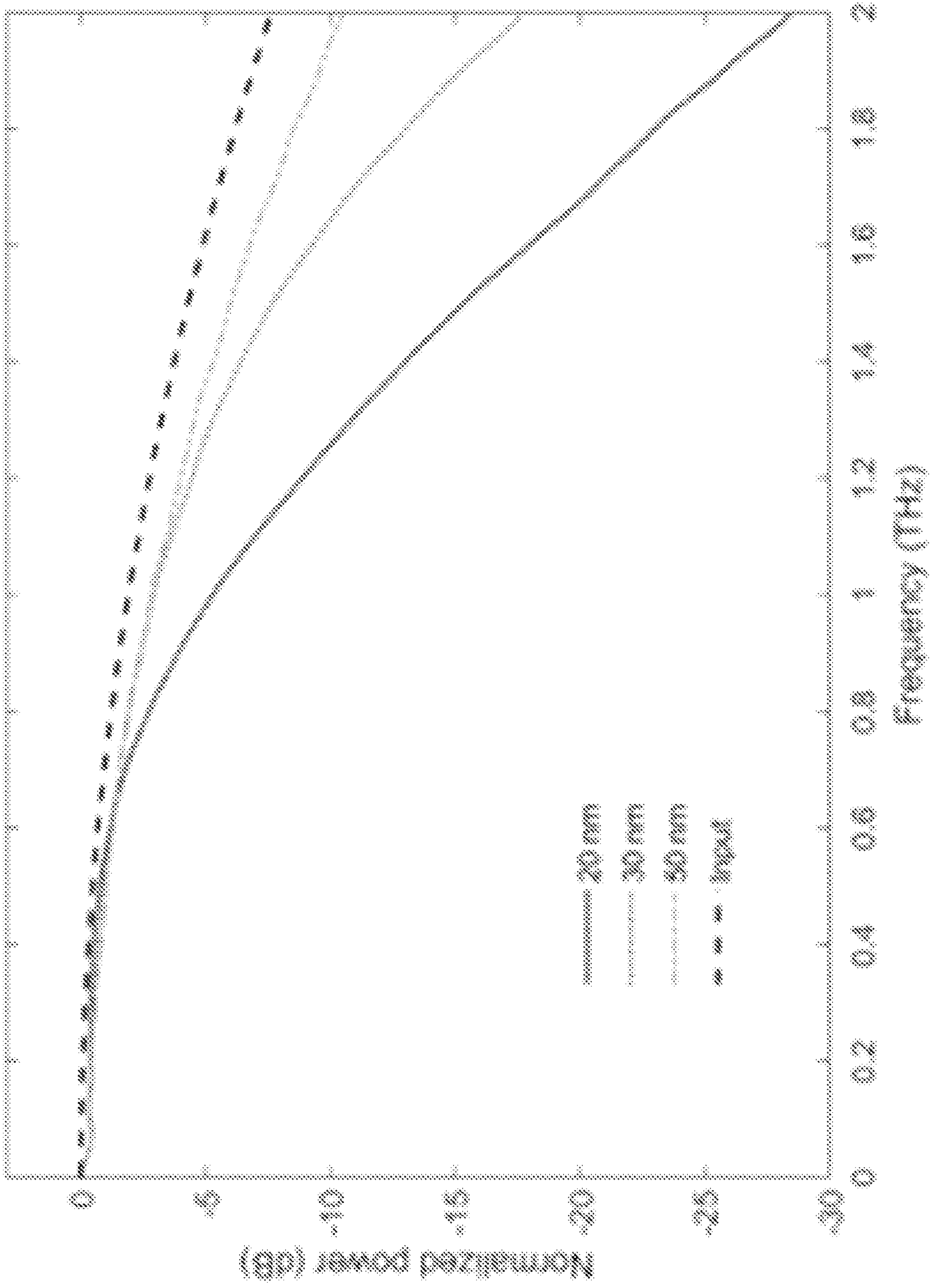

Normalized power (dB)
0
-5
-10
-15
-20
-25
-30
Frequency (THz)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
20 nm
30 nm
50 nm
Input

FIG. 11