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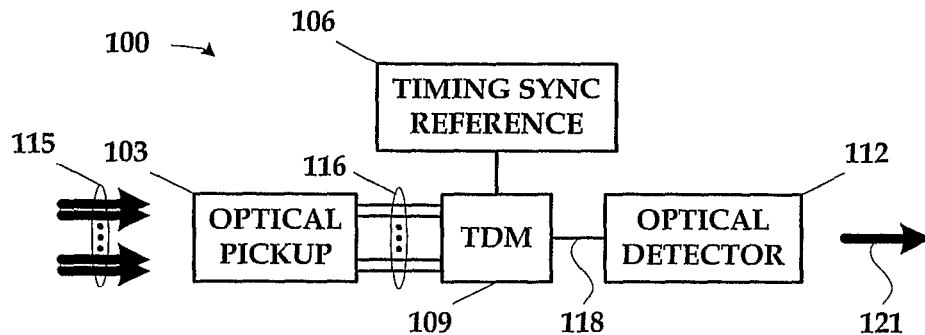
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(54) Title: SINGLE DETECTOR RECEIVER FOR MULTI-BEAM LADAR SYSTEMS



(57) Abstract: A LADAR apparatus and a method for use in receiving a LADAR signal are disclosed. The apparatus includes an optical pickup capable of picking up a plurality of optical signals; a timing synchronization reference; a time domain multiplexer capable of multiplexing the optical signals into a multiplexed optical signal relative to the timing synchronization reference; and an optical detector capable of detecting the multiplexed optical signal. The method include time domain multiplexing a plurality of LADAR signals into multiplexed LADAR signal; detecting the multiplexed LADAR signal; and demultiplexing the detected LADAR signal.



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SINGLE DETECTOR RECEIVER FOR MULTI-BEAM LADAR SYSTEMS

BACKGROUND OF THE INVENTION

5 1. FIELD OF THE INVENTION

The present invention pertains to LADAR systems, and, more particularly, to a LADAR receiver for use in a multi-beam LADAR system.

10 2. DESCRIPTION OF THE RELATED ART

Many military and civilian applications rely on optical techniques such as laser detection and ranging ("LADAR"). At a very high level, LADAR works much like the more familiar radio wave detection and ranging ("RADAR"), in which radio waves are transmitted into the environment and reflected back, the reflections giving range and position information for the objects that generate them. LADAR does roughly the same thing, but using light rather than radio waves. Although there are some significant differences in performance, they are similar in at least this one basic respect.

Some LADAR systems employ a laser signal that is a pulsed, split-beam laser signal. That is, the LADAR transmitter transmits a laser signal in short bursts rather than continuously. The laser signal is often split into several spaced apart beamlets. Each pulse of the single beam is split, and so the laser signal transmitted is actually a series of grouped beamlets. The beamlets are then reflected to a LADAR receiver that picks up the reflected beamlets so that they can be detected, conditioned, and processed.

To actually detect the reflected laser signal, many LADAR transceivers use avalanche photodiodes ("APDs") because they are fast, high gain photo-multiplication devices. Although highly sensitive in the avalanche mode of operation, APDs can be unpredictable with non-linear and inconsistent responsivity between devices. These problems are exacerbated when APDs are used in multi-channel systems because their gain variation can make channel equalization difficult. Still further, the use of multiple APDs also means that the performance of the system as a whole hinges on the weakest APD, which statistically lowers performance. APDs are also expensive and their support electronics can be complex. Since each detector requires duplication of electronics in a multi-channel receiver, reducing the required number of

APDs is important to reducing overall cost and packaging volume in a multi-beam LADAR system.

The present invention is directed to resolving, or at least reducing, one or all of the problems mentioned above.

SUMMARY OF THE INVENTION

The invention includes, in its various aspects and embodiments, a LADAR apparatus and a method for use in receiving a LADAR signal. The apparatus includes an optical pickup capable of picking up a plurality of optical signals; a timing synchronization reference; a time domain multiplexer capable of multiplexing the optical signals into a multiplexed optical signal relative to the timing synchronization reference; and an optical detector capable of detecting the multiplexed optical signal. The method include time domain multiplexing a plurality of LADAR signals into multiplexed LADAR signal; detecting the multiplexed LADAR signal; and demultiplexing the detected LADAR signal. In other aspects, the invention includes analogous means for performing the recited functions.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may be understood by reference to the following description taken in conjunction with the accompanying drawings, in which like reference numerals identify like elements, and in which:

FIG. 1 conceptually illustrates in a block diagram an optical detection apparatus for use in a multi-beam LADAR system in accordance with the present invention;

FIG. 2 is a block diagram of the time domain multiplexer of the optical detection apparatus of **FIG. 1**;

FIG. 3A – FIG. 3B conceptually illustrate two alternative embodiments of the delay in **FIG. 2**;

FIG. 4 depicts one particular embodiment of a LADAR system acquiring data about a field of view through an optics package aboard a platform shown therein, the optics package being constructed and operated in accordance with the present invention;

FIG. 5 illustrates selected timing parameters for the time domain multiplexing of the apparatus in **FIG. 1**;

FIG. 6A – FIG. 6C conceptually illustrate alternative embodiments of the combiner in **FIG. 2**; and

FIG. 7 – FIG. 12 illustrate particular embodiments of LADAR receivers constructed in accordance with the present invention.

While the invention is susceptible to various modifications and alternative forms, the drawings illustrate specific embodiments herein described in detail by way of example. It should be understood, however, that the description herein of specific embodiments is not intended to limit the invention to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

Illustrative embodiments of the invention are described below. In the interest of clarity, not all features of an actual implementation are described in this specification. It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort, even if complex and time-consuming, would be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

FIG. 1 illustrates an optical detection apparatus 100 for use in a multi-beam LADAR system. The optical detection apparatus 100 comprises an optical pickup 103, a timing synchronization reference 106, a time domain multiplexer ("TDM") 109, and an optical detector 112. The optical pickup 103, in operation, picks up a plurality of optical signals 115. The optical signals 115 are, in the illustrated embodiment, reflections of a multi-beam LADAR signal, as will be described further below. Once picked-up, the optical signals 115 are transmitted through a plurality of channels 116, one channel 116 for each of the optical signals 115. The time domain multiplexer 109 then multiplexes the optical signals 115 into a multiplexed optical signal 118 relative to the timing synchronization reference 106. The

optical detector 112 then detects the multiplexed optical signal 118 and, typically, converts it to an electrical signal 121.

Some aspects of the illustrated embodiment may be implemented in conventional fashion. For instance, the optical pickup 103 comprises a plurality of fibers (not shown), *e.g.*,
5 an array of optical fibers, although other techniques may be employed. Similarly, the timing synchronization reference 106 may comprise a backscatter reference (not shown) or a trigger signal (also not shown) for a laser (not shown) generating the LADAR signal. Similarly, the optical detector 112 may be implemented using an avalanche photodiode (“APD”) such as are well known and commonly used in the art for this purpose.

10 However, the time domain multiplexer 109 is implemented in accordance with the present invention. As is shown in **FIG. 2**, the time domain multiplexer 109 may include a delay 200 for each of the optical signals 115 and a combiner 203. More particularly, the delay 200 introduces a delay in the propagation of each channel 116. The combiner 203 combines the delayed optical signals 115 into the multiplexed signal 121, and the multiplexing is
15 performed at a time measured relative to the timing synchronization reference 106. Since each of the optical signals 115 is delayed by a staggered amount, the information of interest they carry is likewise staggered. Consequently, when the optical signals 115 are combined, no information is overwritten. Because the time domain multiplexer 109 performs the multiplexing relative to the timing synchronization reference 106 and the delays are by known
20 amounts, the capture electronics (not shown) can extract the information.

The invention admits variation in the manner in which the delay 200 may be introduced. Brute force techniques might include using mirrors or varying lengths of the channels 116 to lengthen the path of propagation, but more sophisticated techniques might be used. **FIG. 3A – FIG. 3B** depict two alternative implementations for the delay 200. Note that
25 these two implementations are illustrative only, and that other embodiments of the delay 200 may be employed.

In **FIG. 3A**, a unique, staggered delay is introduced into each of the channels 116 by varying the lengths of the fibers 300 (only one indicated) defining the channels 116. For illustrative purposes, the delay 200’ is shown for seven channels 116, although the number of
30 channels 116 is not material to the practice of the invention. The varying length of the fibers 300 is conveyed by the varied number and size of the loops 303 (only one indicated) therein. Each loop 300, depending on its size, introduces a known delay into the channel 116 that is

proportional to its length. Note that the geometry of the loops 303 is not what is important to the practice of the invention, but the length of the fiber 300. Thus, the extra length in the fibers 303 need not necessarily be formed or positioned into loops. Note also that, in variations of this embodiment, one of the channels 116 might not have any loops 303.

5 However, it may take relatively long lengths of the fiber 300 to introduce a significant enough delay given the speed at which the optical signals 115 will propagate. In some embodiments, design constraints may mitigate against long lengths of fiber 300. **FIG. 3B** illustrates a delay 200" that addresses this concern. In the delay 200", each of the channels 116 includes a fiber 300' (only one indicated) with one or more loops 303' (only one indicated) of
10 varying number and size. However, each channel 116 also includes an optical circulator 306, a lens 309, and a mirror 312 (only one of each indicated).

 The optical circulators 306 are three-port circulators. Each optical circulator 306 receives the respective optical signal 115 from the optical pickup 103, shown in **FIG. 1**, on one port 315. The optical circulator 306 then redirects the optical signal 115 through a second port
15 318 and to the lens 309 and mirror 312 over that part of the fiber 300' containing the loop(s) 303'. The lens 309 collimates the beam received from the optical pickup 103 over the channels 116 such that the beam retro-reflects off the mirror 312 and back to the fiber 300' with maximum coupling efficiency and fine attenuation resolution. The mirror 312 reflects the optical signals 115 back to the optical circulator 306 through the same length of the fiber 300'
20 containing the loop(s) 303'. The optical circulator 306 then receives the reflected optical signal 115 on the second port 318 and redirects it to the combiner 203, shown in **FIG. 2**, through a third port 321. Because the optical signal 115 travels the length of the fiber 300' containing the loops 303' twice, this implementation essentially halves the amount of fiber 300' relative to the amount of fiber 300 in the delay 200' of **FIG. 3A**.

25 The amount of delay introduced into the channels 116 is not material to the practice of the invention. However, there are some timing constraints. As those in the art having the benefit of this disclosure will appreciate, the optical signals 115 typically will not be continuous because they typically will be pulsed. Or, if the optical signals 115 are continuous, the desired information will not be continuous, but will rather be pulsed. This is a function of
30 how LADAR works. Note that an excess range variance may "push or overflow" a pulse into the wrong time bin. To reduce this risk, existing range data from various test flights could be analyzed to calculate an acceptable fiber-optic delay. Staggered delays will likely be on the

order of 1 - 5 $\mu\text{sec}/\text{step}$. Extra attention may be desirable for LADAR at shallow depression angles due to the potential overflow of pulses into the wrong range bin.

In the alternate approach, for example, two detectors could support 8-channels with a 1500 meter range-gate at the present laser pulse rate. There would be four 10-microsecond bins spread across the period between laser firings. This would be accomplished with three fiber-optic spools of 10, 20 and 30 microseconds delay per detector. In the unlikely case that a return pulse exceeded the expected range-gate period, it would be "pushed" into the next channel's range bin. If this is a concern, a variable optical amplifier ("VOA") could be activated at the end of the period to block any outliers. Again the VOA must be somewhat fast acting, but it need not achieve as much attenuation as in the previous case. The penalty for using the absolute-method is the need for much longer fiber-optic delays and of course, more than one detector will be required in most applications. Its advantages are a) no VOA is necessarily needed and b) no activation pulse is required that might cause synchronization problems. A VOA can also be used as part of the AGC implementation although a slow-acting, low-attenuation device would be adequate in this application.

For example, **FIG. 4** depicts one particular embodiment of a LADAR system in accordance with the present invention. This particular LADAR system is a multi-beam pulsed imaging system. A frame of image data is composed of groups (or nods) of scan lines formed from multiple beams with individual receiver channels. Every firing of the laser produces a set of scene pixels. Each of the receive data channels (plus a reference) has a separate fiber-coupled photo-detector to convert the optical return into an electrical pulse. Signal processing then extracts digital range and intensity values for each pixel. The laser firing also produces a large "backscatter" pulse that can overload the detectors. This causes the detectors to go into saturation and then require a recovery period before returning to normal operation.

More particularly, the LADAR system acquires data about a field of view 425 through LADAR transceiver 400 aboard a platform 410. The LADAR transceiver includes a detection side comprising the optical detection apparatus 100 of **FIG. 1**. The LADAR transceiver 400 transmits the laser signal 405, as represented by the arrow 465, through the field of view 425. The platform 410 may be, for example, a reconnaissance drone or a flying submunition in the illustrated embodiment. In alternative embodiments, the platform 410 may be a ground vehicle, or a watercraft, or perhaps even a stationary post. There is no requirement that the

platform 410 be a vehicle. The nature of the platform 410 in any given implementation is immaterial.

The LADAR transceiver 400 transmits the laser signal 405 using an acquisition technique described above is what is known as a “scanned” illumination technique. The laser signal 405 is typically a pulsed, split-beam laser signal. The LADAR transceiver 400 produces a pulsed (*i.e.*, non-continuous) single beam that is then split into several beamlets spaced apart from one another by a predetermined amount. Each pulse of the single beam is split, and so the laser signal 405 transmitted during the elevational scan 450 in **FIG. 4** is actually, in the illustrated embodiment, a series of grouped beamlets.

Suitable mechanisms for use in generation laser signal 405 are disclosed in:

- U.S. Letters Patent No. 5,200,606, entitled “Laser Radar Scanning System,” issued April 6, 1993, to LTV Missiles and Electronics Group as assignee of the inventors Nicholas J. Krasutsky, *et al.*; and
- U.S. Letters Patent No 5,224,109, entitled “Laser Radar Transceiver,” issued June 29, 1993, to LTV Missiles and Electronics Group as assignee of the inventors Nicholas J. Krasutsky, *et al.*

However, any suitable mechanism known to the art may be employed. Note that the detection side of the transceivers disclosed in the patents listed above are replaced by the present invention.

More technically, the LADAR transceiver 400 transmits the laser signal 405 to scan a geographical area called a “scan pattern” 420. Each scan pattern 420 is generated by scanning elevationally, or vertically, several times while scanning azimuthally, or horizontally, once within the field of view 425 for the platform 410. **FIG. 4** illustrates a single elevational scan 430 during the azimuthal scan 440 for one scan pattern 420. Thus, each scan pattern 420 is defined by a plurality of elevational scans 450 such as the elevational scan 430 and the azimuthal scan 440. The principal difference between the successive scan patterns 420 is the location of the platform 410 at the start of the scanning process. An overlap 460 between the scan patterns 420 is determined by the velocity of the platform 410. The velocity, depression angle of the sensor with respect to the horizon, and total azimuth scan angle of the LADAR platform 410 determine the scan pattern 420 on the ground. Note that, if the platform 410 is relatively stationary, the overlap 460 may be complete, or nearly complete.

Thus, the LADAR system 400 transmits the pulsed laser signal 405 into field of view 425. Objects in the field of view 425 reflect the pulsed laser signal 405 back to the platform 410. The LADAR system 400 receives the reflected laser signal 405, which is actually a set of reflected beamlets since the transmitted laser signal comprises beamlets. It is this set of received beamlets that comprise the optical signals 115 in **FIG. 1**.

Still referring to **FIG. 4**, the estimated time of return for the reflected beamlets from the expected range can be obtained from an estimated flight time. The flight time can be estimated from factors such as the depression angle of transmission and platform velocity. The time at which each pulse of the laser signal 405 is fired is also known. From these pieces of information, a window in time is defined in which it can be expected that the optical signals 115 will arrive for detection. This kind of information is frequently used in LADAR systems for performing what is known as "range gating," and techniques for gauging these timing parameters are well known to the art. The window for detecting any given pulse of the laser signal 405 is, at the most, the period from the time at which the current pulse of beamlets arrives until the estimated arrival time for the next succeeding pulse. Typically, the window is defined to be much shorter based on the expected flight time, and the detection is gated to accommodate the window.

FIG. 5 is a representative timing diagram for one particular embodiment. For LADAR applications, where the relative timing dispersion of the beamlet pulses is small, only short fiber delays are needed. The fiber delays will then be multiples of the maximum expected dispersion. The dispersion will be smallest for "steep" depression angle systems. Also, in this case, the occurrence of a particular pulse should be known to properly demultiplex the combined pulses. The maximum fiber delays occur when the group of beamlet pulses can individually occur anywhere within the system range gate period. The fiber delays will then be multiples of the range gate. In this case, the demultiplexing will be strictly based on the laser clock timing; no particular pulse dependency is required. Of course, long fibers have more cost, size and attenuation than with the short arrangement.

FIG. 5 illustrates some of these timing parameters in part for four channels 116₀ – 116₃ and the multiplexed optical signal 118 in one particular embodiment. Note that **FIG. 5** does not represent a complete picture of the conditioning of the optical detection apparatus 100 of **FIG. 1**. Note also that the illustrated timing parameters are implementation specific, and will vary in alternative embodiments.

The backscatter pulse 500, which is the timing synchronization reference 106 in this particular embodiment, is shown as having entered each of the channels 116₀ – 116₁. Note that, in this particular embodiment, the backscatter pulse 500 should not be a “dropout” pulse in order to properly demultiplex the information during subsequent processing. Individual data pulses 503₀ – 503₃, received via the optical pickup 103, are shown in the channels 116₀ – 116₃. In the illustrated embodiment, the data pulses 503₀ – 503₃ are separated by 0.1 μsec apiece. Thus, if the data pulse 503₀ arrives at, for instance, 0.8 μsec, the data pulses 503₁ – 503₃ arrive at 0.9, 1.0, and 1.1 μsec, respectively. Note that these numbers are representative only, and that arrival times will be implementation and context specific. The data pulses 503₀ – 503₃ are then introduced to fiber optic delays, as described above, of 0.0, 1.0, 2.0, and 3.0 μsec, respectively. The expected maximum spread of the returned, data pulses 503₀ – 503₃ about a specific range determines the minimum fiber optic step delay (1.0 μsec, here). Thus, anticipated platform operational scenarios should be considered so as to support, as well as determine, the assumptions on which the step delay is formulated.

A combined data pulse 506₀, comprising the combined data pulses 503₀ – 503₃ after the fiber optic delays, is shown in the multiplexed optical signal 118. Previous backscatter pulses 500₀ – 500₂ are also shown in the multiplexed optical signal 118, as are previous composite data pulses 506₁ – 506₃. The individual data pulses comprising the composite data pulses 506₁ – 506₃ are not shown in the channels 116₀ – 116₃ for the sake of clarity and so as not to obscure the present invention.

One of the channels, *i.e.*, the channel 116₀, has no fiber optic delay and thus be the first pulse in the received group to reach the detector. This first pulse will be used to initiate the demultiplexing sequence. A series of timing windows will then open to extract each pulse. Any pulse detected within a given window will be defined as originating from the corresponding optical channel. Multiple pulses within a window can be treated as they are now, as a function of the selected pulse-logic mode. Note that, if necessary to compensate for delay changes due to fiber-optic thermal expansion, a correction factor can be generated by a look-up-table in subsequent processing or by using a reference pulse for calibration.

Note that the intervening period between the backscatter pulses 500₀ – 500₂ and the composite pulses 506₀ – 506₃ is not constant, which results in a collision between the

backscatter pulse 500₂ and the composite pulse 506₂. Such collisions result from fiber optic delays less than the maximum expected range delay unless the backscatter pulses 500, 500₀ – 500₂ are blocked from entering the respective fibers. This, and many of the difficulties in these timing considerations, can be mitigated or eliminated if the fiber optic step delay is longer than
5 the maximum expected range.

In this alternate method, if the inserted delay-step is increased to exceed the sensor's maximum absolute range-return, then the relative grouping is not a concern. Each channel is treated independently and no initiation-pulse is required. The time bins will be in fixed locations that are spread out between laser firings. In this case, the maximum number of data
10 channels to be supported per detector is the laser-firing period divided by the maximum range-gate time. However, this would limit the number of channels per detector given the present assumptions regarding laser pulse rate ("LPR") and maximum range. Typically, two to four detectors would be required depending on this calculation and other considerations. Such an approach would also lead to more fiber optic attenuation and packaging problems, and more
15 potential for pulse transmission effects (*e.g.*, spreading, temperature, *etc.*).

The combiner 203, shown in **FIG. 2**, can multiplex the signals in any suitable manner known to the art. **FIG. 6A – FIG. 6C** conceptually illustrate three alternative embodiments 203' – 203'' for implementing the combiner 203 in **FIG. 2**. Turning first to **FIG. 6A**, the combiner 203' comprises a lens 600 that focuses the optical signals 115 emerging from the
20 fibers 300 of the channels 116₀ – 116_x onto the active surface 603 of the optical detector 112. The optical detector 112 then simultaneously detects all the energy from each of the channels 116₀ – 116_x. The combiner 203'' is a tree coupler, in which a plurality of individual, 2-to-1 couplers 606 (only one designated) are used to ultimately combine all channels 116₀ – 116_x (seven are shown for purposes of illustration) into the combined signal 118. In **FIG. 6C**, the
25 combiner 203''' comprises a plurality of cascaded tap couplers 612 (only one indicated).

In each of the cases shown in **FIG. 6A – FIG. 6C**, the information in each channel 116₀ – 116_x is delayed by a known amount. Furthermore, the delayed optical signal 115 of each channel 116₀ – 116_x is multiplexed into the combined signal 118 at a known time because it is done so relative to the timing and synchronization reference 106. Accordingly, the desired
30 information can be combined in this manner without losing any of the information and in such a fashion that it can later be separated out. Note that, if desired, the last pulse (instead of the first pulse) to reach the detector can be used to initiate the demultiplexing sequence in

alternative embodiments. In that case, the entire digitized pulse train would need to be stored prior to demultiplexing. For instance, the pulse train could be stored in the FGPA (not shown).

These alternative embodiments and other variations may be combined in a number of ways to produce a number of different designs. **FIG. 7 – FIG. 11** illustrate several alternative, particular implementations of LADAR receivers in accordance with the present invention. Note that each of these LADAR receivers could be used to implement the detection side of a LADAR transceiver (not shown). Indeed, each of the LADAR receivers in **FIG. 7 – FIG. 11** is intended for use in a gimbaled LADAR transceiver for use in a scanned illumination type of application as is illustrated in **FIG. 4**. Many of the embodiments in **FIG. 7 – FIG. 11** share common components, with like parts bearing like numbers.

Turning now to **FIG. 7**, a LADAR receiver 700 is shown. The receiver 700 comprises an on-gimbal subassembly 703 and an off-gimbal subassembly 706. Note that whether any particular component is “off-gimbal” or “on-gimbal” is not material to the practice of the invention. The on-gimbal subassembly 703 includes:

- a back-scatter reference 709 implementing the timing and synchronization reference 106 of **FIG. 1**; and
- a fiber array 712 implementing the optical pickup 103 of **FIG. 1**.

The off-gimbal subassembly 706 includes:

- a delay 200', as shown in **FIG. 3A**;
- an $m \times 1$ tree coupler 203", such as is shown in **FIG. 6B**;
- a fast variable optical attenuator (“VOA”) 715 that controls the gain of the combined signal 118 and blocks backscatter; and
- an avalanche photodiode (“APD”) 718 that implements the optical detector 112 of **FIG. 1**.

The on-gimbal subassembly 703 is optically connected to the off-gimbal assembly 706 by and optical connection 721 between the two. The optical connection 721 in this particular embodiment is implemented by optical fibers 724 and a pair of mated optical connectors 727.

More particularly, the back scatter reference 709 detects the firing of the laser (not shown) via, *e.g.*, an APD (not shown). The back-scatter reference 709 signals the tree coupler 203" over the optical line 730 of the firing so that the tree coupler 203" can synchronize its operation to the operation of the rest of the transceiver. The fiber array 712 picks up the return

pulses 115, shown in **FIG. 1**, and transmits them over the optical connection 721 to the off-gimbal subassembly 706.

The VOA 715 is a fast acting VOA to block the "backscatter" fire pulse from getting to the detector(s), *i.e.*, the APD 718. This will occur with common transmit/receive aperture optics. With separate optics, a fast VOA may not be required. The VOA 715 is also not required to block the backscatter for the case of "long" fiber delays since there is no possibility of pulse/backscatter timing overlap. The VOA can be either in the transmit path, or the receive path, or both. However, in the illustrated embodiment, a fast-acting VOA is used to suppress the interference of multiple backscatter pulses on the data pulses when they are all combined at the detector. Ideally the VOA should attenuate the backscatter interference pulse to below the A/D threshold and then return to minimum attenuation in less than a microsecond. If such a VOA is impractical, then an alternate absolute scheme can be implemented wherein the inserted delay-step is increased to exceed the sensor's maximum absolute range-return.

In the off-gimbal subassembly 706, the optical connection 721 transmits the picked-up optical signals 115 to the delay 200', which introduces delay into the channels $116_0 - 116_x$ as illustrated in **FIG. 3A** and as discussed above. The delayed optical signals 115 then propagate through the channels $116_0 - 116_x$ to the tree coupler 203". The tree coupler 203" then combines the delayed optical signals 115 as shown in **FIG. 6B** and also as discussed above. The fast VOA 715 then controls the gain of the combined signal 118 output by the tree coupler 203" to prevent the APD 718 from being over- or under-saturated. The APD 718 detects the combined signal 118 and converts it into an electrical signal that can then be further conditioned and processed.

FIG. 8 illustrates an alternative LADAR receiver 800. The LADAR receiver 800 comprises an on-gimbal subassembly 703, first shown in **FIG. 7** and discussed above, optically connected over an optical connection 721 to an off-gimbal subassembly 803. The off-gimbal subassembly 803, like the off-gimbal assembly 706 in **FIG. 7**, also employs a delay 200', as is shown in **FIG. 3A**. However, the off-gimbal subassembly 803 employs a combiner 203', such as is shown in **FIG. 6A** and as discussed above. However, because combination occurs at the APD 718, the single fast VOA 715 of **FIG. 7** has been replaced by a multi-channel fast VOA 806.

FIG. 9 illustrates an alternative LADAR receiver 900. The LADAR receiver 900 also comprises an on-gimbal subassembly 703, first shown in **FIG. 7** and discussed above, optically connected over an optical connection 721 to an off-gimbal subassembly 903. However, the off-gimbal subassembly 903 employs a delay 200' and combiner 203'', conceptually illustrated in better detail in **FIG. 6C**. However, the LADAR receiver 900 also includes two optional features. First, the LADAR receiver 900 includes a fast switch 906 and a redundant optical detector, *i.e.*, the APD 718' for situations in which the APD 718 becomes disabled or otherwise becomes inoperable. Second, the LADAR receiver 900 includes a reference detector, *i.e.*, the PIN diode 909 that optically taps the line 912 for, *e.g.*, closed loop automatic gain control, field calibration, or electronic optical counter counter measure ("EOCCM") purposes.

FIG. 10 illustrates a third alternative LADAR receiver 1000 comprising an on-gimbal subassembly 703, first shown in **FIG. 7** and discussed above, optically connected over an optical connection 721 to an off-gimbal subassembly 1003. Note that the attenuation occurs before the delay, and so the fast VOA 715 has been replaced by a multi-channel fast VOA 806. Furthermore, the fast switch 906 in **FIG. 9** has been replaced by a polarization splitter 1006 such that the second APD 718' may be used for a polarimetric LADAR. Note that the optical fibers in this embodiment should be polarization maintaining fibers.

FIG. 11 illustrates a fourth alternative LADAR receiver 1100. The LADAR receiver 1100 also comprises an on-gimbal subassembly 703, first shown in **FIG. 7** and discussed above, optically connected over an optical connection 721 to an off-gimbal subassembly 1103. Note that the off-gimbal subassembly 1103 does not include a second APD 718'. The off-gimbal subassembly 1103 also does not attenuate the optical signals, although variants could do so either before the delay 200'' using a multi-channel VOA 715', as in the embodiment of **FIG. 10**, or after the delay 200'' using a VOA 715, as in the embodiment of **FIG. 9**. Note also that the off-gimbal subassembly 1103 also employs the delay 203'' rather than the delay 203'.

Thus, the present invention takes advantage that in an air-to-ground multi-beam LADAR system, each set of return pulses has a "tight" relative range grouping. The sensor depression angle produces a ground footprint that causes the return pulses to have "similar" range values. This new approach inserts a staggered amount of (fiber-optic) delay into each receive channel. These staggered optical delays will "spread out" a set of return pulses into separate (offset) time bins. The fixed delays will have been selected to assure that each bin is

wide enough to account for the maximum expected range variances within each pixel set. The multiple fiber outputs are then applied to a single detector. Thus, the detector will “see” (for each laser firing) a series of compartmentalized pulses. The detector output will be digitized for further processing within a field-programmable-gate-array (“FPGA”) in accordance with conventional practice. The pulse train will then be demultiplexed into individual pulses for analysis.

The major electronic advantage is the hardware reduction of eight or more channels into a single channel. This includes detectors, post amplifiers, AGC components and high-speed A/Ds. Also a reduced FPGA pin count will lead to a smaller, less costly package. A single-detector system will also eliminate all channel-to-channel component variances that would have occurred downstream of the detector inputs. Cross-coupling, layout and board noise issues will be greatly reduced. The electronics board would be universal; no redesign would be necessary to support any number of channels. Furthermore, since the detectors are inherently fragile, minimum usage will equate to higher system reliability. It may be more cost-effective to obtain a small number of high-quality detectors than a very large quantity of mediocre detectors. A reduction in board complexity will put less pressure on maintaining a compact detector size.

This concludes the detailed description. The particular embodiments disclosed above are illustrative only, as the invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. For instance, Figure 12 illustrates another alternative embodiment 1200 arrived at by “mixing and matching” components previously described with reference to other embodiments. Furthermore, the present invention may be employed in construction site surveying and monitoring, autonomous vehicle navigation, danger environment control, manufacturing process control, and remote sensing. Also, if desired, the last pulse—instead of the first pulse—reaching the detector could be used to initiate the demultiplexing sequence, although, in that case, the entire digitized pulse-train would need to be stored within the FPGA. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are

considered within the scope and spirit of the invention. Accordingly, the protection sought herein is as set forth in the claims below.

CLAIMS**WHAT IS CLAIMED:**

- 1 A LADAR apparatus, comprising:
an optical pickup capable of picking up a plurality of optical signals;
a timing synchronization reference;
a time domain multiplexer capable of multiplexing the optical signals into a
5 multiplexed optical signal relative to the timing synchronization reference; and
an optical detector capable of detecting the multiplexed optical signal.
2. The LADAR apparatus of claim 1, wherein the optical pickup comprises a plurality of fibers.
3. The LADAR apparatus of claim 1, wherein the timing synchronization reference
10 comprises a backscatter reference or a laser trigger signal.
4. The LADAR apparatus of claim 1, wherein the time domain multiplexer includes:
a delay for each of the optical signals, each delay being staggered and being measured
relative to the timing synchronization reference; and
a combiner capable of combining the delayed optical signals into the multiplexed
15 signal.
5. The LADAR apparatus of claim 4, wherein the delay comprises varying lengths of optical fiber, each optical signal propagating through a unique length of fiber.
6. The LADAR apparatus of claim 5, wherein the delay further comprises:
a plurality of optical circulators, one for each of the optical signals, positioned at one
20 end of the respective length of optical fiber; and
a plurality of reflectors, one for each of the optical signals, positioned at the opposite
end of the respective length of optical fiber.
7. The LADAR apparatus of claim 4, wherein the combiner comprises one of a tree coupler or a cascade of tap couplers.
- 25 8. The LADAR apparatus of claim 4, wherein the combiner comprises:

the active surface of the optical detector; and
a lens focusing the picked-up, delayed optical signals onto the active surface.

9. The LADAR apparatus of claim 1, further comprising a PIN detector tapping the multiplexed optical signal.

5 10. The LADAR apparatus of claim 1, further comprising:
a second optical detector; and
at least one of a switch and a polarization splitter through which the second optical
detector receives the multiplexed optical signal.

11. The LADAR apparatus of claim 1, further comprising a variable optical attenuator.

10 12. The LADAR apparatus of claim 11, wherein the variable optical attenuator comprises a
single channel variable optical attenuator capable of attenuating the multiplexed optical signal.

13. The LADAR apparatus of claim 11, wherein the variable optical attenuator comprises a
multi-channel variable optical attenuator capable of individually attenuating the plurality of
optical signals.

15 14. The LADAR apparatus of claim 1, wherein the optical detector comprises an avalanche
photodiode.

15 A LADAR apparatus, comprising:
means for picking up a plurality of optical signals;
means for time domain multiplexing the optical signals; and
20 means for detecting the multiplexed optical signal.

16. The LADAR apparatus of claim 15, wherein the pickup means comprises a plurality of
fibers.

17. The optical detecting apparatus of claim 15, wherein the time domain multiplexing
means includes:

25 means for synchronizing the multiplexing;
means for delaying each of the optical signals by a staggered amount measured relative
to the synchronizing means; and

means for combining the delayed optical signals into the multiplexed signal.

18. The LADAR apparatus of claim 17, wherein the synchronizing means comprises a backscatter reference or a laser trigger signal.

19. The LADAR apparatus of claim 17, wherein the delaying means comprises varying
5 lengths of optical fiber, each optical signal propagating through a unique length of fiber.

20. The LADAR apparatus of claim 19, wherein the delaying means further comprises:
a plurality of optical circulators, one for each of the optical signals, positioned at one
end of the respective length of optical fiber; and
a plurality of reflectors, one for each of the optical signals, positioned at the opposite
10 end of the respective length of optical fiber.

21. The LADAR apparatus of claim 17, wherein the combining means comprises one of a tree coupler or a cascade of tap couplers.

22. The LADAR apparatus of claim 17, wherein the combining means comprises:
the active surface of the optical detector; and
15 a lens focusing the picked-up, delayed optical signals onto the active surface.

23. The LADAR apparatus of claim 15, further comprising a PIN detector tapping the multiplexed optical signal.

24. The LADAR apparatus of claim 15, further comprising:
second means for detecting the multiplexed optical signal; and
20 means for directing the multiplexed optical signal to the second detecting means.

25. The LADAR apparatus of claim 24, wherein the directing means comprises at least one of a switch and a polarization splitter.

26. The LADAR apparatus of claim 15, further comprising a variable optical attenuator.

27. The LADAR apparatus of claim 15, wherein the detecting means comprises an
25 avalanche photodiode.

28. A method, comprising:
time domain multiplexing a plurality of LADAR signals into multiplexed LADAR
signal;
detecting the multiplexed LADAR signal; and
5 demultiplexing the detected LADAR signal.
29. The method of claim 28, wherein time domain multiplexing the LADAR signals
includes:
inserting a unique, staggered delay into each of the LADAR signals; and
combining the delayed LADAR signals.
- 10 30. The method of claim 29, wherein inserting the delays includes propagating the received
LADAR signals through varied lengths of optical fibers.
31. The method of claim 30, wherein inserting the delays further includes circulating the
LADAR fibers through the optical fibers to a respective reflector and back through a lens.
32. The method of claim 29, wherein combining the delayed LADAR signals includes
15 combining them through one of a tree coupler or a cascade of tap couplers.
33. The method of claim 29, wherein the wherein combining the delayed LADAR signals
includes focusing the delayed LADAR signals onto the active surface of the optical detector.
34. The method of claim 28, further comprising detecting the combined LADAR signals.
35. The method of claim 28, further comprising:
20 splitting multiplexed LADAR signal; and
detecting the split multiplexed LADAR signal.
36. The method of claim 28, further comprising switching the multiplexed LADAR signal
between a first and a second detector.
- 25 37. The method of claim 28, further comprising attenuating the multiplexed LADAR
signal.

38. A LADAR apparatus, comprising:

means for time domain multiplexing a plurality of LADAR signals into multiplexed
LADAR signal;

means for detecting the multiplexed LADAR signal; and

5 means for demultiplexing the detected LADAR signal.

39. The LADAR apparatus of claim 38, wherein time domain multiplexing means includes:

means for inserting a unique, staggered delay into each of the LADAR signals; and

means for combining the delayed LADAR signals.

40. The LADAR apparatus of claim 39, wherein the inserting means includes means for

10 propagating the received LADAR signals over varied distances.

41. The LADAR apparatus of claim 40, wherein the inserting means further includes means
for circulating the LADAR signals to a respective reflector and back through a lens.

42. The LADAR apparatus of claim 39, wherein the combining means includes one of a
tree coupler or a cascade of tap couplers.

15 43. The LADAR apparatus of claim 39, wherein the wherein the combining means includes
means for focusing the delayed LADAR signals onto the active surface of the optical detector.

44. The LADAR apparatus of claim 38, further comprising means for detecting the
combined LADAR signals.

45. The LADAR apparatus of claim 38, further comprising:

20 means for splitting multiplexed LADAR signal; and

means for detecting the split multiplexed LADAR signal.

46. The LADAR apparatus of claim 38, further comprising means for switching the
multiplexed LADAR signal between a first and a second detector.

47. The LADAR apparatus of claim 38, further comprising means for attenuating the
25 multiplexed LADAR signal.

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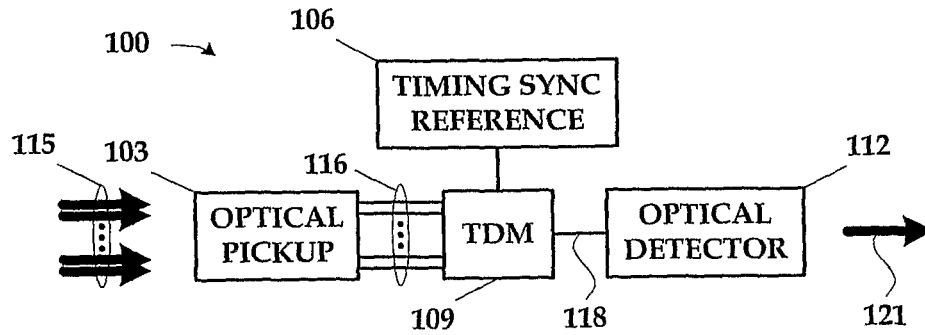


FIG. 1

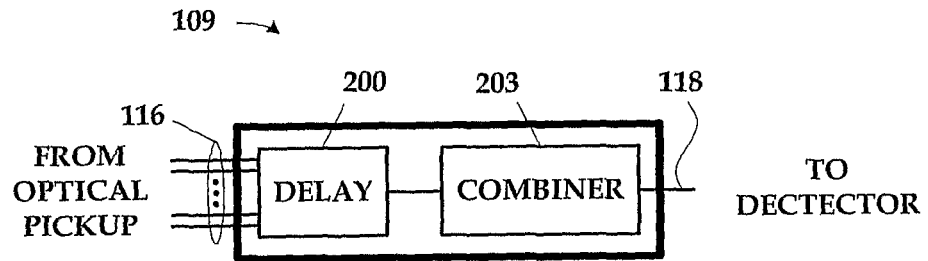


FIG. 2

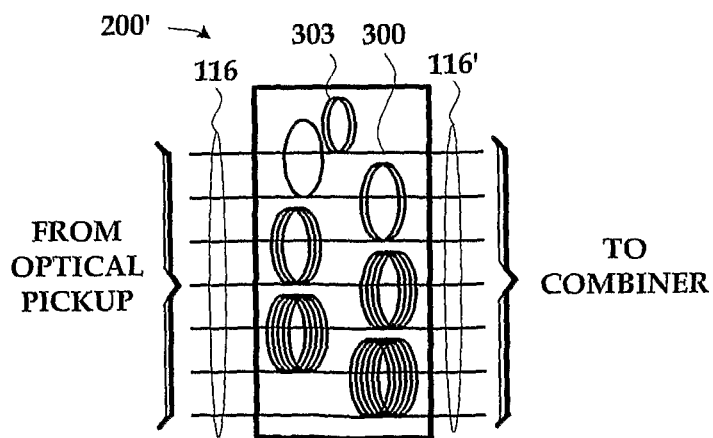


FIG. 3A

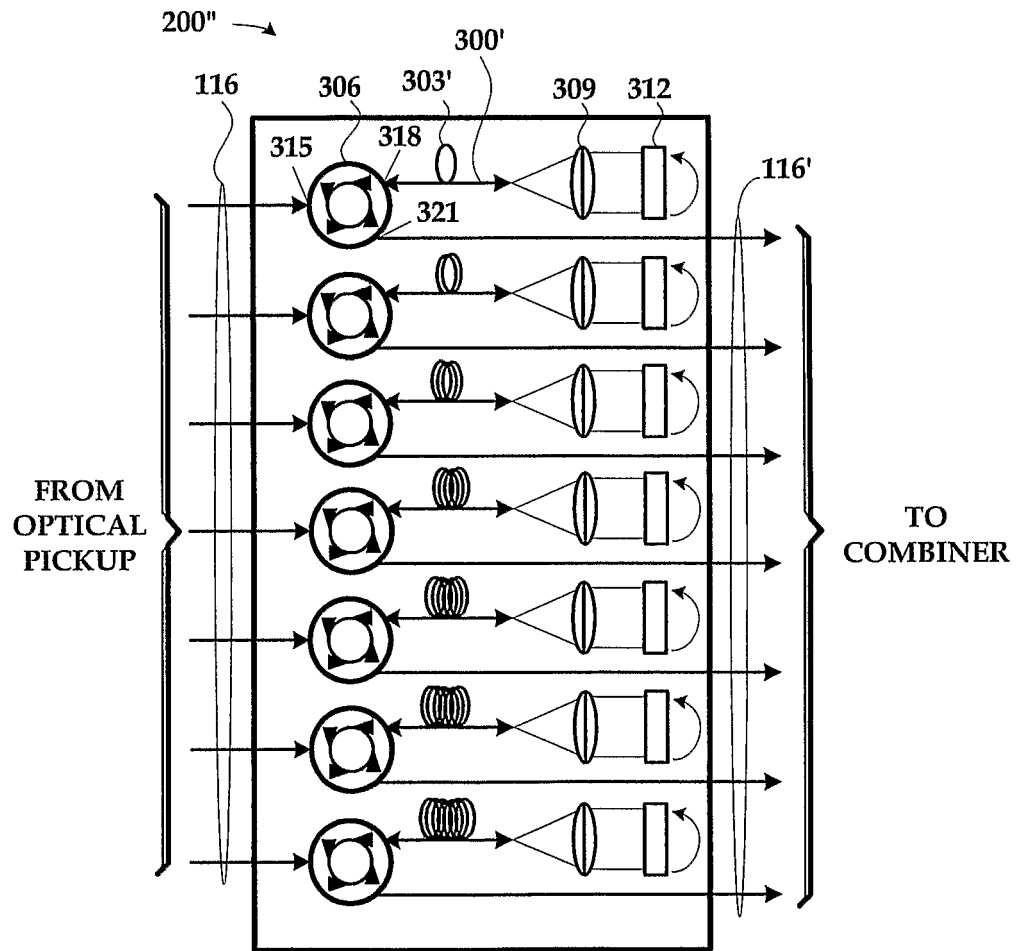


FIG. 3B

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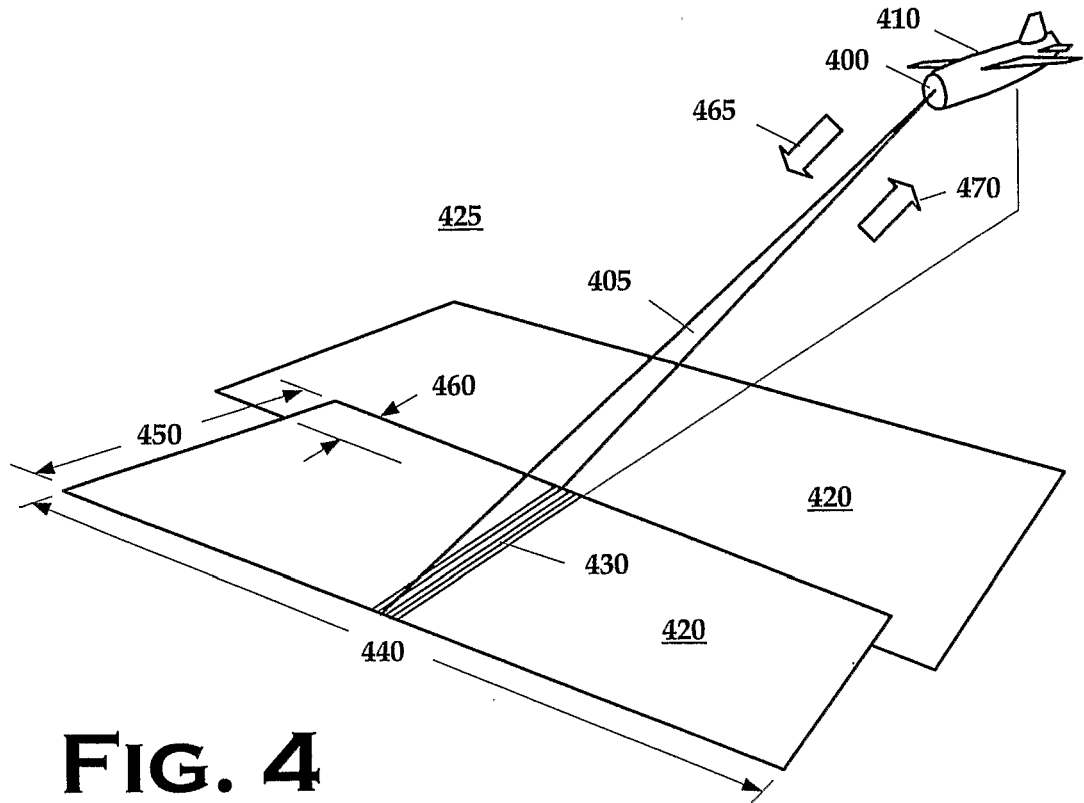


FIG. 4

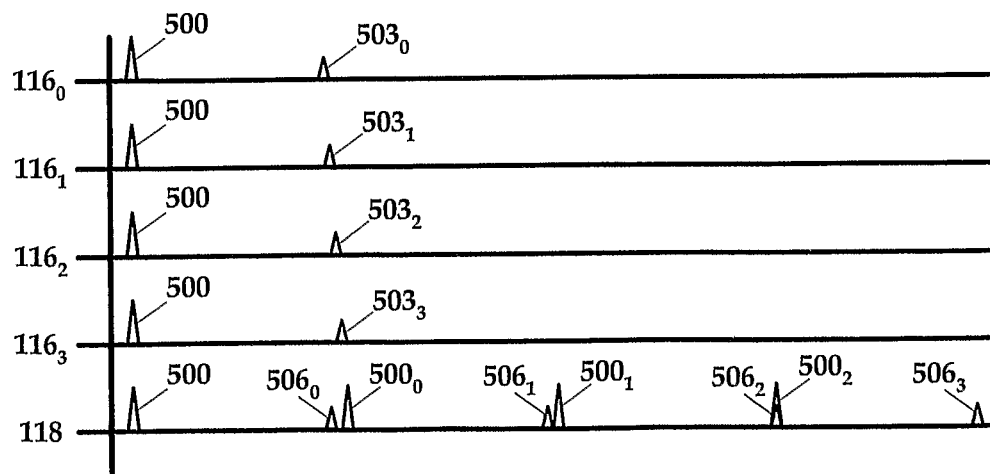


FIG. 5

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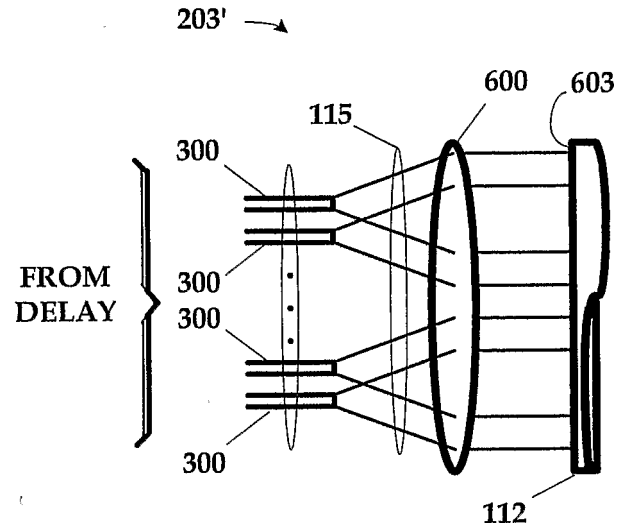


FIG. 6A

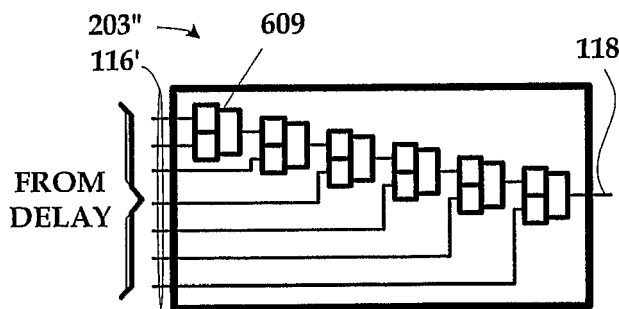


FIG. 6B

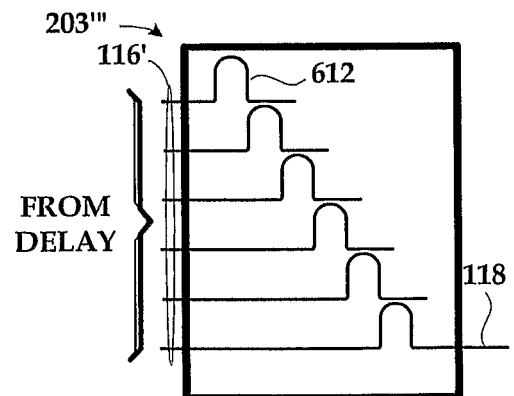


FIG. 6C

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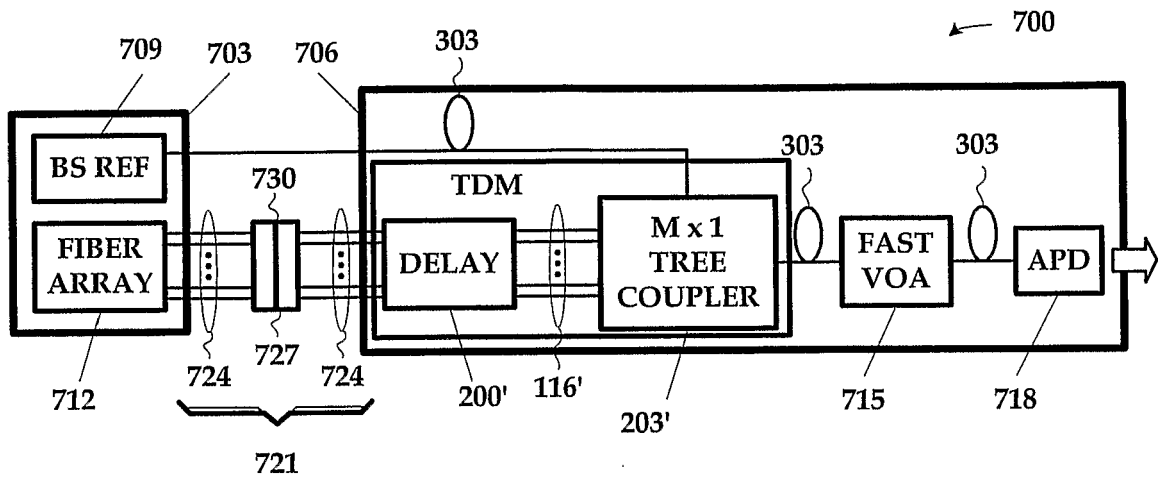


FIG. 7

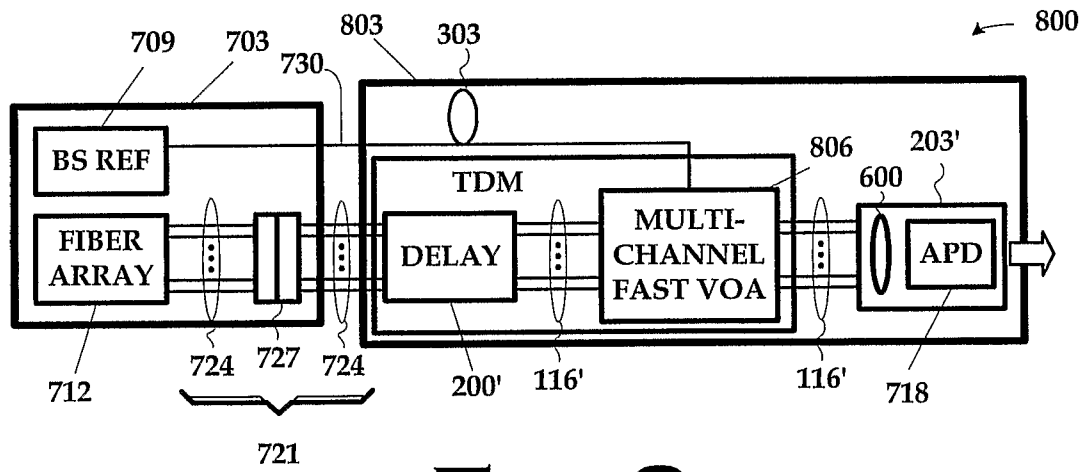


FIG. 8

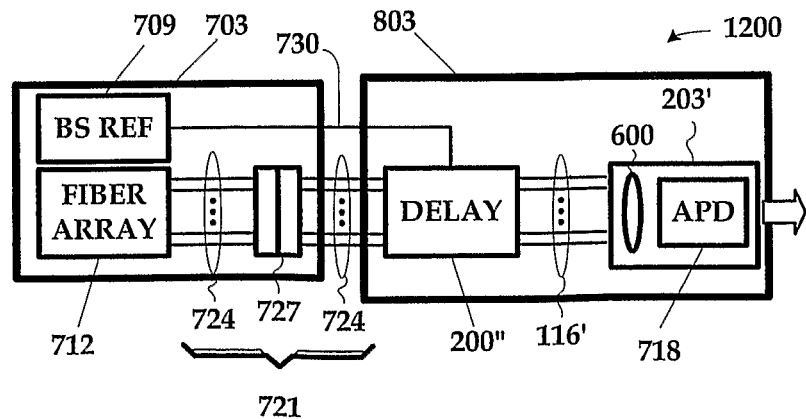


FIG. 12

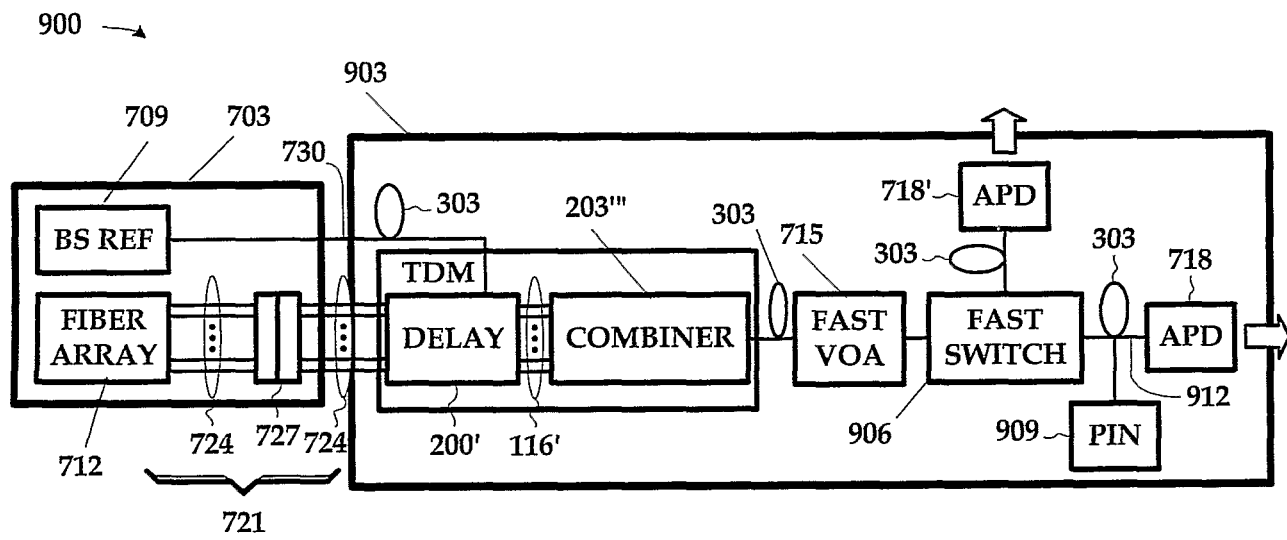


FIG. 9

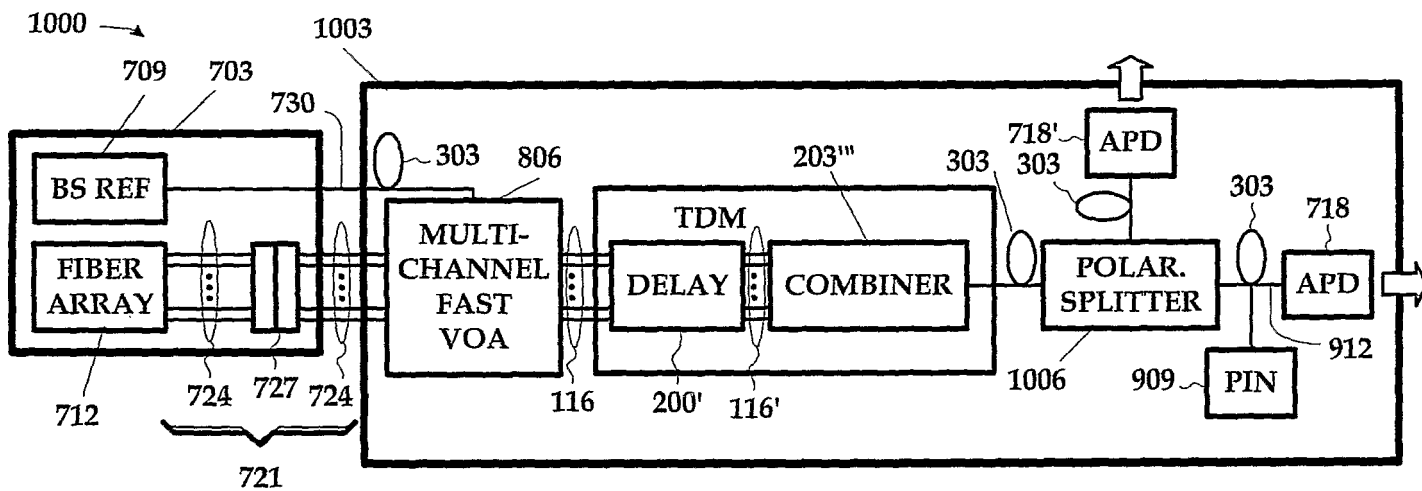


FIG. 10

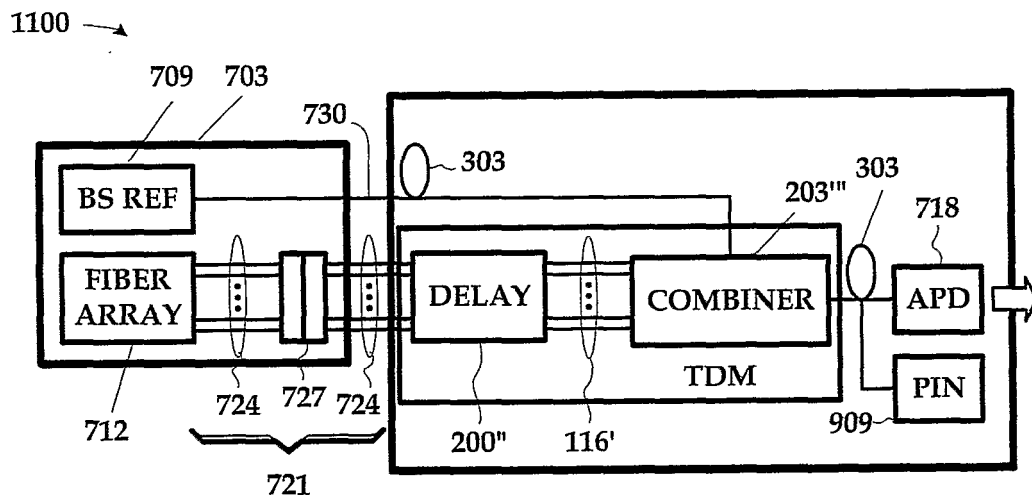


FIG. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/003607

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01S7/486 G01S7/481 G01S7/499 G01S17/42

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)
G01S

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

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

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 380 391 A (BUSER ET AL) 19 April 1983 (1983-04-19) column 4, line 46 - column 5, line 37; claims 1-10; figures	1-47
A	US 4 164 373 A (JOHNSON, LARRY C ET AL) 14 August 1979 (1979-08-14) column 3 - column 6; figures	1-47
A	EP 0 566 027 A (CARELLO S.P.A) 20 October 1993 (1993-10-20) column 2, line 34 - column 4, line 38; figures 1,2	1-47
A	US 5 696 577 A (STETTNER ET AL) 9 December 1997 (1997-12-09) the whole document	1-47

Further documents are listed in the continuation of Box C.

See patent family annex.

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- *P* document published prior to the international filing date but later than the priority date claimed

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Date of the actual completion of the international search

14 July 2006

Date of mailing of the international search report

24/07/2006

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Authorized officer

Devine, J

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No PCT/US2006/003607

Patent document cited in search report	Publication date	Publication date	Patent family member(s)	Publication date
US 4380391	A	19-04-1983	NONE	
US 4164373	A	14-08-1979	NONE	
EP 0566027	A	20-10-1993	IT 1259539 B	20-03-1996
US 5696577	A	09-12-1997	NONE	