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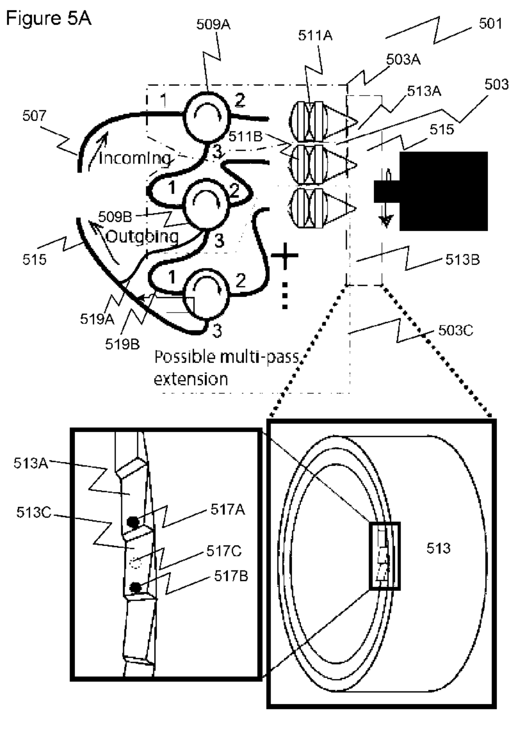
Figure 5A



(57) Abstract: An optical delay line system comprising: a plurality of cascading delay lines adapted for use in an optical system, wherein a first cascading delay line of at least two of the plurality of cascading delay lines is arranged to: direct the first optical signal towards a first optical delay element; and receive a second optical signal, wherein the second optical signal is a version of the first optical signal that has acquired a first time-dependent optical delay introduced by the first optical delay element; wherein a second cascading delay line of at least two of the plurality of cascading delay lines is arranged to: direct the second optical signal towards a second optical delay element; and receive a third optical signal, wherein the third optical signal is a version of the second optical signal that has acquired a second time-dependent optical delay introduced by the second optical delay element, and direct the third optical signal to either a further cascading delay line of the plurality of cascading delay lines or to the optical system.

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IMPROVEMENTS IN OPTICAL DELAY LINES

Technical Field

[0001] The present invention relates generally to improvements in optical delay lines. In particular, the present invention relates to an optical delay system and method of controlling optical delay in an optical delay line system.

Background

[0002] Optical delay lines are utilised in systems for measuring laser pulses and for imaging. High speed temporal optical delay lines are widely used in many optical systems, including, for example in systems that utilise ultrafast pulse measurement, Doppler phase shifting and optical coherence tomography.

[0003] Previous approaches have employed resonant fibre stretchers to achieve 18 mm delays with a repetition rate of 2 kHz, electro optical modulators combined with dispersion in fibres to reach delays of ~ 10 mm with repetition rates of 500 MHz or arrays of mirrors mounted on a fast spinning motor (2.45 mm scanning range at 4 kHz repetition rate). While electro-optic modulators are able to deliver the scan depth and ultra-high scan rates desirable for time domain optical coherence tomography (OCT), they are very expensive and also require arm length matching of potentially very long fibres for them to be employed in such systems. The same is true for the resonant fibre stretchers, which, while cheaper, in turn only deliver scan rates of up to 2 kHz.

[0004] Basic linear optical delay lines provide high accuracy, but are limited to relatively low repetition rates (100s of Hz).

[0005] Rotating optical delay lines, on the other hand, achieve much higher speeds. There are two classes of rotating delay lines including small angle tilted mirrors and multi-facet rotating mirrors.

[0006] Small tilt mirrors generate high repetition rates, however these scanners have a low duty cycle and poor linearity.

[0007] Multi-facet mirror scanners using cube mirrors or mirror arrays operate with higher duty cycle (single direction) and linearity at a lower repetition rate. Although mirror arrays achieve high repetition rates of a few kHz accompanied by high linearity, they remain bulky, requiring high torque motors to drive them. Repetition rates in rotating mirror scanners are ultimately limited by the size of the mirror, which dictates the number of facets (n) covering a given circumference (2πr). However, smaller mirrors also have limited scan depth and repetition rates.

[0008] One example of a use of a high speed delay line is in video rate optical coherence tomography that is an established clinical imaging technique in the field of ophthalmology [16] and optical biopsy. The limiting factor for video rate time domain (TD) OCT is the scan rate of the delay line that had previously reached a few kHz. For spectral domain (SD) or Fourier domain (FD) OCT, the speed depends largely on the sweeping frequency of a swept source laser and frame rate of line charged coupled device (CCD) capable of reaching hundreds of kHz scan rates. Current commercial SD OCT systems based on swept sources generally operate between 4 to 400 kHz. Even the most sophisticated approaches so far using mirror arrays are only able to deliver 4 kHz scan rates, which is considered too low for video rate time domain OCT systems.

Summary

[0009] It is an object of the present invention to substantially overcome, or at least ameliorate, one or more disadvantages of existing optical delay line arrangements.

[0010] Disclosed are arrangements which seek to address the above problems by providing scan rate and scan depth (i.e. temporal) scalability for optical delay systems by using a cascading optical delay system with multiple passes through an optical delay element.

[0011] Exploiting the scalability of the scan rate and scan depth provides a dynamic delay line that outperforms previously known optical delay line systems.

[0012] According to a first aspect of the present disclosure, there is provided a method for ultra-fast optical delay modulation with a repetition rate of up to 41 kHz while maintaining high linearity and duty cycle.

[0013] According to a second aspect of the present disclosure, there is provided a method for further improving the scan rate or scan depth of the optical delay line system by cascading multiple reflections or transmissions of optical beams, or spatially controlling reflections or transmissions of optical beams, directed to and received from one or more optical delay elements (e.g. on a rotating phase plate) as per the methods and systems disclosed herein.

[0014] According to another aspect of the present disclosure, there is provided an apparatus or system for implementing any one of the aforementioned methods.

[0015] According to another aspect of the present disclosure, there is provided a computer program product including a computer readable medium having recorded thereon a computer program for implementing any one of the methods described herein.

[0016] According to a further aspect, the present disclosure provides an optical delay line system comprising: a plurality of cascading delay lines adapted for use in an optical system, wherein a first cascading delay line of at least two of the plurality of cascading delay lines is arranged to: direct the first optical signal towards a first optical delay element; and receive a second optical signal, wherein the second optical signal is a version of the first optical signal that has acquired a first time-dependent optical delay introduced by the first optical delay element; wherein a second cascading delay line of at least two of the plurality of cascading delay lines is arranged to: direct the second optical signal towards a second optical delay element; and receive a third optical signal, wherein the third optical signal is a version of the second optical signal that has acquired a second time-dependent optical delay introduced by the second optical delay element, and direct the third optical signal to either a further cascading delay line of the plurality of cascading delay lines or to the optical system.

[0017] According to yet a further aspect, the present disclosure provides a method of controlling optical delay in an optical delay line system for use in an optical system, the method comprising the steps of: receiving a first optical signal from an optical system; directing the first optical signal towards a first optical delay element, receiving a second optical signal, wherein the second optical signal is a version of the first optical signal that has acquired a first time-dependent optical delay introduced by the first optical delay element; directing the second optical signal towards a second optical delay element; receiving a third optical signal, wherein the third optical signal is a version of the second optical signal that has acquired a second time-dependent optical delay introduced by the second optical delay element and directing the third optical signal towards a further optical delay element or the optical system.

[0018] Other aspects are also disclosed.

Brief Description of the Drawings

[0019] At least one embodiment of the present invention will now be described with reference to the drawings and appendices, in which:

[0020] Figs. 1A and 1B form a schematic block diagram of a general purpose computer system upon which arrangements described can be practiced;

[0021] Fig 2 depicts a process according to an embodiment of the present invention;

[0022] Figs 3A to 3D depict a spiral phase plate, intensity distribution obtained by reflecting a Gaussian laser beam off this phase plate resulting in a Laguerre-Gaussian beam, a segment (element) of the phase plate and low coherence interference fringes obtained from using the phase plate as a delay line respectively;

[0023] Fig 4A depicts a Gaussian beam on top of a 4-sector spiral phase plate, with an example of a Laguerre Gaussian Beam which can be obtained by reflecting a Gaussian beam off a spiral phase plate at the bottom;

[0024] Figs 4B to 4G depict synchronous and asynchronous modes of operation according to embodiments of the present invention;

[0025] Fig 5A shows an optical delay line system according to an embodiment of the present invention;

[0026] Fig 5B shows an optical coherence tomography system with the optical delay line system of Fig 5A according to an embodiment of the present invention;

[0027] Figs 6A-6F show various results of an optical delay line system operating in synchronous and asynchronous modes according to embodiments of the present invention;

[0028] Figs 7A and 7B show the results of a video rate OCT imaging scan according to an embodiment of the present invention;

[0029] Figs 8A-8D show the results of a further scan according to an embodiment of the present invention;

[0030] Fig 9 shows a transmissive rotating phase plate used with optical delay lines in accordance with an embodiment of the present invention;

[0031] Figures 10A and 10B show examples of a linear optical delay element transport system used with optical delay lines in accordance with embodiments of the present invention;

Detailed Description including Best Mode

[0032] Where reference is made in any one or more of the accompanying drawings to steps and/or features, which have the same reference numerals, those steps and/or features have for the purposes of this description the same function(s) or operation(s), unless the contrary intention appears.

[0033] It is to be noted that the discussions contained in the "Background" section and that above relating to prior art arrangements relate to discussions of documents which form public knowledge through their respective publication. Such should not be interpreted as a representation by the present inventor(s) or the patent applicant that such documents in any way form part of the common general knowledge in the art.

Computer Description

[0034] Figs. 1A and 1B depict a general-purpose computer system 1300, upon which the various arrangements described can be practiced.

[0035] As seen in Fig. 1A, the computer system 1300 includes: a computer module 1301; input devices such as a keyboard 1302, a mouse pointer device 1303, a scanner 1326, a camera 1327, an imaging system (such as an OCT system for example) 1382 and a microphone 1380; and output devices including a printer 1315, a display device 1314 and loudspeakers 1317. An external Modulator-Demodulator (Modem) transceiver device 1316 may be used by the computer module 1301 for communicating to and from a communications network 1320 via a connection 1321. The communications network 1320 may be a wide-area network (WAN), such as the Internet, a cellular telecommunications network, or a private WAN. Where the connection 1321 is a telephone line, the modem 1316 may be a traditional “dial-up” modem. Alternatively, where the connection 1321 is a high capacity (e.g., cable) connection, the modem 1316 may be a broadband modem. A wireless modem may also be used for wireless connection to the communications network 1320.

[0036] It will be understood that the imaging system 1382, such as an OCT system, may incorporate various elements of the general-purpose computer system therein rather than being attached to the general-purpose computer system.

[0037] The computer module 1301 typically includes at least one processor unit 1305, and a memory unit 1306. For example, the memory unit 1306 may have semiconductor random access memory (RAM) and semiconductor read only memory (ROM). The computer module 1301 also includes a number of input/output (I/O) interfaces including: an audio-video interface 1307 that couples to the video display 1314, loudspeakers 1317 and microphone 1380; an I/O interface 1313 that couples to the keyboard 1302, mouse 1303, scanner 1326, camera 1327 and optionally a joystick or other human interface device (not illustrated); and an interface 1308 for the external modem 1316 and printer 1315. In some implementations, the modem 1316 may be incorporated within the computer module 1301, for example within the interface 1308. The computer module 1301 also has a local network interface 1311, which permits coupling of the computer system 1300 via a connection 1323 to a local-area communications network 1322, known as a Local Area Network (LAN). As illustrated in Fig. 1A, the local communications network 1322 may also couple to the wide network 1320 via a connection 1324, which would typically include a so-called “firewall” device or device of similar functionality. The local network interface 1311 may comprise an Ethernet circuit card, a Bluetooth® wireless arrangement or an IEEE 802.11 wireless arrangement; however, numerous other types of interfaces may be practiced for the interface 1311.

[0038] The I/O interfaces 1308 and 1313 may afford either or both of serial and parallel connectivity, the former typically being implemented according to the Universal Serial Bus (USB) standards and having corresponding USB connectors (not illustrated). Storage devices 1309 are provided and typically include a hard disk drive (HDD) 1310. Other storage devices such as a floppy disk drive and a magnetic tape drive (not illustrated) may also be used. An optical disk drive 1312 is typically provided to act as a non-volatile source of data. Portable memory devices, such optical disks (e.g., CD-ROM, DVD, Blu-ray Disc™), USB-RAM, portable, external hard drives, and floppy disks, for example, may be used as appropriate sources of data to the system 1300.

[0039] The components 1305 to 1313 of the computer module 1301 typically communicate via an interconnected bus 1304 and in a manner that results in a conventional mode of operation of the computer system 1300 known to those in the relevant art. For example, the processor 1305 is coupled to the system bus 1304 using a connection 1318. Likewise, the memory 1306 and optical disk drive 1312 are coupled to the system bus 1304 by connections 1319. Examples of computers on which the described arrangements can be practised include IBM-PC’s and compatibles, Apple Mac™ or like computer systems.

[0040] The control methods described herein may be implemented using the computer system 1300 wherein the processes of Fig. 2 and associated control methods, to be described, may be implemented as one or more software application programs 1333 executable within the computer system 1300. In particular, the steps of the control methods are effected by instructions 1331 (see Fig. 1B) in the software 1333 that are carried out within the computer system 1300. The software instructions 1331 may be formed as one or more code modules, each for performing one or more particular tasks. The software may also be divided into two separate parts, in which a first part and the corresponding code modules performs the control methods and a second part and the corresponding code modules manage a user interface between the first part and the user.

[0041] The software may be stored in a computer readable medium, including the storage devices described below, for example. The software is loaded into the computer system 1300 from the computer readable medium, and then executed by the computer system 1300. A computer readable medium having such software or computer program recorded on the computer readable medium is a computer program product. The use of the computer program product in the computer system 1300 preferably effects an advantageous apparatus for controlling an optical delay line system.

[0042] The software 1333 is typically stored in the HDD 1310 or the memory 1306. The software is loaded into the computer system 1300 from a computer readable medium, and executed by the computer system 1300. Thus, for example, the software 1333 may be stored on an optically readable disk storage medium (e.g., CD-ROM) 1325 that is read by the optical disk drive 1312. A computer readable medium having such software or computer program recorded on it is a computer program product. The use of the computer program product in the computer system 1300 preferably effects an apparatus for controlling an optical delay line system.

[0043] In some instances, the application programs 1333 may be supplied to the user encoded on one or more CD-ROMs 1325 and read via the corresponding drive 1312, or alternatively may be read by the user from the networks 1320 or 1322. Still further, the software can also be loaded into the computer system 1300 from other computer readable media. Computer readable storage media refers to any non-transitory tangible storage medium that provides recorded instructions and/or data to the computer system 1300 for execution and/or processing. Examples of such storage media include floppy disks, magnetic tape, CD-ROM, DVD, Blu-ray™ Disc, a hard disk drive, a ROM or integrated circuit, USB memory, a magneto-optical disk, or a computer readable card such as a PCMCIA card and the like, whether or not such devices are internal or external of the computer module 1301. Examples of transitory or non-tangible computer readable transmission media that may also participate in the provision of software, application programs, instructions and/or data to the computer module 1301 include radio or infra-red transmission channels as well as a network connection to another computer or networked device, and the Internet or Intranets including e-mail transmissions and information recorded on Websites and the like.

[0044] The second part of the application programs 1333 and the corresponding code modules mentioned above may be executed to implement one or more graphical user interfaces (GUIs) to be rendered or otherwise represented upon the display 1314. Through manipulation of typically the keyboard 1302 and the mouse 1303, a user of the computer system 1300 and the application may manipulate the interface in a functionally adaptable manner to provide controlling commands and/or input to the applications associated with the GUI(s). Other forms of functionally adaptable user interfaces may also be implemented, such as an audio interface utilizing speech prompts output via the loudspeakers 1317 and user voice commands input via the microphone 1380.

[0045] Fig. 1B is a detailed schematic block diagram of the processor 1305 and a “memory” 1334. The memory 1334 represents a logical aggregation of all the memory modules (including the HDD 1309 and semiconductor memory 1306) that can be accessed by the computer module 1301 in Fig. 1A.

[0046] When the computer module 1301 is initially powered up, a power-on self-test (POST) program 1350 executes. The POST program 1350 is typically stored in a ROM 1349 of the semiconductor memory 1306 of Fig. 1A. A hardware device such as the ROM 1349 storing software is sometimes referred to as firmware. The POST program 1350 examines hardware within the computer module 1301 to ensure proper functioning and typically checks the processor 1305, the memory 1334 (1309, 1306), and a basic input-output systems software (BIOS) module 1351, also typically stored in the ROM 1349, for correct operation. Once the POST program 1350 has run successfully, the BIOS 1351 activates the hard disk drive 1310 of Fig. 1A. Activation of the hard disk drive 1310 causes a bootstrap loader program 1352 that is resident on the hard disk drive 1310 to execute via the processor 1305. This loads an operating system 1353 into the RAM memory 1306, upon which the operating system 1353 commences operation. The operating system 1353 is a system level application, executable by the processor 1305, to fulfil various high level functions, including processor management, memory management, device management, storage management, software application interface, and generic user interface.

[0047] The operating system 1353 manages the memory 1334 (1309, 1306) to ensure that each process or application running on the computer module 1301 has sufficient memory in which to execute without colliding with memory allocated to another process. Furthermore, the different types of memory available in the system 1300 of Fig. 1A must be used properly so that each process can run effectively. Accordingly, the aggregated memory 1334 is not intended to illustrate how particular segments of memory are allocated (unless otherwise stated), but rather to provide a general view of the memory accessible by the computer system 1300 and how such is used.

[0048] As shown in Fig. 1B, the processor 1305 includes a number of functional modules including a control unit 1339, an arithmetic logic unit (ALU) 1340, and a local or internal memory 1348, sometimes called a cache memory. The cache memory 1348 typically includes a number of storage registers 1344 - 1346 in a register section. One or more internal busses 1341 functionally interconnect these functional modules. The processor 1305 typically also has one or more interfaces 1342 for communicating with external devices via the system bus 1304, using a connection 1318. The memory 1334 is coupled to the bus 1304 using a connection 1319.

[0049] The application program 1333 includes a sequence of instructions 1331 that may include conditional branch and loop instructions. The program 1333 may also include data 1332 which is used in execution of the program 1333. The instructions 1331 and the data 1332 are stored in memory locations 1328, 1329, 1330 and 1335, 1336, 1337, respectively. Depending upon the relative size of the instructions 1331 and the memory locations 1328-1330, a particular instruction may be stored in a single memory location as depicted by the instruction shown in the memory location 1330. Alternately, an instruction may be segmented into a number of parts each of which is stored in a separate memory location, as depicted by the instruction segments shown in the memory locations 1328 and 1329.

[0050] In general, the processor 1305 is given a set of instructions which are executed therein. The processor 1305 waits for a subsequent input, to which the processor 1305 reacts to by executing another set of instructions. Each input may be provided from one or more of a number of sources, including data generated by one or more of the input devices 1302, 1303, data received from an external source across one of the networks 1320, 1302, data retrieved from one of the storage devices 1306, 1309 or data retrieved from a storage medium 1325 inserted into the corresponding reader 1312, all depicted in Fig. 1A. The execution of a set of the instructions may in some cases result in output of data. Execution may also involve storing data or variables to the memory 1334.

[0051] The disclosed optical delay line control arrangements use input variables 1354, which are stored in the memory 1334 in corresponding memory locations 1355, 1356, 1357. The optical delay line control arrangements produce output variables 1361, which are stored in the memory 1334 in corresponding memory locations 1362, 1363, 1364. Intermediate variables 1358 may be stored in memory locations 1359, 1360, 1366 and 1367.

[0052] Referring to the processor 1305 of Fig. 1B, the registers 1344, 1345, 1346, the arithmetic logic unit (ALU) 1340, and the control unit 1339 work together to perform sequences of micro-operations needed to perform “fetch, decode, and execute” cycles for every instruction in the instruction set making up the program 1333. Each fetch, decode, and execute cycle comprises:

[0053] a fetch operation, which fetches or reads an instruction 1331 from a memory location 1328, 1329, 1330;

[0054] a decode operation in which the control unit 1339 determines which instruction has been fetched; and

[0055] an execute operation in which the control unit 1339 and/or the ALU 1340 execute the instruction.

[0056] Thereafter, a further fetch, decode, and execute cycle for the next instruction may be executed. Similarly, a store cycle may be performed by which the control unit 1339 stores or writes a value to a memory location 1332.

[0057] Each step or sub-process in the processes of Fig 2 and associated control methods is associated with one or more segments of the program 1333 and is performed by the register section 1344, 1345, 1347, the ALU 1340, and the control unit 1339 in the processor 1305 working together to perform the fetch, decode, and execute cycles for every instruction in the instruction set for the noted segments of the program 1333.

[0058] The optical delay line control method may alternatively be implemented in dedicated hardware such as one or more integrated circuits performing the functions or sub functions of optical delay line control. Such dedicated hardware may include graphic processors, digital signal processors, or one or more microprocessors and associated memories.

[0059] According to the herein disclosure, a method and associated apparatus and/or system is described that provides increased control and improved scan rate and scan depth (i.e. temporal) scalability.

[0060] According to the herein disclosure, a micro-machined structured phase plate is integrated with cascading optical delay lines into a low-coherence interferometer. A ten-fold increase of rate of temporal modulation into a 40 kHz regime is demonstrated. The rate of the temporal modulation is increased with minimal alteration of the reference arm length.

[0061] The concept of tunable temporal modulation of a phase plate is described along with associated references to spatial modulation. The orbital angular momentum of a spiral phase beam relies on the overall phase shift acquired around the circumference of the beam. For single step spiral phase plates, the phase shift is proportional to the physical height of the spiral phase segment upon which the beam is being directed. Alternatively, a multi-step spiral phase plate may be constructed that includes a collection of linear ramps.

[0062] Figure 3a shows a micro-machined spiral phase plate 301. Figure 3b shows spatial modulation of the spiral phase plate with distinct annular intensity rings. Figure 3c shows a zoomed in image of a segment 303 of the phase plate. Figure 3d shows low coherence interference fringes from rotating the spiral phase plate at 300 Hz. In spatial modulation, a broad illumination from an optical source of a known multi-step spiral phase plate, shown in Figure 3a, fabricated using a nano-lathe machine, provides an overall linear delay line around the circumference of the beam that upon reflection changes a Gaussian beam into an LG beam with an annular intensity pattern as shown in Figure 3b.

[0063] The phase plate imparts a given orbital angular momentum of $k\hbar$ to the beam, where k is the helicity or winding and $\hbar$ is the reduced Planck constant. On the other hand, a known imaging system using an optical beam focused onto a single segment of a rotating spiral plate, shown in Figure 3c, will experience a fixed phase shift over multiple segments over the circumference of the phase plate. Each phase plate segment m has a physical height h that corresponds to an integer multiple n of the wavelength of the incident light λ. For a single reflective point, the overall scan rate is the product of the rotation rate f_{rot} and the number of segments k. Figure. 3d shows that known scanning systems using a single beam standard spiral phase plate of 128 segments could potentially reach a 45 kHz scan rate but are severely limited in depth scanning.

[0064] For spatial modulation, the overall linear phase shift is given by $\phi(\theta)=m\theta$. The radial phase variation in a reflective spiral phase plate with m segments each of height $h=h_{\mathrm{tot}}/m$ is given by

$$\phi_{\mathrm{mod}}(\phi) = \frac{h_{\mathrm{tot}}}{m}\frac{2\pi}{\lambda} m \frac{\phi}{2\pi} \tag{1}$$

[0065] The total scan height of the phase plate is $h_{tot} = m\,h$ and λ is the wavelength of light, as shown in Figure. 4a. The temporal modulation creates a time varying phase shift ϕ_{mod} which now depends on the time t instead of the angular position on the phase plate ϕ. To reflect this in equation 1, the angular position is replaced with the angular rotation rate multiplied by the time $\omega_{\mathrm{rot}}t$. The configuration of a single reflection is limiting, even with large number of smaller elements. The overall optical path length is then restricted by the physical height of each segment where there is a limited scan depth and repetition rates, as Figure 3d.

[0066] The use of multiple segments results in a higher repetition rate $m\,f_{\mathrm{rot}}$ with a scan depth of h_{tot}/m *(for a given total height* h_{tot}*)*. The temporal modulation method described herein for spiral phase elements can also be generalised to other rotating or linear delay line elements. As a function of time, the change in optical path length due to reflection from a rotating phase plate is given by

$$\phi_{\mathrm{mod}}(t) = \frac{h_{\mathrm{tot}}}{m}\frac{2\pi}{\lambda} m \frac{\omega_{\mathrm{rot}}t}{2\pi} \tag{2}$$

[0067] Note that the number of segments m cancels out in both equations (1) and (2), which is the operating principle of the spatial modulation. In the temporal case, an increase in the number of segments results in a higher repetition rate ($m\omega_{\mathrm{rot}}$) and reduces the overall scan depth (h_{tot}/m). The herein described technique re-routes a single beam over multiple segments (elements) to improve scan rate and scan depth scalability.

[0068] Given a rotary mirror with segments of individual height h, the use of multiple segments results in a higher repetition rate mf_{rot}. The temporal modulation method described herein for individual phase elements can also be generalised to other rotating or linear delay line elements. As a function of time (t), the change in optical path length due to reflection from a rotating phase plate is given by equation (3):

$$\mathrm{d}(t) = h\,\mathrm{frac}[mf_{\mathrm{rot}}t] \tag{3}$$

[0069] Here, $\mathrm{d}(t)$ denotes the path length at any given time t, and frac[x] represents the fractional part of x. An increase in the number of segments results in a higher repetition rate (mf_{rot}) but doing so requires a reduction of the overall scan depth (h) for a given segment angle.

[0070] In accordance with the herein disclosure, the scan rate limitation of the aforementioned rotary delay line mechanism is overcome by expanding the temporal delay line onto multiple segments over a rotating or linear phase plate by cascading multiple optical delay lines. This leads to an increase in the number of segments being visited by a single beam as it is reflected. For illustration, Figure 4a shows a rotating phase plate 401 having four ramp surfaces (403A – 403D) around its circumference. Each ramp surface varies around the circumference of the phase plate between a minimum height and a maximum height, where each ramp surface has the same minimum and maximum heights.

[0071] Figure. 4b and 4c show two timing examples, the synchronous (4b) and asynchronous (4c) timing using two beams. For the synchronous positioning of the beam routing points over each segment, the incident beam undergoes twice the amount of optical delay before returning back (and being modulated with a sample signal) as indicated by the ramp plot. This synchronous timing indicates an increased scanning depth. Conversely, the asynchronous positioning means that the incident beam undergoes two different phase delays which increases the scan rate instead, as shown in the ramp plots in Figure 4c. Reference is made to Fig. 6C showing the difference in the beam outputs between the two modes of operation.

[0072] That is, figures 4b and 4c show a schematic illustrating a multiple pass approach for a single optical beam being applied to the rotating phase plate of Figure 4a. Figure 4b shows the optical beam making two passes to the phase plate, where each pass is at a synchronised position such that the initial beam and the reflected beam are applied to different phase ramp surfaces (or segments) but at the same depth. That is, the first initial beam is applied to a first phase ramp surface (or segment) forming part of the rotating phase plate at a chosen height h_1

and the second reflected beam is applied to a second phase ramp surface (or segment) forming part of the rotating phase plate at a chosen height h_2, where $h_1 = h_2$. That is the initial beam and reflected beam are applied to the rotating phase plate at the same depth of the respective segment but at different positions circumferentially or radially. Figure 4c shows an asynchronous scan of the phase ramp, where the optical beam makes two passes to the phase plate, where each pass has an asynchronous position such that the initial beam is applied to a first position on the edge of a first phase ramp (or segment) and the reflected beam is applied to a second position on an edge of a second (i.e. different) phase ramp (or segment). The first and second positions (i.e. heights) are not the same such that $h_1 \neq h_2$. For a two-fold increase of scan rate using two cascaded delay lines one chooses $h_2 = h_1/2$, i.e. the second reflection point is half-way along the ramp for a linear ramp. In the general case of n cascaded delays, each delay would be $1/n$ further along the ramp, i.e. $h_n = h_1/n_{tot} * n$. The synchronous phase step provides double (n-times for n cascaded delays) depth at the same scan rate, whereas asynchronous positioning produces twice (n-times for n cascaded delays) the repetition rate.

[0073] Figures 4D to 4G show further details of the timing examples shown in Figures 4B and 4C.

[0074] A fibre based cascading delay line system 501 is described according to an embodiment that uses two optical delay lines (503A, 503B) to provide the cascading delay as shown in Figure 5a. It will be understood that more than two optical delay lines may be used as indicated by one or more optional additional optical delay line(s) 503C.

[0075] It will be understood that the optical delay line system may, in any part of the system, use an optical medium other than optical fibres. For example, the optical delay line system may use air as the optical medium, where the beam orientation and direction is controlled to ensure that it is captured by the components of the system.

[0076] A double cascaded delay line system is described which is scalable by the number of delays. According to this example, a portion of an optical beam being used in an optical system is fed as an input optical signal 507 into the optical delay line system 501. The input optical signal 507 is directed to the first optical delay line 503A. In particular, the input optical signal 507 is directed to a first optical circulator 509A of the first optical delay line 503A. The optical circulator 509A directs the input signal 507 to a first focussing optic 511A. In this example, the focussing optic 511A includes two lenses that are used to focus the input signal 507 onto elements 513x (i.e. 513A, 513B etc.) of the phase plate 515. The focussing optic 511A also receives a first reflected light beam reflected off an element of the phase plate. The first reflected light beam (the reflected input signal) is directed back through the first optical circulator 509A towards the second optical delay line 503B. In particular, the first reflected light beam is directed to a second optical circulator 509B of the second optical delay line 503B. The second optical circulator 509B directs the first reflected light beam to a second focussing optic 511B. In this example, the focussing optic 511B includes two lenses that are used to focus the input signal 507 onto elements 513x (i.e. 513A, 513B etc.) of the phase plate 515. The focussing optic 511B also receives a second reflected light beam reflected off an element of the phase plate. This second reflected beam, is directed by the second optical circulator 509B along optical path 519A as an output beam 515 towards the optical measurement system. As an alternative, further cascading optical delay lines may be incorporated where the second reflected beam, is directed by the second optical circulator 509B along optical path 519B to a further optical circulator within the further cascading optical delay line.

[0077] In summary, the optical signal coming from an optical delay element is a version of the optical signal directed towards that optical element after it has acquired a time-dependent optical delay introduced by the optical delay element.

[0078] It will be understood that the elements towards or onto which the input light signal and reflected beam(s) may be directed may be the same element or different elements. That is, the initial light beam from the first optical delay line 503A may be directed towards a first element 513A of the phase plate 515, and a reflected light beam from the second optical delay line 503B may be directed towards the same first element 513A. In this example where beams are directed towards the same first element, the location of the beams on the element would be different, but may be at the same radial angle on the phase plate but at a different radial distance from the centre of the plate. Alternatively where the beams are directed towards the same first element, the location of the beams may be at different radial angles on the phase plate, but at the same radial distance from the centre of the plate.

[0079] It will be understood that the focussing optic enables the light beam to be directed towards a desired element of the phase plate and a desired position on that element, and so could include a mirror, lens, multiple lenses, multiple mirrors or any combination thereof.

[0080] Although the positional control of the focussing optics for directing each light beam onto the element(s) of the phase plate may be a manual process, it will be understood that a computing device (as described with reference to Fig 1A and 1B) may be used as a control system to control the positioning of the focussing optics. For example, the computing device may provide a user interface to enable a user to input or control a variable that is output from the computing device to control a positioning device connected to the focussing optics.

[0081] For example, a position controller may be one or more of: a motor (or other positional actuator) to move the position, direction or orientation of the optical circulator to change the direction of the optical beam(s), a motor (or other positional actuator) to move the position, direction or orientation of the focussing optics to change the focus and/or direction of the optical beam(s), a beam steering device to change the position, focus and/or direction of the optical beam(s), or any other suitable position controller for controlling the direction, position or focus of the optical beam(s). In particular, the position controller is arranged to control the position of the optical delay elements relative to the optical beam (or signal).

[0082] For example, a step motor may be controlled by the computing device to move the position of the focussing optics in order to direct the beam of light associated with each focussing optic. Further, the control system may be used to control the speed of rotation of the motor that is used to rotate the phase plate. As more optical delay lines are added to the system, the control of the positioning of each light beam (as the number of reflected beams increases) becomes more complex and so the desired position of each beam relative to each other may be monitored and controlled relative to the desired scan depth and scan rate. A feedback system may be employed where the current scan rate and scan depth are fed back to the control system, and the control system determines whether adjustments are required based on the desired scan rate and scan depth. As will be explained in more detail below, synchronous and asynchronous positioning of the light beams may be controlled by the computing control system dependent on the desired scan rate and scan depth.

[0083] As shown in Fig. 5A, two light beams are directed onto elements of the rotating phase plate 515, where the second light beam is a reflected version of the first light beam (input beam) and a third light beam (output 515) is a reflected version of the second light beam. That is, the second light beam (optical signal) is a version of the first light beam (optical signal) that has acquired a first time-dependent optical delay introduced by the first element of the rotating phase plate 515. As the light beam is cascaded through further optical delay lines, the beam acquires further time-dependent optical delays based on the elements of the rotating phase plate.

[0084] The collimated output 517A of the first optical delay line 503A is focused onto the first segmented (or ramped) surface of an element 513A of the rotating phase plate 515. The returning beam 503B is then re-directed to the second optical delay line 503B and onto the second segmented (or ramped) surface of an element 513C of the rotating phase plate 515.

[0085] The approximate position on the phase plate 515 of the two light beams (517A, 517B) is indicated by dots 517A and 517B in Figure 5A. The position of the two beams (517A and 517B) produces a synchronous output as explained in more detail herein. According to this example, the phase plate in Fig 5A is shown to have 69 segments around the circumference of the phase plate. According to this example, the maximum height of an individual segment or element h = 200 µm, and the elements have a ramp profile with a smooth surface. Fig 5A also shows the position of two beams (517A and 517C) that produces an asynchronous output as explained in more detail herein.

[0086] Figure 5B shows an example of the optical delay line system with a cascading fibre-based reflection system integrated into a time-domain optical coherence tomography system. The round trip of the incident and returning beams is circled back using a 50/50 fibre splitter.

[0087] It will be understood that this round trip could be circled back into the optical system using other optical arrangements (e.g. a further optical circulator) or that other interferometer topologies (i.e. Mach-Zehnder interferometer topology) may be used that do not require re-circulation of this delayed signal.

[0088] In more detail, the time domain OCT system 551 shown in Figure 5B has an SLED 553 that generates light of wavelength 1310 ± 85 nm that is launched into a first 90/10 fibre splitter 555, where 10% is projected onto the side of the rotating phase plate and retro reflected onto a photodiode (PD) 556 to provide a timing pulse for synchronising each rotation, where the timing pulse 558 is fed back to the data acquisition system 1301. The remaining 90% of the light is directed to a beam splitter 557, where the beam is directed towards a second 90/10 splitter 559. The second 90/10 splitter 559 outputs 10% of the signal to a reference arm 561 and the other 90% to a sample arm 563 of an optical system. As would be known in the art, the OCT system analyses the optical length of the two arms (sample and reference) in to obtain relevant measurements of the sample. The system is initially setup so that the sample and reference arms have the same optical length (or delay). By measuring changes in the signal in the reference arm with respect to the signal from the sample arm, the sample can be analysed.

[0089] In the reference arm, a 50:50 beam splitter 565 is used to launch an initial beam 507 into the optical delay line system 501 and onto a first element (segmented surface) of the phase plate (see Figure 5a). An output beam 515 re-enters the 50:50 splitter 565 and combines with a sample signal 569 obtained from the imaging system sample arm in the 90:10 splitter 559. The eventual interference signal is then detected by the balanced photodiode and measured by the data acquisition/computing system 1301. On the sample arm 563, a two-axis galvo mirror 571 is positioned to provide raster scanning for tomographic imaging. The signal is then digitised and filtered using data acquisition/computing system 301 for real-time processing.

[0090] The temporal tunability of the rotating phase plate is accomplished by the asynchronous and synchronous timing of the cascading fibre arrangements as shown in Figures 4a- 4c.

[0091] The rotating phase plate used here comprises of 69 mirror segments (elements). At a rotation rate of 300 Hz this gives a basic scan rate of 20.7 kHz, and a scan depth of 200 μm (based on the physical height of all the elements of the phase plate on which the beam is directed). Under the synchronous positioning, the scan depth should also double and under asynchronous the scan rate should also double. The timing of the optical delay system can be adjusted without further extension of the overall path length of the optical delay system.

[0092] Figures 6a-6f show the performance of a system using cascading optical delay lines with a segmented phase plate in terms of duty cycle and single depth scan (i.e. single beam pass) respectively. Figures 6a, 6b and 6c show the results of an asynchronous method, while Figures 6d, 6e and 6f show the results of the synchronous method. The duty cycle is based on the back reflected signal (output of the delay line system) by measuring the time during which a non-zero reflected signal is detected with respect to the time required to complete one scan of a segment (or half segment if in asynchronous mode). The duty cycle is effectively a measurement of efficiency of reflections from the elements on the phase plate in the system, which may be reduced where a beam hits an edge of an element and so is not reflected back (zero reflected signal).

[0093] Figures 6a – 6f show experimental data of the reflected power and interference signals when the beams are asynchronous (6a, 6b, 6c) and synchronously matched (6d, 6e, 6f) respectively. For asynchronous matched paths, the reflected power measurement shows a repetition rate of 42.7 kHz that corresponds to readout of interference fringes in Fig 6c. For synchronous matching, repetition rate is maintained at 20.5 kHz (Fig. 6e) that corresponds to the interference fringes in Fig. 6F. For asynchronous matching, the repetition rate is maintained at 42.7 kHz (Fig 6B) that correspond to the interference fringes shown in Fig 6C. As the beam transits between individual segments, the duty cycle of the repetition reduces for each asynchronous path with minimal change to the axial resolution. This cascading path approach may increase the repetition rate by including more segments. Depending on the number of cascading optical delay lines, the configuration is scalable with the possibility of reaching sub-MHz frequency or millimetre scan range that is limited by duty cycle. Figures 6A and 6D correspond to the asynchronous mode and synchronous mode of operation respectively. Fig 6A is representative of the signals generated in accordance with the optical beams generated according to the method described with reference to Fig 4C. Fig 6D is representative of the signals generated in accordance with the optical beams generated according to the method described with reference to Fig 4B.

[0094] Figures 6A and 6D show the relationship between the initial optical signals and reflected optical signals for each of the synchronous and asynchronous modes of operation. The first pass (initial signal delay line), second pass (second delay line which uses the reflected signal from the first delay line as input) and sum of the two signals are shown.

[0095] To further validate the imaging speed, a thin reflective film is placed onto an audio speaker that is modulated at around 40 Hz, with the results shown in Figures 7a and 7b. Figures 7a and 7b show video rate OCT imaging signal at 600 Hz with asynchronous beam positioning on a vibrating reflective film at 40 Hz. Fig 7a shows each B-scan of the sample over 200 µm depth and Fig 7b shows a plot of the full oscillatory motion over multiple cycles. Using the asynchronous configuration to achieve 42.7 kHz scan rate, the achievable frame rate is equivalent to 600 fps per B-scan, thus capturing millisecond dynamic of the vibrating film (slightly tilted).

[0096] An example showing extended scan depth is provided where synchronous timing is used. Several thin films are stacked on top of each other to construct a thick sample ~ 500 µm. Figure 8a shows the double depth image (as illustrated in Figure. 4b) where the synchronous position of the beam achieves twice the scan depth (400 µm). Figure 8b shows an asynchronous scan that achieves 200 µm scan depth. The extended depth imaging is also confirmed with imaging through a thick opaque leaf sample as shown in Figure 8c. Figure. 8c shows the 3D reconstructed image of the leaf produced by the synchronous method. Figure 8d shows an image of the venation structure in the leaf that is present specifically at around

300 µm in depth, taken from the volumetric data of Figure 8c, and thus also produced by the synchronous method.

[0097] The herein described system provides flexibility and simplicity to switch between deeper imaging depth and faster imaging. By applying the optical beam to two segments of the phase plate, a time-domain OCT system is provided that operates at video rates at > 40 kHz (depth scan) that potentially achieves (600 x 68) lines per second. As discussed before, this technique has the capability to scale up by increasing the number of phase plate segments the beam is applied to by cascading further optical delay lines, wherein the physical space between each fibre in the delay lines is sufficiently spaced to ensure good coupling.

[0098] Using the herein described dual optical delay line arrangement, the system has a scan rate of 20 and 40 kHz. The rotating phase plate is spun with a low torque motor (~ 300Hz) inside a reference arm of a time domain OCT. The new video rate time-domain optical coherence tomography imaging system achieves imaging speeds of up to 600 fps – B scan and is capable of capturing a fast vibrating film (40 Hz).

[0099] Figure 2 is a process flow diagram of a method for controlling an optical signal in an optical delay line system. At step S201, a first optical signal is received from an optical system. At step S203, the first optical signal is directed to a first optical delay element (such as an element on a phase plate). At step S205, a second optical signal is received, where the second optical signal is a time-dependent optically delayed version of the first optical signal. At step S207, the second optical signal is directed to a second optical delay element. At step S209, a third optical signal is received, where the third optical signal is a time-dependent optically delayed version of the second optical signal. At step S211, the third optical signal is directed towards either a further optical delay element or the optical system.

[00100] It will be understood that any suitable component(s), including optical fibres, mirrors, lenses, circulators and other optical components, may be used to control the optical beam direction or routing to, from and/or within one or more optical delay lines.

[00101] It will be understood that any suitable phase plate configuration may be used where at least two beams can be reflected from or transmitted through one or more elements of the phase plate such that the beam position may be adjusted between i) a first synchronous mode where the depth (i.e. height of the element) of the initial beam and reflected beam is the same, and ii) a second asynchronous mode where the depth (i.e. height of the element) of the initial

beam and depth of the reflected beam is different. For example, it will be understood that the rotating phase plate may have a single step rotating that goes from a minimum to a maximum height around the entire circumference of the plate. By positioning the beams accordingly, the initial beam and reflected or transmitted beam may be at the same height or different heights. As a further alternative, there may be two or more steps (elements) around the circumference of the phase plate.

[00102] A further example of an optical delay system using an alternative rotating phase plate will now be described with reference to Figure 9. A first cascading delay line 1001 includes an optical fibre 901, optical focussing devices 903A and 903B, and optical focussing devices 909A and 909B. The first cascading delay line 1001 receives an optical signal from an optical system (such as an OCT system) via an optical fibre 901 (or other suitable beam routing mechanism). The optical signal is provided to the optical focussing devices (903A, 903B) to direct (or focus) the optical beam towards the rotating phase plate 905.

[00103] The rotating phase plate 905 in this example has multiple optical delay elements (907A, 907B, 907C) formed from a transparent or semi-transparent material, such as glass or any suitable polymer material. The difference between the refractive index of the optical delay element material and the surrounding medium (e.g. air) causes the change in path length, phase change or optical delay. Thus, as the thickness of the material in the element changes, due to the ramp profile (for example), varying optical delays are provided dependent on the positioning of the optical signal on the optical delay element. As in the example described with reference to Fig. 5A, the optical signal coming from the optical delay element is a version of the optical signal directed towards the optical element that has acquired a time-dependent optical delay introduced by the optical delay element.

[00104] According to this example, the optical signal received through the input beam routing device (901), e.g. fibre, is not reflected back to the optical focussing devices (903A, 903B) but is transmitted through the optical delay element 907A of the phase plate 905 to the optical focussing devices (909A, 909B). The optical focussing devices (909A, 909B) combined with an optical beam routing device (911) direct the optical signal to the next cascading delay line 1003. This next cascading delay line 1003 includes optical focussing devices (913A, 913B), optical fibre (911) and optical focussing devices (915A, 915B). The same process as described with reference to the first cascading delay line occurs using the optical fibre 911 (or other suitable optical routing device), optical focussing devices (913A, 913B), optical delay element 907B of the phase plate 905 and optical focussing devices (915A, 915B).

[00105] The optical fibre 917A directs the optical signal either back to the optical system, or towards a further cascading delay line 1005 via fibre 917B. The further cascading delay line includes optical focussing devices (919A, 919B), optical focussing devices (921A, 921B) and optical fibre 923. The optical signal received at the third cascading delay line is directed towards optical delay element 907C of the rotating phase plate 905.

[00106] It will also be understood that the optical delay element(s) may be formed on or from devices other than rotating phase plates. For example, a series of optical delays may be provided by two optical fibres that are stretched and which are at a constant offset to one another, where the optical beam is passed through the optical fibres multiple times.

[00107] As a further alternative, a linear configuration of optical delay elements in the form of ramps, for example, may be used where the optical delay elements are moved in such a fashion that the delayed beams change their respective delays synchronously and where the herein described technique is used to cascade the individual delays in either a synchronous or asynchronous fashion. Therefore, the multiple optical delay elements provide a general time dependent optical delay with multiple individual points that can be accessed independently and that are inherently at a constant relative scan position.

[00108] One example of an alternative mechanism for moving the optical delay element(s) relative to the optical beam(s) is shown in Fig. 10A where a first optical delay line 1010A has a first optical signal routing device 1012A, which in this example is an optical circulator. The optical signal is fed from the first optical signal routing device 1012A to a first optical signal focussing device 1014A. The first optical signal focussing device 1014A directs the optical signal towards a first optical delay element 1016A that is formed on, attached to or otherwise engaged with an optical delay element transport mechanism 1018. For example, the transport mechanism 1018 may be any suitable platform upon which the optical elements are placed or positioned. The transport mechanism 1018 is arranged to move up and down in a reciprocal manner through interaction with a position controller (not shown), such as a step motor for example. In the example shown in Figure 10A, the optical delay elements are reflective and reflect the optical beam back to the first optical delay line 1010A in a similar manner to that shown and described with reference to Fig 5A.

[00109] Additional optical delay lines (1010B, 1010C, 1010D, 1010E etc.) are provided to cascade the optical signal through multiple optical signal routing devices (1012B, 1012C, 1012D, 1012E etc.) and multiple optical signal focussing devices (1014B, 1014C, 1014D, 1014E

etc.) where the outputs and inputs of the multiple optical signal focussing devices (1014B, 1014C, 1014D, 1014E etc.) direct the optical signal to and receive the optical signal from multiple optical delay elements (1016B, 1016C, 1016D, 1016E etc.).

[00110] A further example of an alternative mechanism for moving the optical delay element(s) relative to the optical beam(s) is shown in Fig. 10B where the same optical delay lines (1010A – 1010E etc.) are used. In this example, the optical signal is directed towards a optical delay elements (1018A, 1018B, 1018C, 1018D, 1018E etc.) that are formed on, attached to or otherwise engaged with an optical delay element transport mechanism (1020, 1022). In this example, the optical delay elements (1018A, 1018B, 1018C, 1018D, 1018E etc.) are formed on, attached to or otherwise engaged with a belt 1020, which is positionally controlled by way of, for example, a motor connected to one or more rotating elements (1022A, 1022B). As in Figure 10A, the transport mechanism (1020, 1022) is arranged to move up and down in a reciprocal manner through interaction with a position controller (not shown), such as a step motor for example. As an alternative, the transport mechanism (1020, 1022) may be arranged to move the belt in one direction in a repeating loop through interaction with a position controller (not shown), such as a motor for example.

[00111] It will be understood that the examples shown in Figures 10A and 10B may be modified to include transmissive, transparent or semi-transparent optical delay elements, where in this example, the platform or belt (support structure) upon which the optical delay elements are mounted or supported is arranged so that the optical beam is not affected by the support structure. In this example, it will be understood that optical circulators would not necessarily be required.

[00112] It will be understood that other arrangements may be envisaged, such as the use of a single flat mirror and a number of individual optical delays positioned next to each other directing the optical beam towards the mirror. In this example, the mirror may be controlled by the position controller to move (reciprocate) the mirror up and down. According to this example, it will be understood that the optical delay system could only operate in a synchronous mode.

[00113] It will be understood that both higher scan depth and higher scan rate are possible depending upon the exact timing and reflection point of the optical beams onto the elements in the individual passes.

Industrial Applicability

[00114] The arrangements described are applicable to the computer and data processing industries and particularly for the optical imaging and measurement industries. For example, the optical delay lines described herein may be used in many optical applications including optical communications, optical ranging, laser imaging and optical coherence tomography.

[00115] The foregoing describes only some embodiments of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiments being illustrative and not restrictive.

[00116] In the context of this specification, the word “comprising” means “including principally but not necessarily solely” or “having” or “including”, and not “consisting only of”. Variations of the word "comprising", such as “comprise” and “comprises” have correspondingly varied meanings.

CLAIMS:

1. An optical delay line system comprising:

a plurality of cascading delay lines adapted for use in an optical system,

wherein a first cascading delay line of at least two of the plurality of cascading delay lines is arranged to:

direct the first optical signal towards a first optical delay element; and

receive a second optical signal, wherein the second optical signal is a version of the first optical signal that has acquired a first time-dependent optical delay introduced by the first optical delay element;

wherein a second cascading delay line of at least two of the plurality of cascading delay lines is arranged to:

direct the second optical signal towards a second optical delay element; and

receive a third optical signal, wherein the third optical signal is a version of the second optical signal that has acquired a second time-dependent optical delay introduced by the second optical delay element, and

direct the third optical signal to either a further cascading delay line of the plurality of cascading delay lines or to the optical system.

2. The optical delay line system of claim 1 further comprising a rotating phase plate comprising at least the first and second optical delay elements and a motor arranged to rotate the rotating phase plate.

3. The optical delay line system of claim 2, wherein the first and second optical delay elements are positioned radially around the rotating phase plate.

4. The optical delay line system of claim 3, wherein the first and second optical delay elements are reflective or transmissive optical delay elements.

5. The optical delay line system of claim 2 further comprising a control system arranged to control a speed of the motor.

6. The optical delay line system of claim 1 further comprising at least one position controller for controlling the position of at least one of the first optical signal with respect to the first

optical delay element and the second optical signal with respect to the second optical delay element.

7. The optical delay line system of claim 6, further comprising a control system for controlling the position controller to effect a synchronous mode of operation or asynchronous mode of operation based on the relative positions of the first optical signal on the first optical delay element and the second optical signal on the second optical delay element.

8. The optical delay line system of claim 1, wherein at least one of the first cascading delay line and second cascading delay line are arranged to direct the first optical signal towards a point on the first optical delay element or second optical signal towards a point on the second optical delay element to effect a synchronous mode of operation or asynchronous mode of operation.

9. The optical delay line system of claim 1, wherein the first optical delay element and second optical delay element are the same optical delay element.

10. The optical delay line system of claim 1, wherein the first optical delay element and second optical delay element are different optical delay elements.

11. The optical delay line system of claim 1, wherein the first cascading delay line comprises a first optical signal routing device and a first optical focussing device, and the second cascading delay line comprises a second optical signal routing device and a second optical focussing device,

wherein the first optical signal routing device is arranged to route the first optical signal to the first optical focussing device, and the first optical focussing device is arranged to direct the first optical signal towards the first optical delay element and receive the second optical signal,

wherein the first optical signal routing device is further arranged to route the second optical signal to the second cascading delay line,

wherein the second optical signal routing device is arranged to route the second optical signal to the second optical focussing device, and the second optical focussing device is arranged to direct the second optical signal towards the second optical delay element and receive the third optical signal, and wherein the second optical signal routing device is further arranged to route the third optical signal to the further cascading delay line or the optical system.

12. An optical system comprising one or more optical delay line systems of claim 1.

13. A method of controlling optical delay in an optical delay line system for use in an optical system, the method comprising the steps of:

    receiving a first optical signal from an optical system;

    directing the first optical signal towards a first optical delay element,

    receiving a second optical signal, wherein the second optical signal is a version of the first optical signal that has acquired a first time-dependent optical delay introduced by the first optical delay element;

    directing the second optical signal towards a second optical delay element;

    receiving a third optical signal, wherein the third optical signal is a version of the second optical signal that has acquired a second time-dependent optical delay introduced by the second optical delay element and

    directing the third optical signal towards a further optical delay element or the optical system.

14. The method of claim 13 further comprising the step of positioning the first optical signal onto the first optical delay element and/or the second optical signal onto the second optical delay element.

15. The method of claim 13 further comprising the step of directing the first optical signal or second optical signal towards a point on the first and second optical delay elements to effect a synchronous mode of operation or asynchronous mode of operation.

16. The method of claim 14 or claim 15, further comprising the step of controlling the position of the first and/or second optical signal to effect a synchronous mode of operation or asynchronous mode of operation.

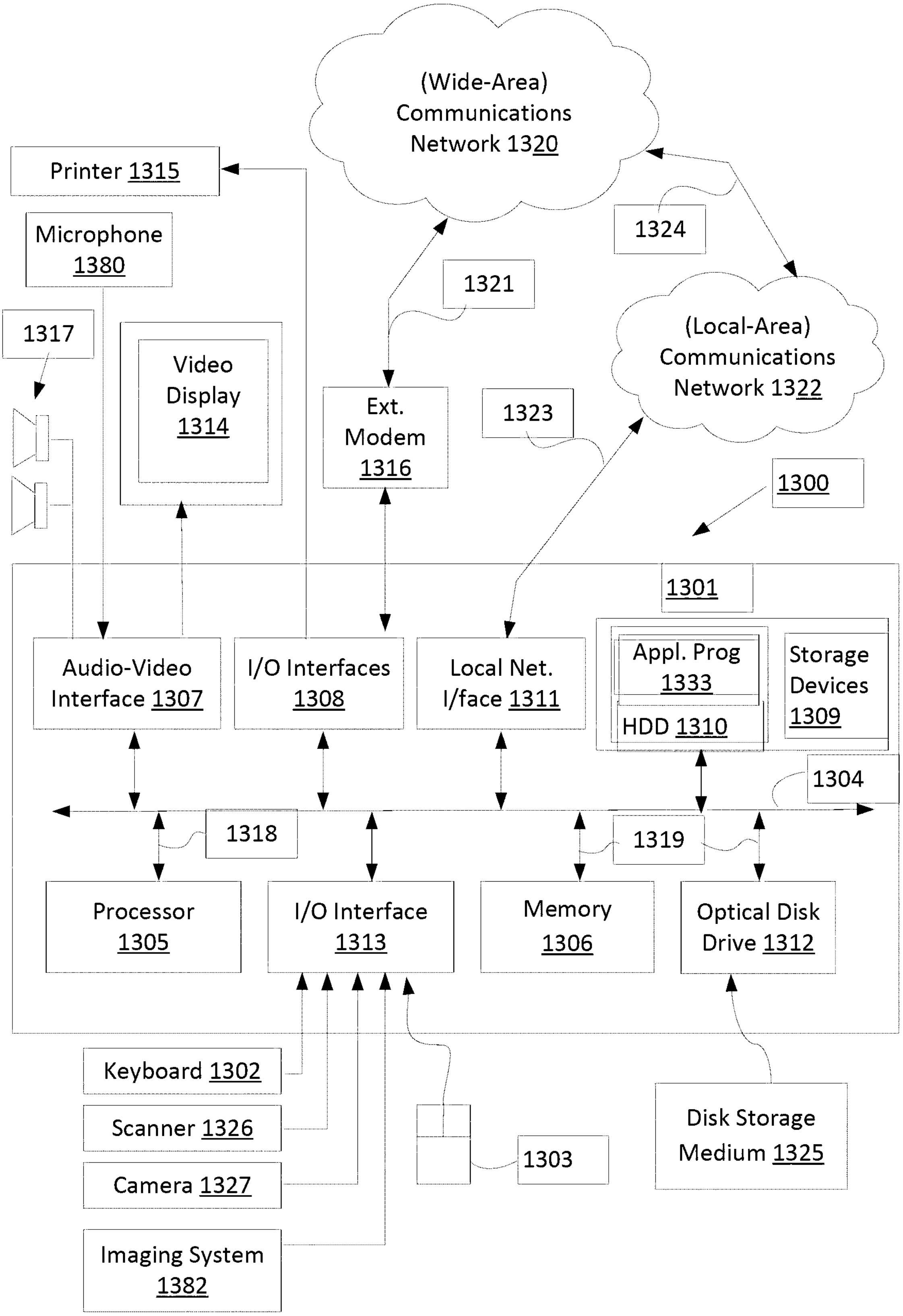
(Wide-Area) Communications Network 1320
Printer 1315
Microphone 1380
1324
1321
1317
Video Display 1314
(Local-Area) Communications Network 1322
Ext. Modem 1316
1323
1300
1301
Audio-Video Interface 1307
I/O Interfaces 1308
Local Net. I/face 1311
Appl. Prog 1333
HDD 1310
Storage Devices 1309
1304
1318
1319
Processor 1305
I/O Interface 1313
Memory 1306
Optical Disk Drive 1312
Keyboard 1302
Scanner 1326
Camera 1327
1303
Disk Storage Medium 1325
Imaging System 1382

Figure 1A

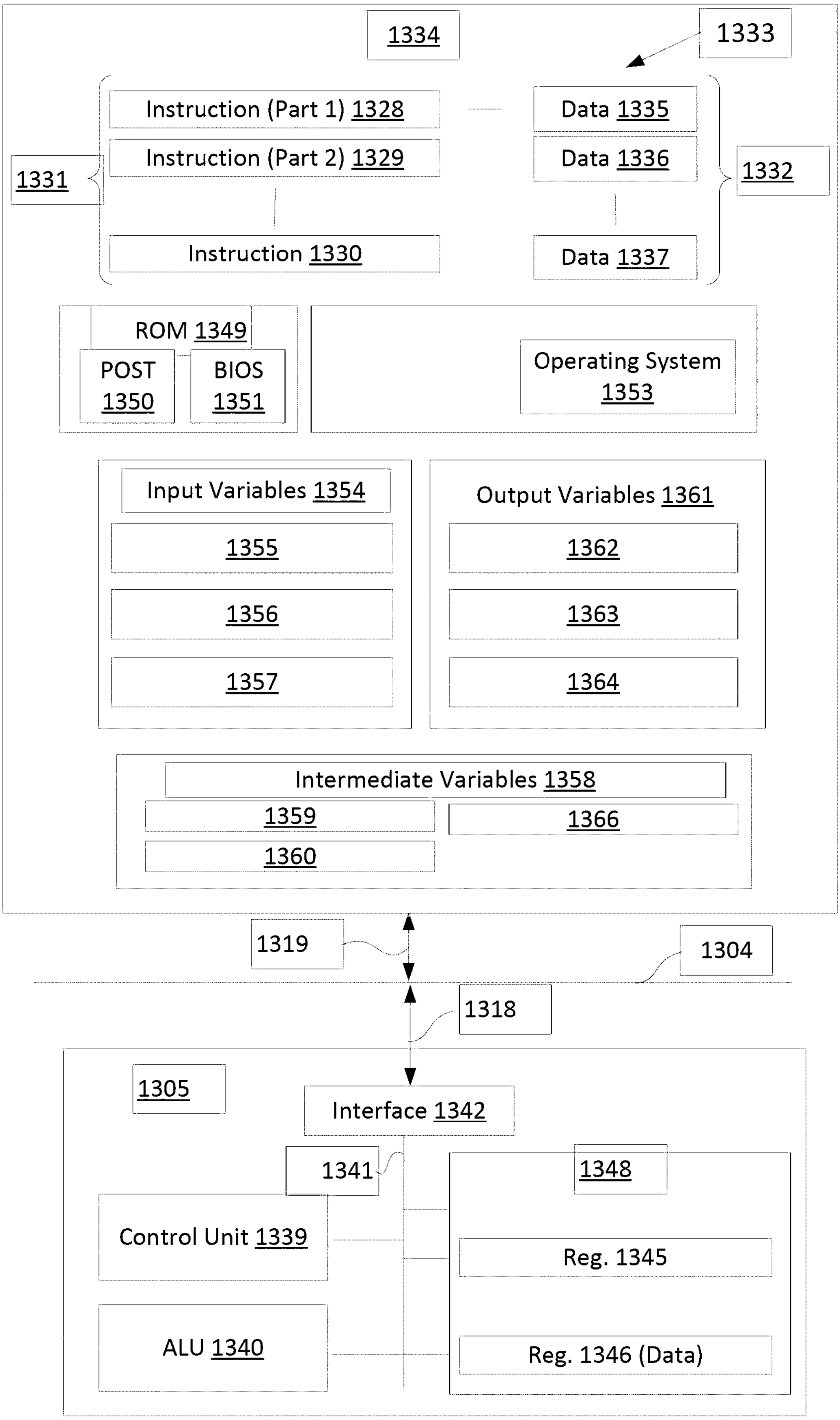
1334
1333
Instruction (Part 1) 1328
Data 1335
Instruction (Part 2) 1329
Data 1336
1331
1332
Instruction 1330
Data 1337
ROM 1349
POST 1350
BIOS 1351
Operating System 1353
Input Variables 1354
1355
1356
1357
Output Variables 1361
1362
1363
1364
Intermediate Variables 1358
1359
1366
1360
1319
1304
1318
1305
Interface 1342
1341
1348
Control Unit 1339
Reg. 1345
ALU 1340
Reg. 1346 (Data)

Figure 1B

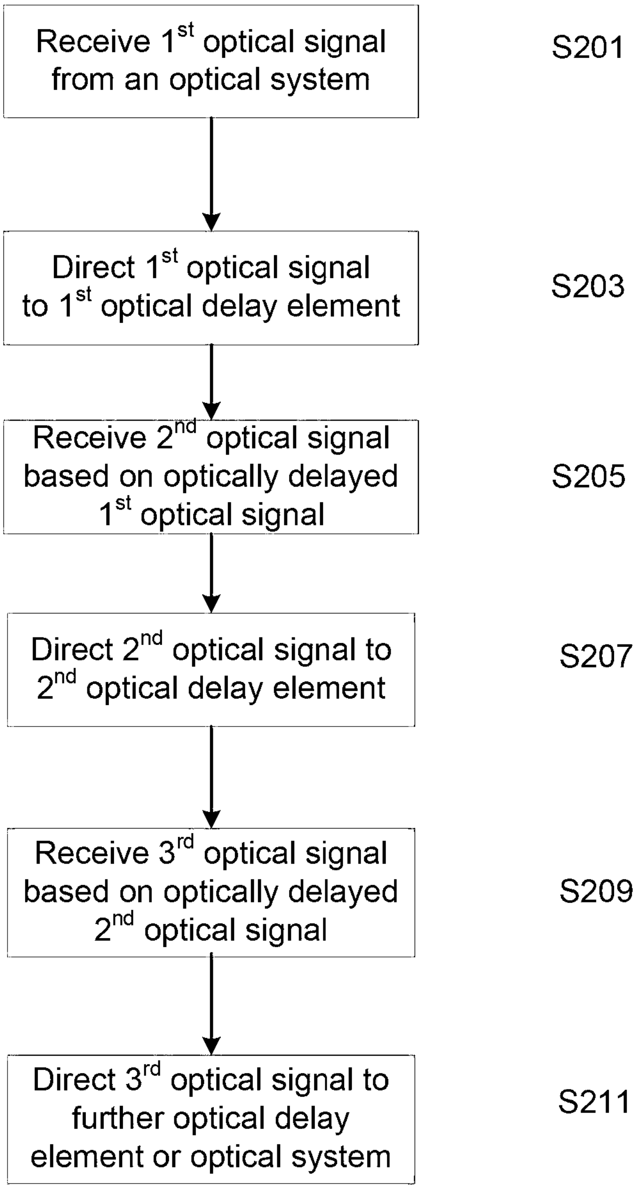
Receive 1st optical signal from an optical system
S201
Direct 1st optical signal to 1st optical delay element
S203
Receive 2nd optical signal based on optically delayed 1st optical signal
S205
Direct 2nd optical signal to 2nd optical delay element
S207
Receive 3rd optical signal based on optically delayed 2nd optical signal
S209
Direct 3rd optical signal to further optical delay element or optical system
S211

Figure 2

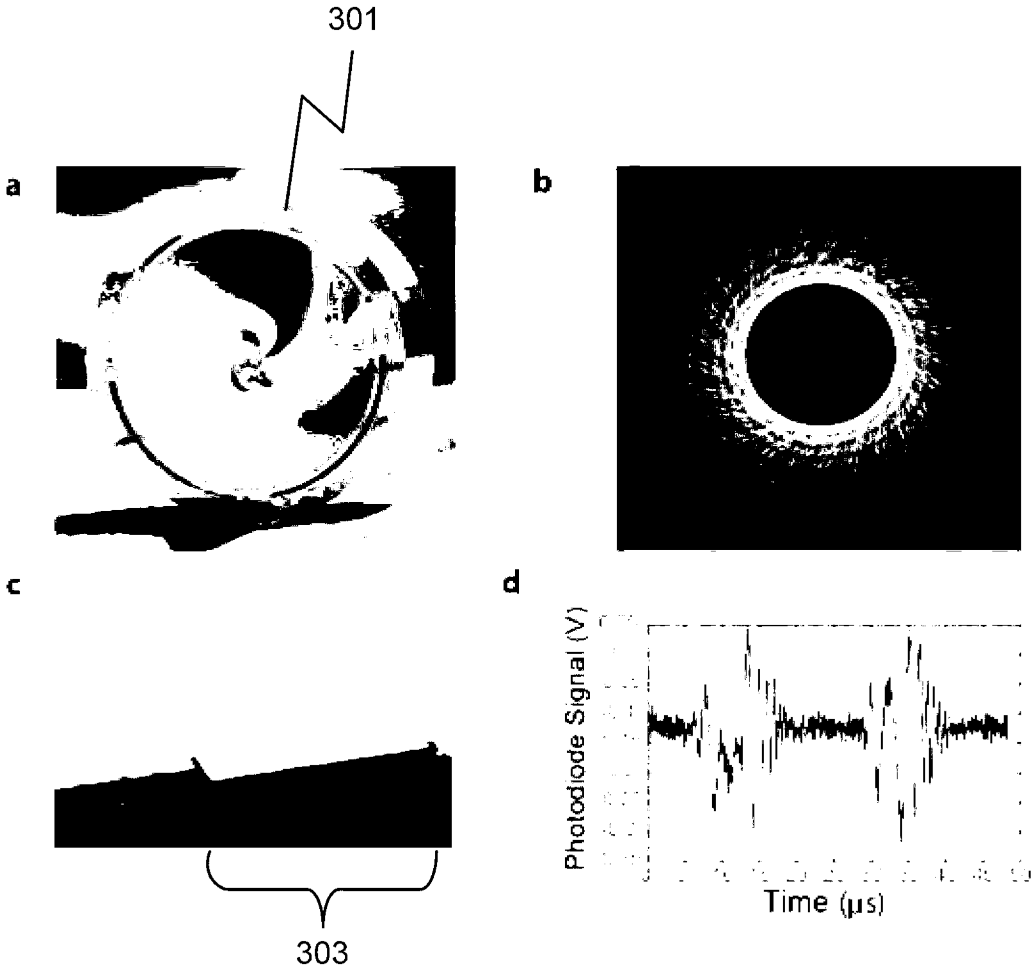

Figure 3

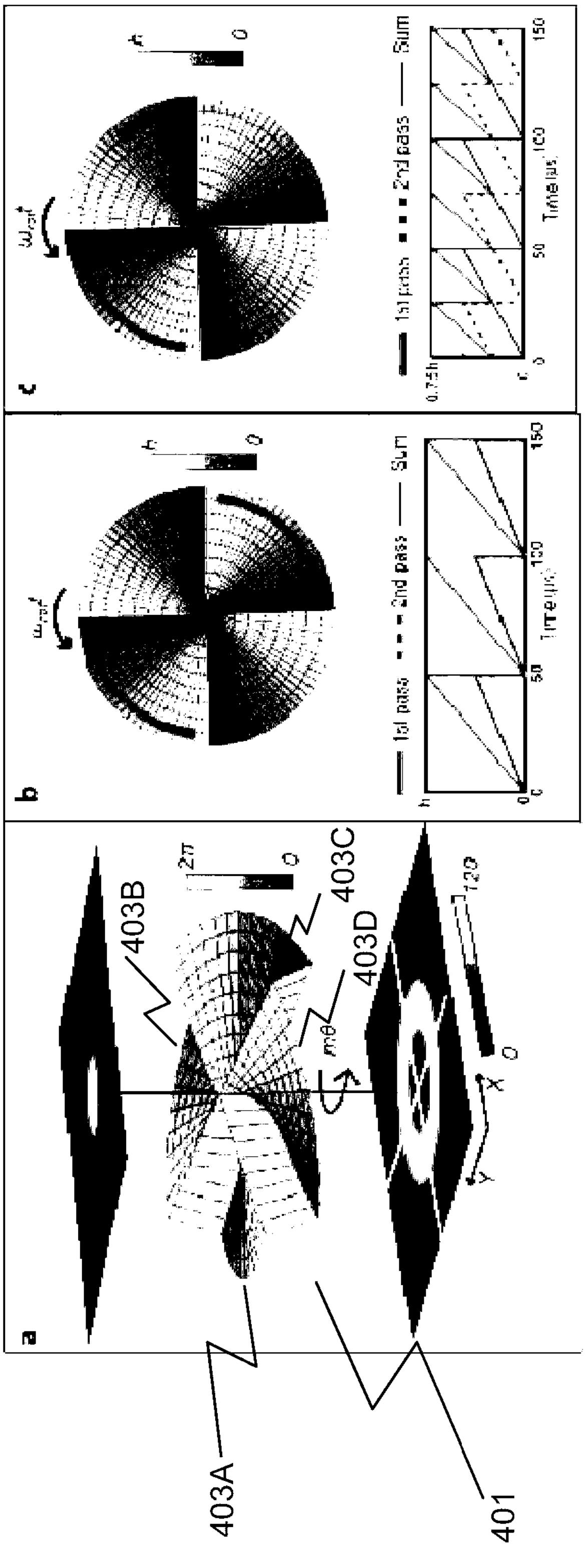
a
403A
403B
403C
403D
401
2π
0
mθ
x
y
0
120
b
c
$\omega_{rot}t$
h
0
1st pass
2nd pass
Sum
0.75h
0
50
100
150
Time (μs)

Figure 4A-4C

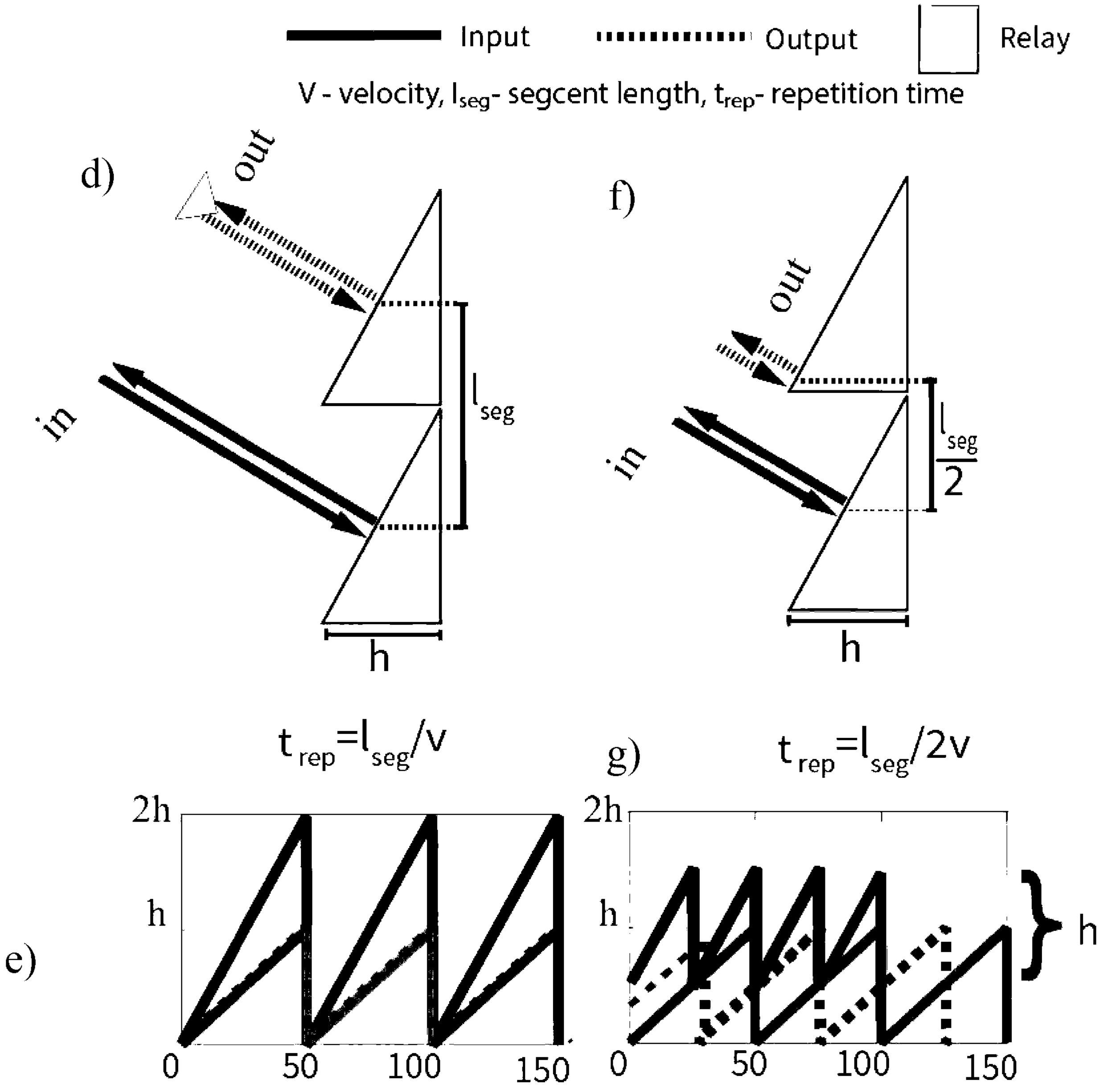
Input
Output
Relay
V - velocity, l_seg- segcent length, t_rep- repetition time
d)
out
in
l_seg
h
f)
out
in
l_seg/2
h
t_rep=l_seg/v
g)
t_rep=l_seg/2v
2h
h
e)
0
50
100
150
2h
h
0
50
100
150
h

Figure 4D-4G

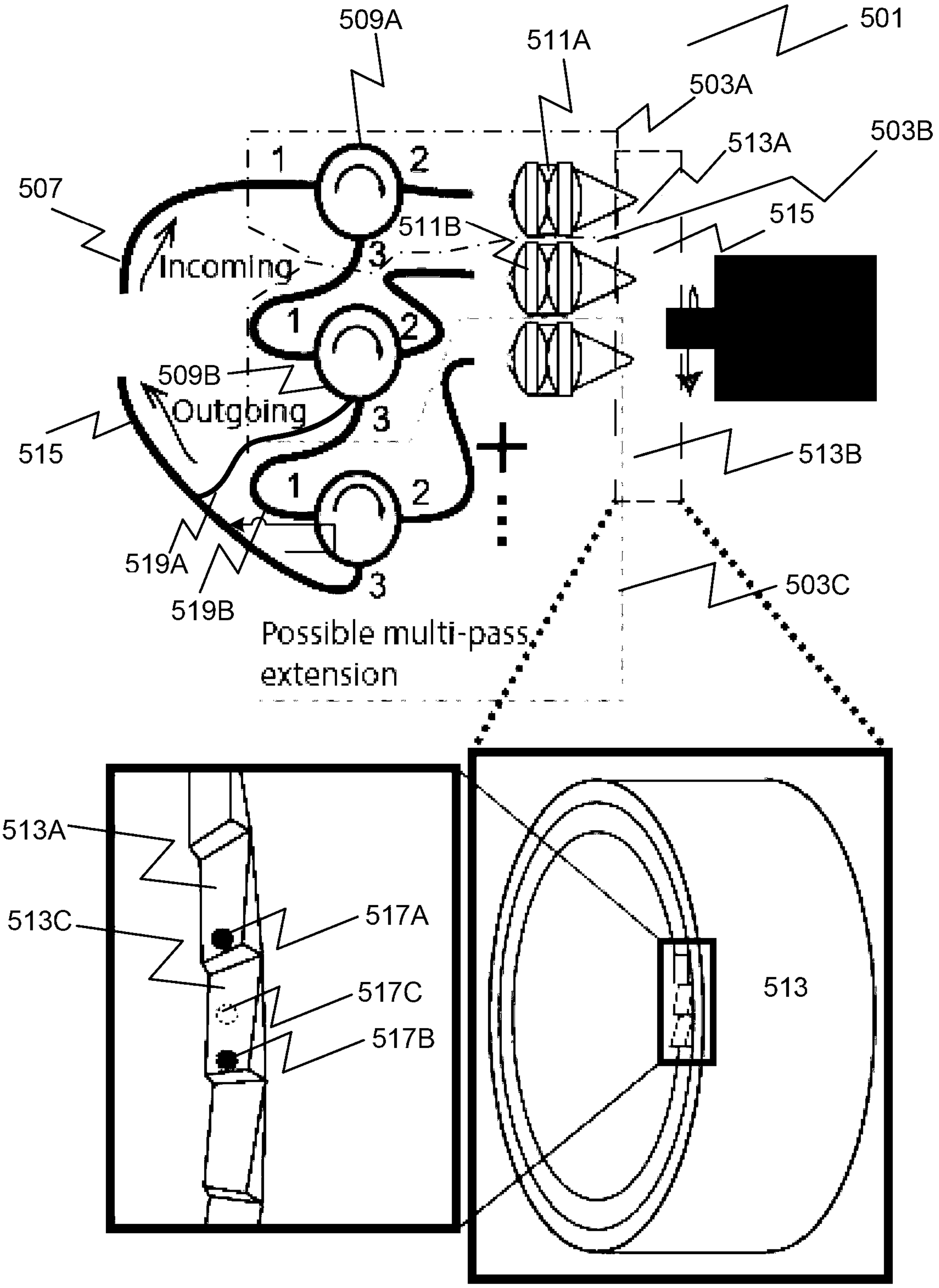
509A
511A
501
503A
513A
503B
507
1
2
511B
515
Incoming
3
1
2
509B
Outgoing
3
+
1
2
515
513B
519A
519B
3
503C
Possible multi-pass extension
513A
513C
517A
517C
517B
513

Figure 5A

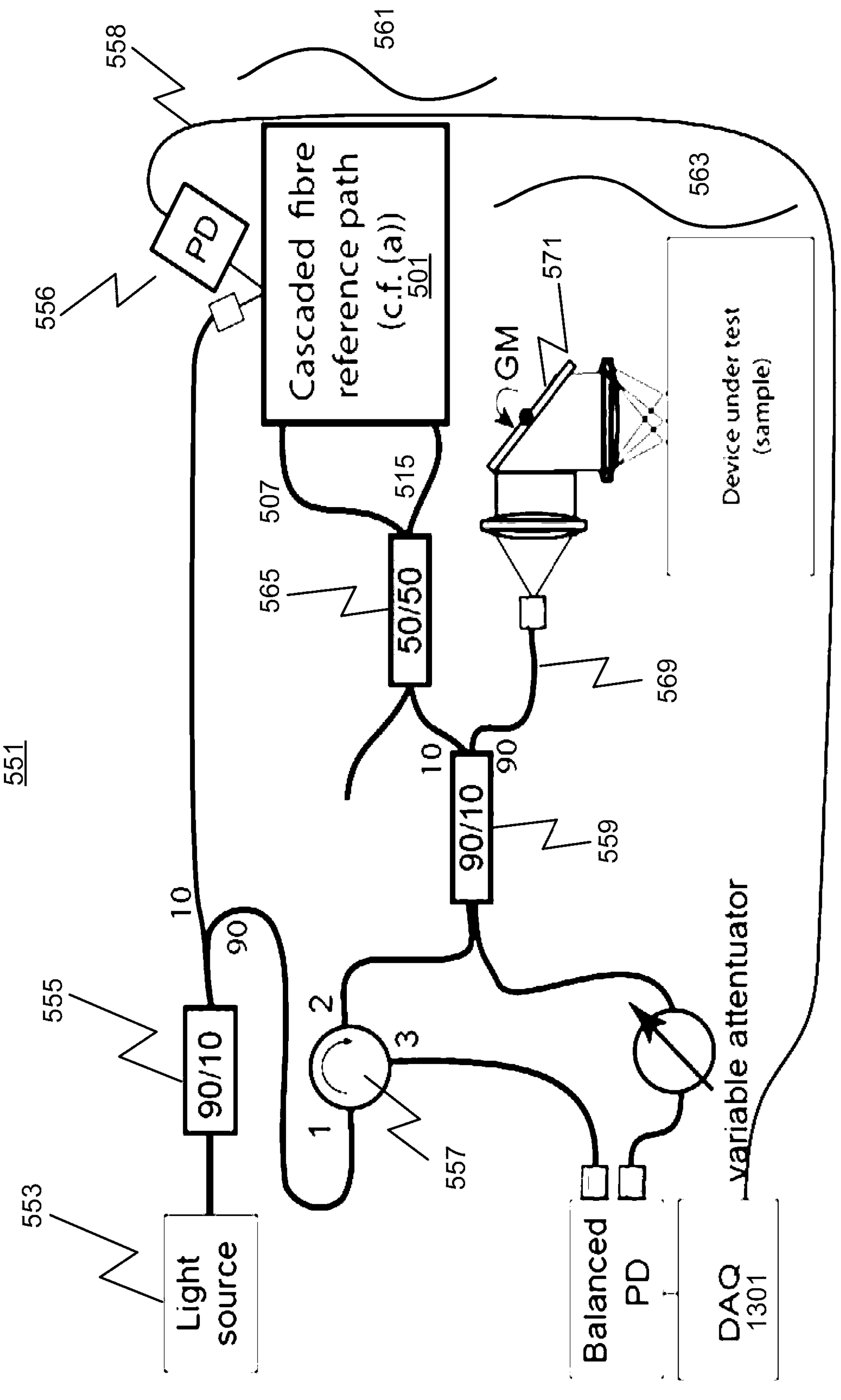
551
558
561
556
PD
Cascaded fibre reference path (c.f. (a)) 501
563
571
GM
Device under test (sample)
507
515
565
50/50
569
10
90
90/10
559
555
90/10
10
90
2
3
1
557
553
Light source
Balanced PD
DAQ 1301
variable attentuator

Figure 5B

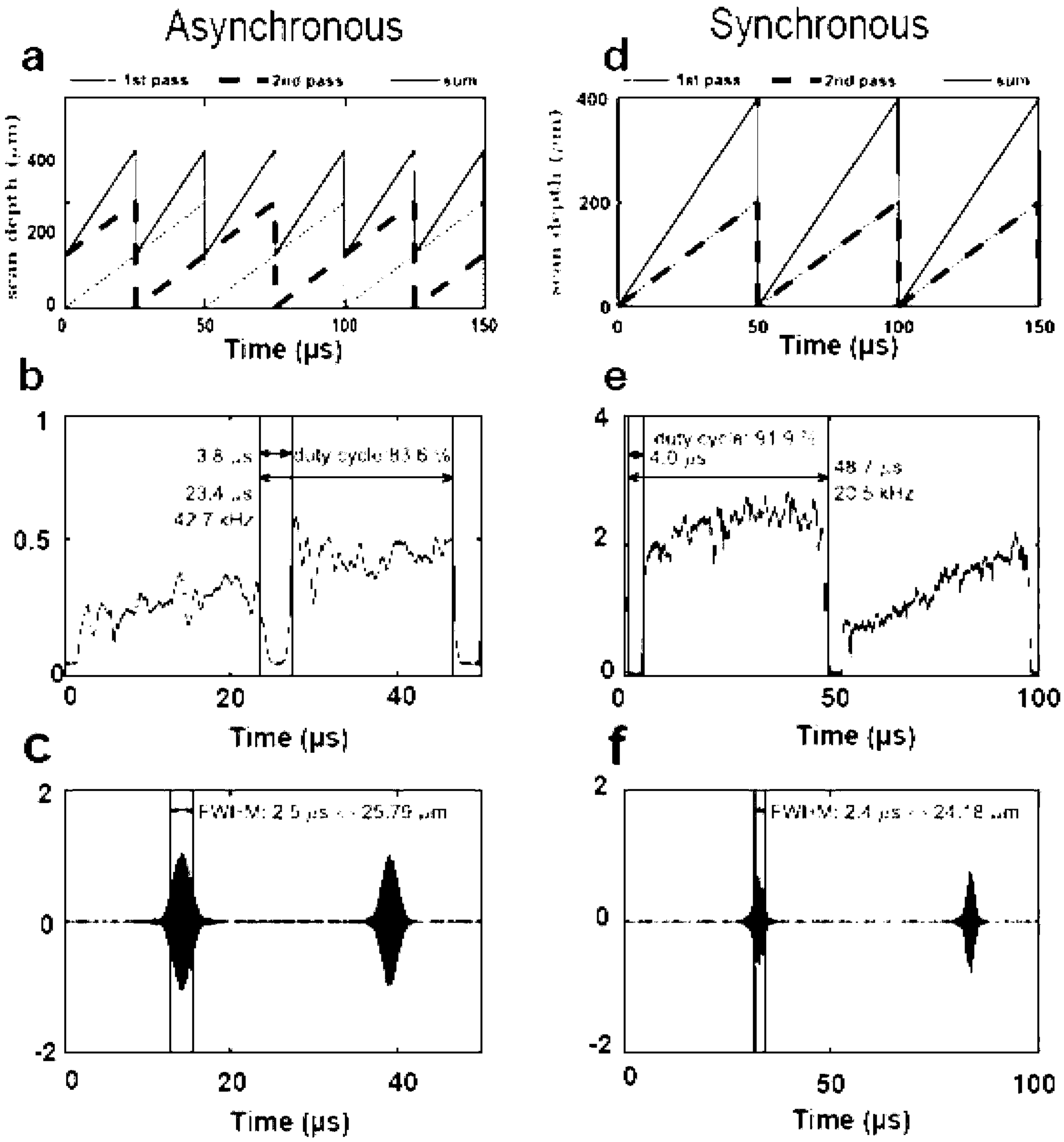
Asynchronous
Synchronous
a
1st pass
2nd pass
sum
scan depth (μm)
400
200
0
0
50
100
150
Time (μs)
d
1st pass
2nd pass
sum
scan depth (μm)
400
200
0
0
50
100
150
Time (μs)
b
1
0.5
0
3.8 μs
duty cycle 83.6 %
23.4 μs
42.7 kHz
0
20
40
Time (μs)
e
4
2
0
duty cycle 91.9 %
4.0 μs
48.7 μs
20.5 kHz
0
50
100
Time (μs)
c
2
0
-2
FWHM: 2.5 μs <-> 25.79 μm
0
20
40
Time (μs)
f
2
0
-2
FWHM: 2.4 μs <-> 24.18 μm
0
50
100
Time (μs)

Figure 6A – 6F

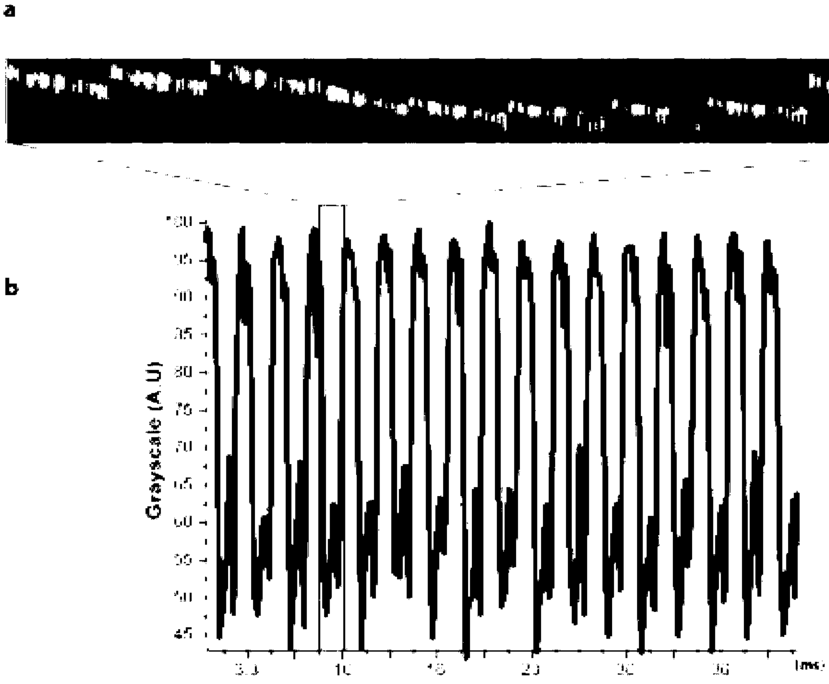
a
Δt ~1.6ms
b
Grayscale (A.U)
100
95
90
85
80
75
70
65
60
55
50
45
5.0
10
15
20
25
30
(ms)

Figure 7

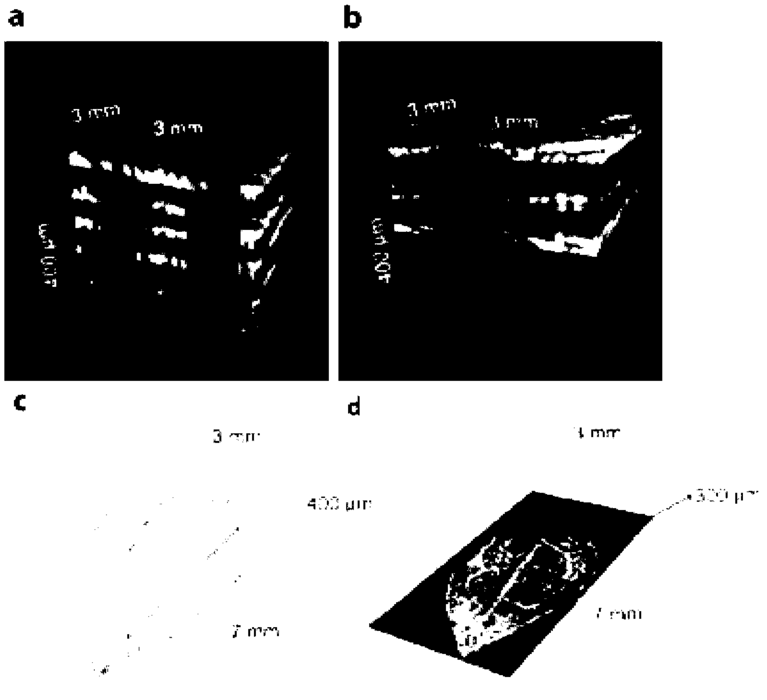

Figure 8

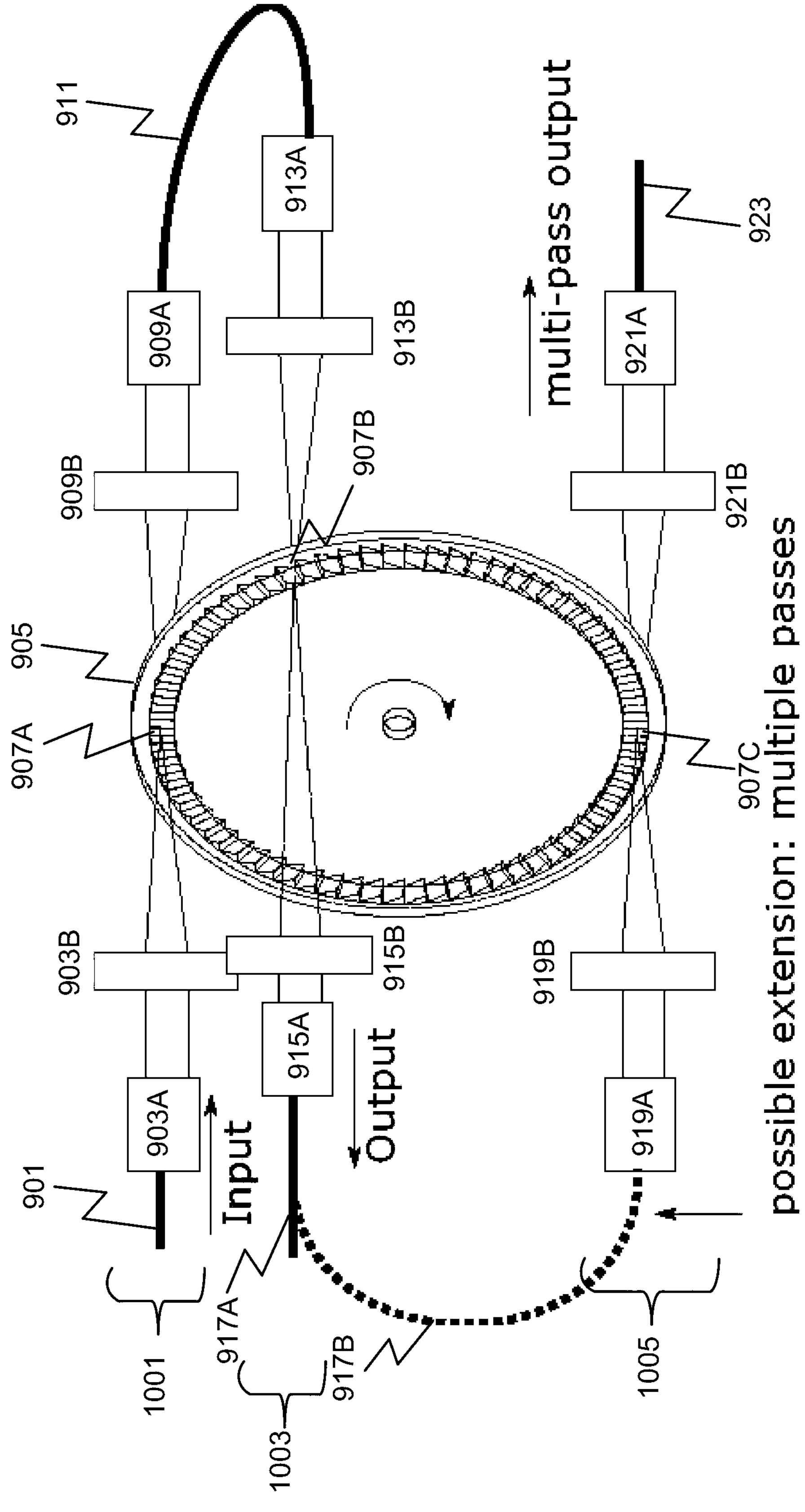
911
913A
909A
913B
909B
907B
multi-pass output
923
921A
921B
905
907A
Ω
907C
903B
915B
919B
possible extension: multiple passes
915A
Output
903A
Input
919A
901
917A
917B
1001
1003
1005

Figure 9

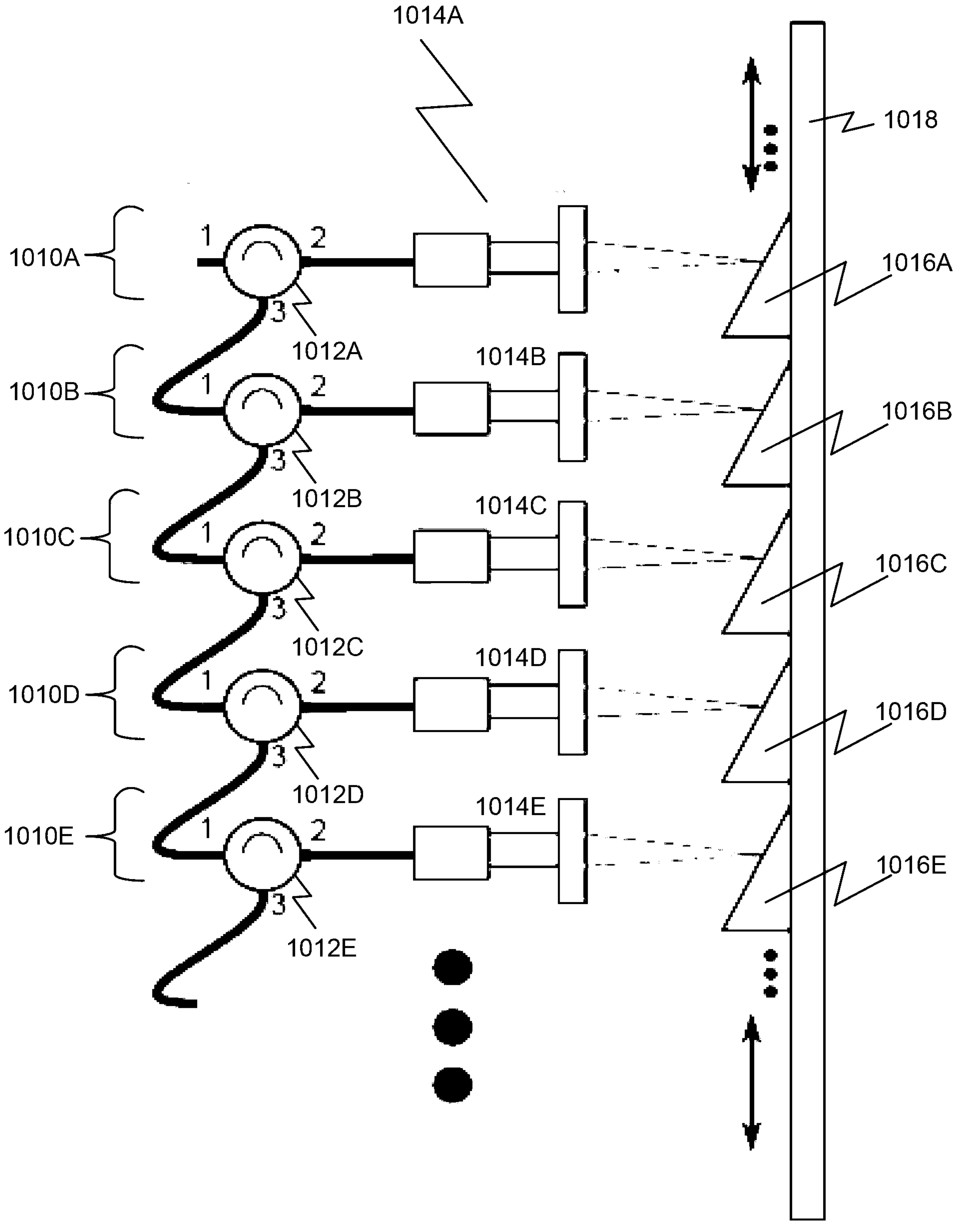
1014A
1018
1010A
1
2
3
1012A
1016A
1010B
1014B
1012B
1016B
1010C
1014C
1012C
1016C
1010D
1014D
1012D
1016D
1010E
1014E
1012E
1016E

Figure 10A

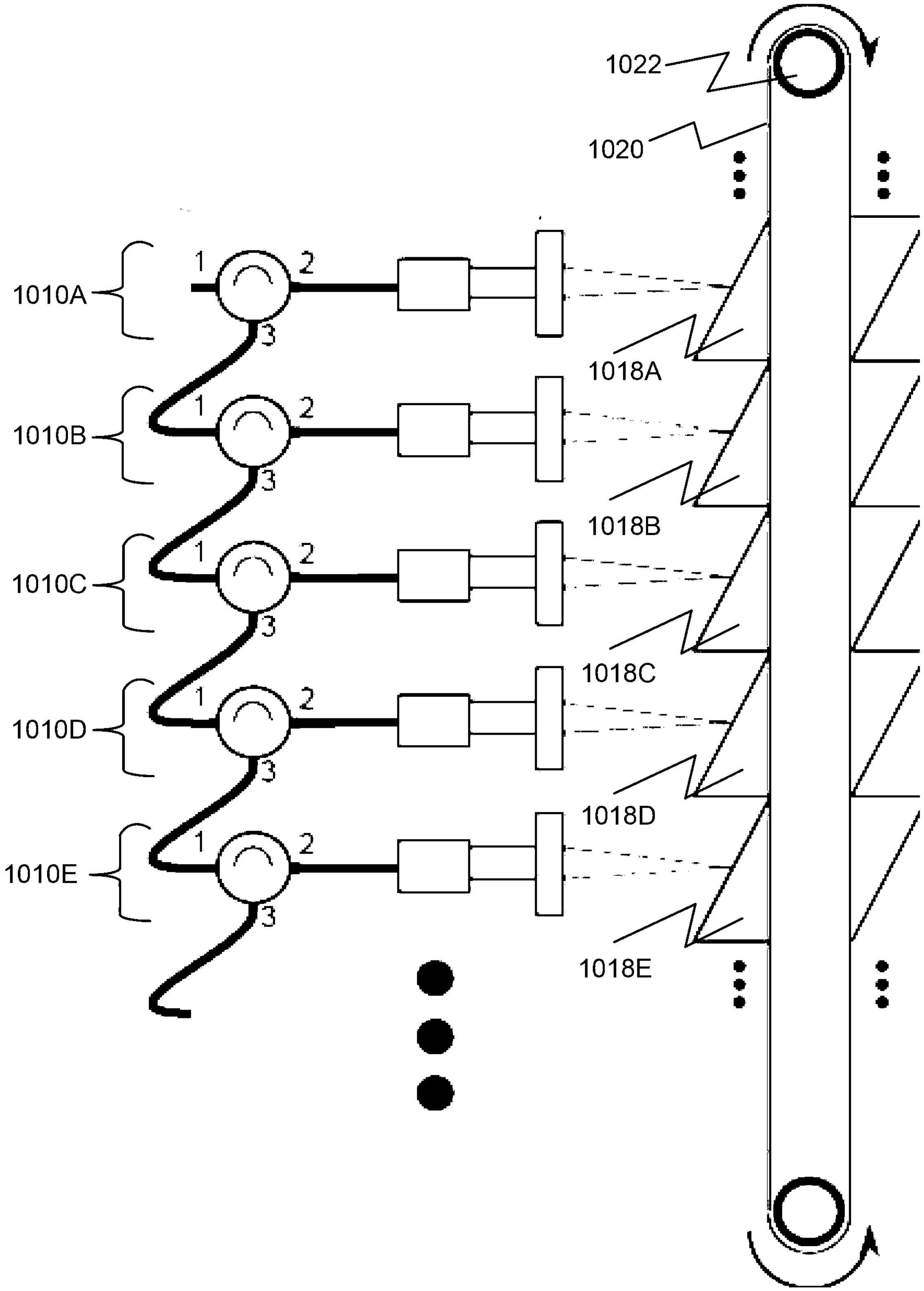
1022
1020
1010A
1
2
3
1018A
1010B
1018B
1010C
1018C
1010D
1018D
1010E
1018E

Figure 10B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2017/000121

A. CLASSIFICATION OF SUBJECT MATTER

G01B 9/02 (2006.01) G02B 5/08 (2006.01)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

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

PATENW, WPIAP, EPODOC: CPC/IPC: G01B9, G02B6/2861, G02B5/08, Applicant/Inventor search, Keywords (optical, delay, cascade, series, multiple, series, mirror, reflect, rotate, phase) & like terms; Google Scholar, Google, Google Patents: Keywords (OCT, optical delay, mirror, rotating, synchronous, phase, cascade, multiple) & like terms; Applicant/Inventor names searched on internal databases provided by IP Australia

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

☒ Further documents are listed in the continuation of Box C ☒ See patent family annex

*	Special categories of cited documents:		
"A"	document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 24 August 2017	Date of mailing of the international search report 24 August 2017
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustralia.gov.au	**Authorised officer** Frank Detering AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. +61262832641

INTERNATIONAL SEARCH REPORT C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		International application No. **PCT/AU2017/000121**
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/0078510 A1 (RUBIO GUIVERNAU et al.) 20 March 2014 Abstract, FIG. 4A/B,17 PARA [0039,0041-0044]	1,6-16
X	US 7433046 B2 (EVERETT et al.) 07 October 2008 Abstract, FIG. 1, 2A/B, COL 5 line 17 - COL 8 line 8, COL 14 lines 54-58	1-16
X	CHEN, N.G., et al., "Rotary mirror array for high-speed optical coherence tomography", Optics Letters (2002), Vol. 27, No. 8, pages 607-609 Abstract, FIG. 1-2, page 608 last paragraph left column - second paragraph right column, page 609 left column	1-16

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2017/000121**

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		**Patent Family Member/s**	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
US 2014/0078510 A1	20 March 2014	US 2014078510 A1	20 Mar 2014
		US 9354040 B2	31 May 2016
		AU 2012260954 B2	18 Jun 2015
		BR 112013029785 A2	17 Jan 2017
		CA 2836609 A1	29 Nov 2012
		CN 103688133 A	26 Mar 2014
		CN 103688133 B	01 Mar 2017
		EP 2710327 A1	26 Mar 2014
		ES 2415555 A1	25 Jul 2013
		ES 2415555 B2	09 Jul 2014
		JP 2014517286 A	17 Jul 2014
		JP 6118796 B2	19 Apr 2017
		WO 2012160005 A1	29 Nov 2012
US 7433046 B2	07 October 2008	US 2006072424 A1	06 Apr 2006
		US 7433046 B2	07 Oct 2008
		EP 1784677 A1	16 May 2007
		EP 1784677 B1	04 May 2011
		WO 2006028926 A1	16 Mar 2006

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.