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[Continued on next page]

(54) Title: FREQUENCY MEASUREMENT FOCAL PLANE ARRAY INPUT CIRCUIT

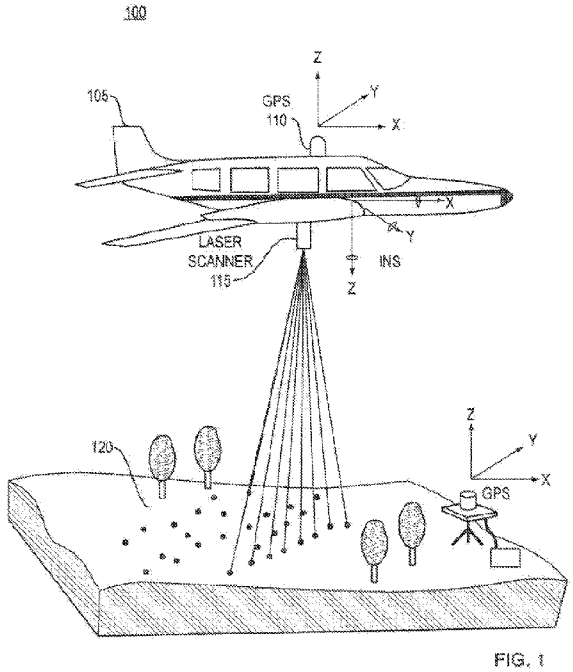


FIG. 1

LADAR SYSTEM ENVIRONMENT

(57) Abstract: The invention measures the frequency of a heterodyne laser radar (LADAR) system signal in the input cell of a focal, plane array (FPA). Embodiments amplify the return signal, and drive it into a counter for a fixed period of time. The frequency is the number of counts divided by the count time. An example design amplifier amplifies the return of a single photon response of an avalanche photodiode with a gain of 100 into a digital signal level at a 200 MHz rate with only 84 μW, demonstrating the feasibility of the approach.

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

FREQUENCY MEASUREMENT FOCAL PLANE ARRAY INPUT CIRCUIT

FIELD OF THE INVENTION

[0001] The invention relates to a circuit and method for measuring the frequency of a heterodyne laser radar (LADAR) system signal in the input cell of a focal plane array (FPA).

BACKGROUND OF THE INVENTION

[0002] LAser raDAR (LADAR) combines laser-focused imaging with radar's ability to calculate distances by measuring the time for a signal to return. Such sensors are used for detection, identification, and precision measurement of the range to a target. Data generated by the sensor can be used for targeting, command, and control computers of automated and semi-automated systems. The data can be used for precision short and long-range target detection, identification, and ranging measurements for command, control, and navigation systems of autonomous, semi-autonomous, and remotely operated manned and unmanned vehicles. In operation, light reflected by backscattering is received at the detector. LADAR detection can be by direct energy detection (amplitude measurement) or by coherent detection. Coherent systems generally use optical heterodyne detection, which, being more sensitive than direct detection, allows them to operate at a much lower power but at the expense of more complex transceiver requirements. LADAR systems can employ two types of pulse models: micropulse and high energy. Micropulse systems use considerably less laser energy, typically on the order of one microjoule. Common wavelengths range from 10 microns to 250 nm (UV).

SUMMARY OF THE INVENTION

[0003] An embodiment provides a device for measuring a frequency of a heterodyne laser radar (LADAR) system signal in an input cell of a focal plane array (FPA) comprising a detector; an AC coupled amplifier input; a counter; and a latch outputting a read out. In embodiments the counter and the latch comprise 14 to 16 bits. In other embodiments, the detector is an avalanche photodiode (APD). In subsequent embodiments the AC coupled amplifier input comprises gain and bandwidth adjustment. For additional embodiments the gain is about 500 and bandwidth from about 25 to 200 MHz. In another embodiment, the APD is a HgCdTe detector. A following embodiment further comprises a LADAR range detector measuring a time of arrival of a return pulse using an external reference clock as a counter clock, and storing a counter value corresponding to the time of arrival of the return LADAR pulse. Subsequent embodiments further comprise a photon counting focal plane array, where the gain of the APD and amplifier is large enough for individual photons to generate a signal large enough to operate the counter. Additional embodiments further comprise a narrow laser cold filter.

[0004] Another embodiment provides a method for measuring a frequency (FM) of a heterodyne laser radar (LADAR) system signal in an input cell of a focal plane array (FPA) comprising providing a LADAR FM FPA circuit; counting a beat frequency, whereby detection and frequency measurement are accomplished; counting photons during a period, whereby photons are passively counted; and clocking start or stop times of counter, whereby ranging is directly detected. In included embodiments a fixed counting period is an entire frame. In yet further embodiments a fixed counting period is less than a frame. In related embodiments a fixed counting period is more than a frame. Further embodiments comprise a range gate. In ensuing embodiments pulses are longer than two times a frame rate. For yet further embodiments, a minimum of count periods is chosen as a count period with least noise counts. For more embodiments, passive and active

counting are simultaneously accomplished. Continued embodiments include a faster frame rate is employed for shorter pulses. For additional embodiments, the system has single photon sensitivity, wherein the LADAR FM FPA circuit comprises an avalanche photodiode (APD) having a gain of about 100 into a digital signal level at a 200 MHz rate with 84 μW.

[0005] A yet further embodiment provides a system for measuring a frequency (FM) of a heterodyne laser radar (LADAR) system signal in an input cell of a focal plane array (FPA) comprising an avalanche photodiode (APD); an AC coupled amplifier comprising gain and bandwidth adjustment input; a counter; a latch outputting a read out; counting a beat frequency, whereby detection and frequency measurement are accomplished; counting photons during a period, whereby photons are passively counted; and clocking start or stop times of counter, whereby ranging is directly detected, wherein the FPA dimensions are 256 by 256, pixel dimensions are about 30 μm, and an avalanche photo diode gain is about 100, adjustable per-pixel.

[0006] The features and advantages described herein are not all-inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification, and claims. Moreover, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes, and not to limit the scope of the inventive subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figure 1 is a depiction of a LADAR system environment configured in accordance with one embodiment of the invention.

[0008] Figure 2 is a LADAR system block diagram configured in accordance with one embodiment of the invention.

[0009] Figure 3 is a frequency measurement (FM) focal plane array (FPA) input circuit block diagram configured in accordance with one embodiment of the invention.

[0010] Figure 4 is a transient analysis graph configured in accordance with one embodiment of the invention.

[0011] Figure 5 is a methods of operation diagram configured in accordance with one embodiment of the invention.

[0012] Figure 6 is an operation flow chart configured in accordance with one embodiment of the invention.

DETAILED DESCRIPTION

[0013] The invention measures the frequency of a heterodyne laser radar (LADAR) system signal in the input cell of a focal plane array (FPA). Embodiments amplify the return signal, and drive it into a counter for a fixed period of time. The frequency is the number of counts divided by the count time. An amplifier is designed to amplify the return of a single photon response of an avalanche photodiode with a gain of 100 into a digital signal level at a 200 MHz rate with only 84 μW.

[0014] **FIG. 1** depicts a LADAR system environment **100**. Platform **105** (not necessarily airborne) incorporates GPS locating information **110**, and supports laser scanner system **115** to scan target area **120**.

[0015] **FIG. 2** is a LADAR system block diagram **200**. Components comprise laser **205**; beam expander **210**; transmitting optics **215**; receiving telescope **220**; target **225**; photodetector **230**; A/D converter **235**; signal and data processor **240**; and output device **245**.

[0016] Embodiments of the invention support focal plane arrays with formats up to 256 x 256. This FPA architecture can also support alternate FPA operating modes, allowing it to do direct detect ranging LADAR or passive photon counting. The circuit can also count photons for very low flux applications or perform direct detect ranging by counting reference clock cycles until return pulse is detected.

[0017] FIG. 3 depicts a frequency measurement focal plane array input circuit 300 for heterodyne LADAR Systems. Elements include linear avalanche photodiode (APD) 305 with DCOM -10V input; 500X AC coupled amplifier 310; gain and bandwidth adjustment input 315; 14 - 16 bit counter 320; optional XCK in for ranging 325; 14 - 16 bit latch 330; and read out 335. LADAR Frequency Measurement FPA embodiments count fast pulses for multiple functions. They measure heterodyne LADAR presence and frequency by counting cycles in a known period. The frequency is equal to the number of counts per count period, assuming the signal is present for the entire count period. Embodiments count passively generated photons for low flux levels. In embodiments, this may require detectors operating at T<80K. When there is sufficient gain to count photons, pulse counting functionality is no different for FPAs. Direct range detection can be performed by counting external reference clock cycles for the return time.

[0018] For additional functionality, detection starts or stops the count of an externally supplied reference clock. For embodiments, the counter has 14 to 16 bits. A 10 KHz frame rate is employed with all digital input and output for embodiments. Embodiments use HgCdTe linear avalanche photo diode (APO) detectors, nominally at 80K operation. They also have input fuse high voltage protection on the read out integrated circuit (ROIC) for shorted detectors. Embodiments are fabricated in 130 nm CMOS processes. The high speed amplifier has programmable gain and bandwidth control. This gain is high enough to count individual photons at 200 MHz (G_{APD} = 100), and gain control is programmable by pixel. Using nonlinear gain allows the counting of very large signals at high gain with no saturation. Array sizes up to 256 x 256 can operate at less than 6W of power; existing cryo coolers are adequate for 6W of cooling. In embodiments, pixel size is nominally 30 μm.

[0019] LADAR FM FPA embodiments provide four functions: detection, frequency measurement, photon counting, and direct range detection.

Detection and Frequency Measurement

[0020] Detection and frequency measurement functions for heterodyne LADAR systems count the beat frequency cycles per fixed period to measure the frequency and indicate detection. A fixed period is nominally an entire frame, but could also employ multiple and/or shorter periods, with a faster frame rate for shorter pulses. A fixed period could be less than a frame time with a range gate. Multiple period / frame capability comprises a register and digital comparator, with >2X logic. For pulses shorter than the frame time, the maximum of count periods is chosen, where the count period is <= pulse/2. For pulses longer than twice the frame time, the minimum of count periods is chosen as the count period with the least noise counts. For cases where noise dark counts are with photon counts, the higher output will indicate detection of the signal and the frequency is recovered with signal processing.

Passive Photon Counting

[0021] For passive photon counting, if the APD FPA has single photon sensitivity (gain > threshold), then it can also count photons (and dark electrons) for very high sensitivity passive applications. However, this is only accurate if the probability of "simultaneous" photons is low. If the dark count rate is low, then passive and active functions can be accomplished at the same time (a small number of counts are passive photons plus noise, and high number of counts are active frequency measurements). A narrow laser cold filter would let few passive photons through, but sufficient for operation.

Direct Detect Ranging

[0022] For direct detect ranging, if the counter is supplied with an external reference clock and some simple logic, this input circuit can also do direct detect LADAR ranging with a digital output. Embodiments stop or start the count using an external reference clock on detection of a pulse. "Start" minimizes counting during detection. A read out reference counter starts at the beginning of the range gate,

and stops with the all the other counters for delay calculation. In embodiments, there are a few test pixels in the corners of the FPA.

[0023] **FIG. 4** is a transient analysis graph **400** demonstrating the feasibility of reasonable performance with circuits that could fit in an FPA. **4A** depicts 0 to 50 ns, and **4B** depicts 50 - 100ns. The five traces are: out0 **405**; out1 **410**; out2 **415**; out3 **420**; and O_P **425**. High Speed Detection in FPA pixels provides full scale output with input equivalent to single photons into the APD at 200 MHz. **FIG. 4** depicts this transient analysis for a C_{inp} of approximately 50 fF, f = 200MHz, and 100 electrons. Embodiments include 84 µW pixel power that is compatible with FPA sizes up to 256 x 256 with 6W total FPA power. Gain is greater than 500, and the bandwidth is from 25 to 200MHz. Gain and bandwidth are selectable with bias and control signal changes. Pixel level programming controls the overall threshold and compensates for non-uniformity. In embodiments, the overall pixel circuit fits within a 30 µm pixel.

[0024] **FIG 5** is a methods of operation diagram **500**. FM FPA LADAR systems **505** have four functions comprising detection **510**; frequency measurement **515**; direct range detection **520**; and photon counting **525**.

[0025] **FIG 6** is an operation flow chart **600**. Embodiments comprise the steps of providing a LADAR FM FPA circuit **605**; counting a beat frequency, whereby detection and frequency measurement are accomplished **610**; counting photons during a period, whereby photons are passively counted **615**; and clocking start or stop times of counter, whereby ranging is directly detected **620**. Steps can be performed in alternate orders.

[0026] The foregoing description of the embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of this disclosure it is to be understood that other similar embodiments may be used or modifications or

additions may be made to the described embodiment for performing the same function of the present invention without deviating therefrom. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

CLAIMS

What is claimed is:

1. A device for measuring a frequency of a heterodyne laser radar (LADAR) system signal in an input cell of a focal plane array (FPA) comprising:

a detector;

an AC coupled amplifier input;

a counter; and

a latch outputting a read out.

2. The device of claim 1, wherein said counter and said latch comprise 14 to 16 bits.

3. The device of claim 1, wherein said detector is an avalanche photodiode (APD).

4. The device of claim 1, wherein said AC coupled amplifier input comprises gain and bandwidth adjustment.

5. The device of claim 1, wherein said gain is about 500 and bandwidth from about 25 to 200 MHz.

6. The device of claim 1, wherein said APD is a HgCdTe detector.

7. The device of claim 1, further comprising a LADAR range detector measuring a time of arrival of a return pulse using an external reference clock as a counter clock, and storing a counter value corresponding to said time of arrival of said return LADAR pulse.

8. The device of claim 3, further comprising a photon counting focal plane array, wherein a gain of said APD and amplifier is large enough for individual photons to generate a signal large enough to operate said counter.

9. The device of claim 1, further comprising a narrow laser cold filter.

10. A method for measuring a frequency (FM) of a heterodyne laser radar (LADAR) system signal in an input cell of a focal plane array (FPA) comprising:

providing a LADAR FM FPA circuit;

counting a beat frequency, whereby detection and frequency measurement are accomplished;

counting photons during a period, whereby photons are passively counted; and

clocking start or stop times of counter, whereby ranging is directly detected.

11. The method of claim 10 wherein a fixed counting period is an entire frame.

12. The method of claim 10 wherein a fixed counting period is less than a frame.

13. The method of claim 10 wherein a fixed counting period is more than a frame.

14. The method of claim 12 comprising a range gate.

15. The method of claim 10 wherein pulses are longer than two times a frame rate.

16. The method of claim 15 wherein a minimum of count periods is chosen as a count period with least noise counts.

17. The method of claim 10 wherein passive and active counting are simultaneously accomplished.

18. The method of claim 10, wherein a faster frame rate is employed for shorter pulses.

19. The method of claim 10 wherein said system has single photon sensitivity, wherein said LADAR FM FPA circuit comprises an avalanche photodiode (APD) having a gain of about 100 into a digital signal level at a 200 MHz rate with 84 μW.

20. A system for measuring a frequency (FM) of a heterodyne laser radar (LADAR) system signal in an input cell of a focal plane array (FPA) comprising:

an avalanche photodiode (APD);

an AC coupled amplifier comprising gain and bandwidth adjustment input;

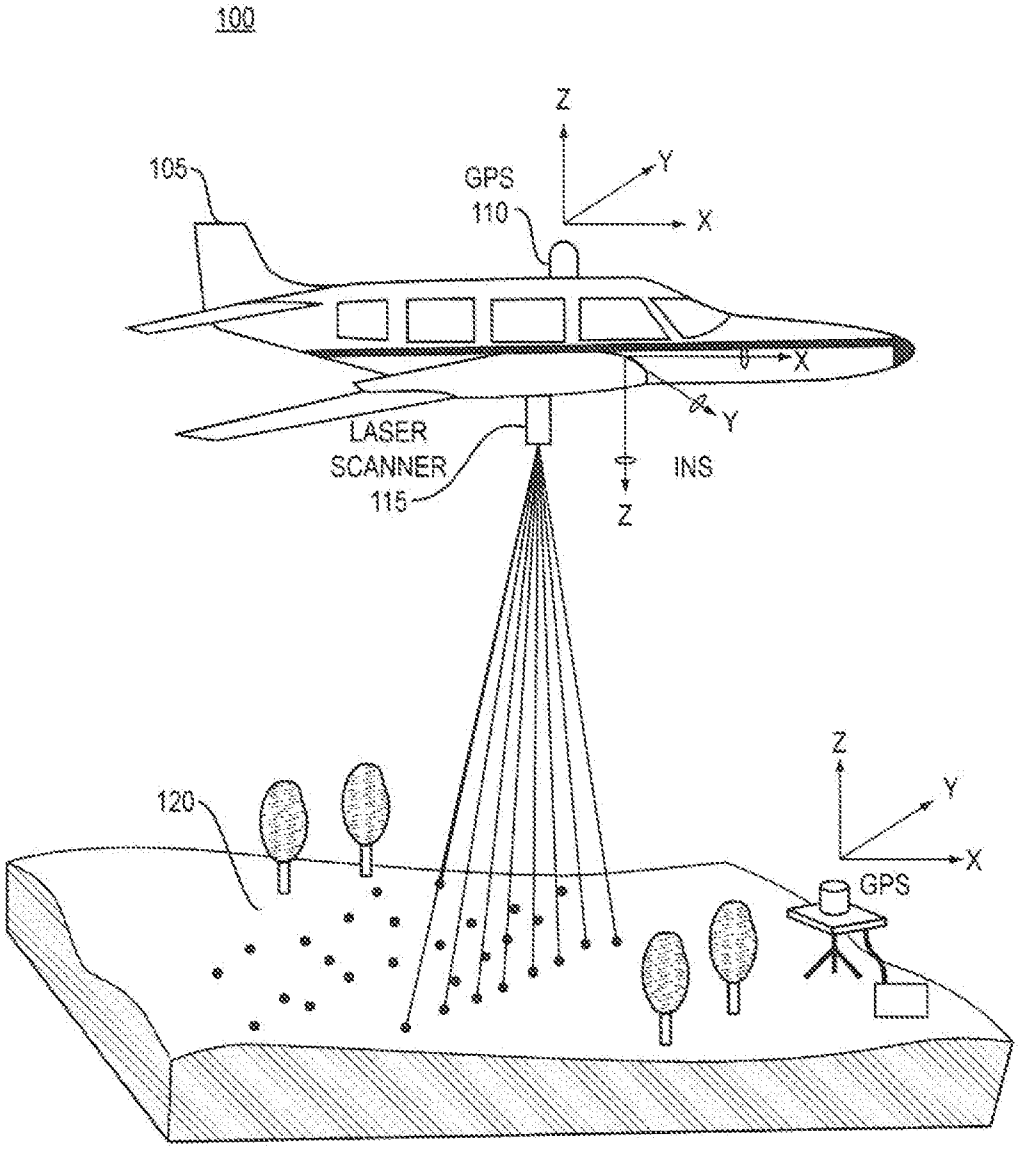
a counter;

a latch outputting a read out;

counting a beat frequency, whereby detection and frequency measurement are accomplished;

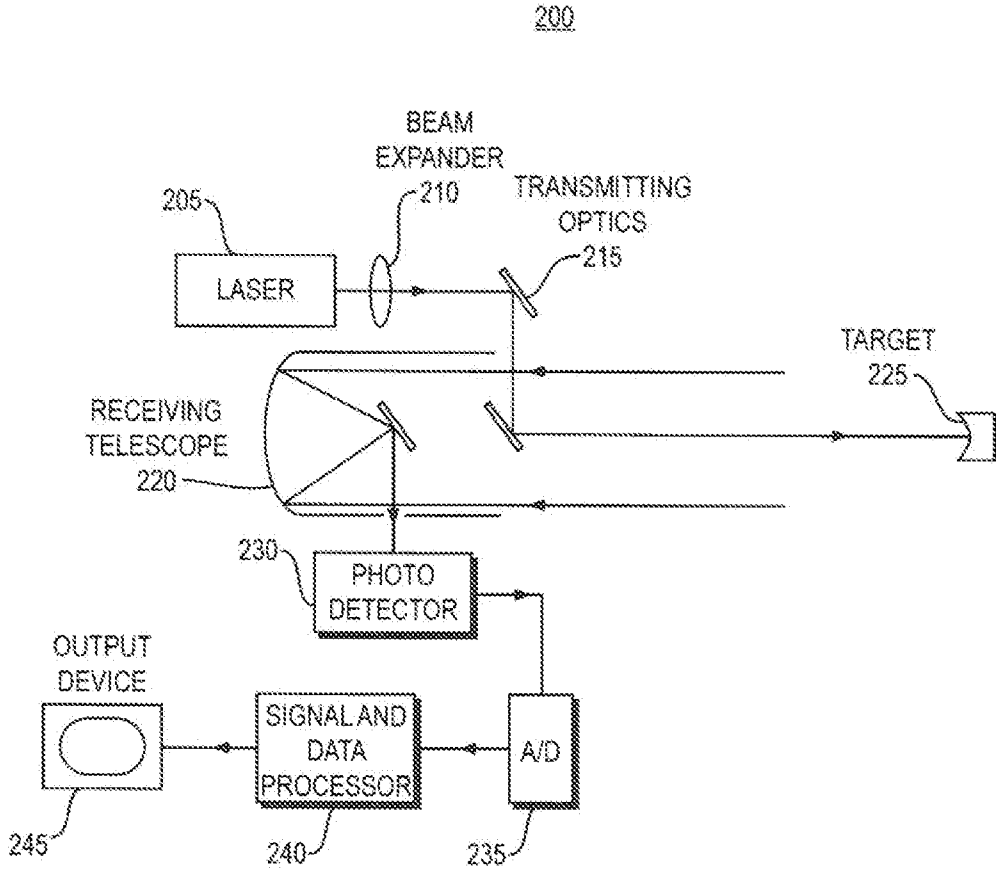
counting photons during a period, whereby photons are passively counted; and

clocking start or stop times of counter, whereby ranging is directly detected, wherein said FPA dimensions are 256 by 256, pixel dimensions are about 30 μm, and an avalanche photo diode gain is about 100, adjustable per-pixel.



LADAR SYSTEM
ENVIRONMENT

FIG. 1



LADAR BLOCK DIAGRAM

FIG. 2

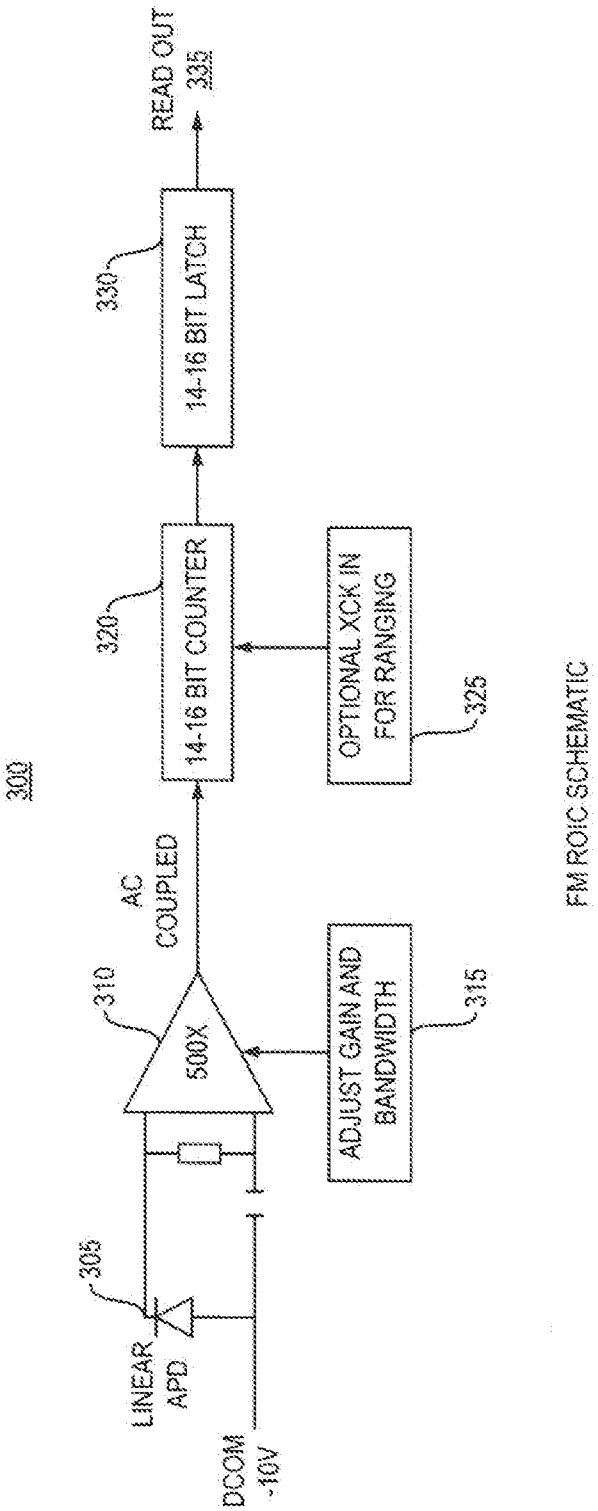

300
305
LINEAR APD
DCOM -10V
310
500X
AC COUPLED
315
ADJUST GAIN AND BANDWIDTH
320
14-16 BIT COUNTER
325
OPTIONAL XCK IN FOR RANGING
330
14-16 BIT LATCH
335
READ OUT
FM ROIC SCHEMATIC

FIG. 3

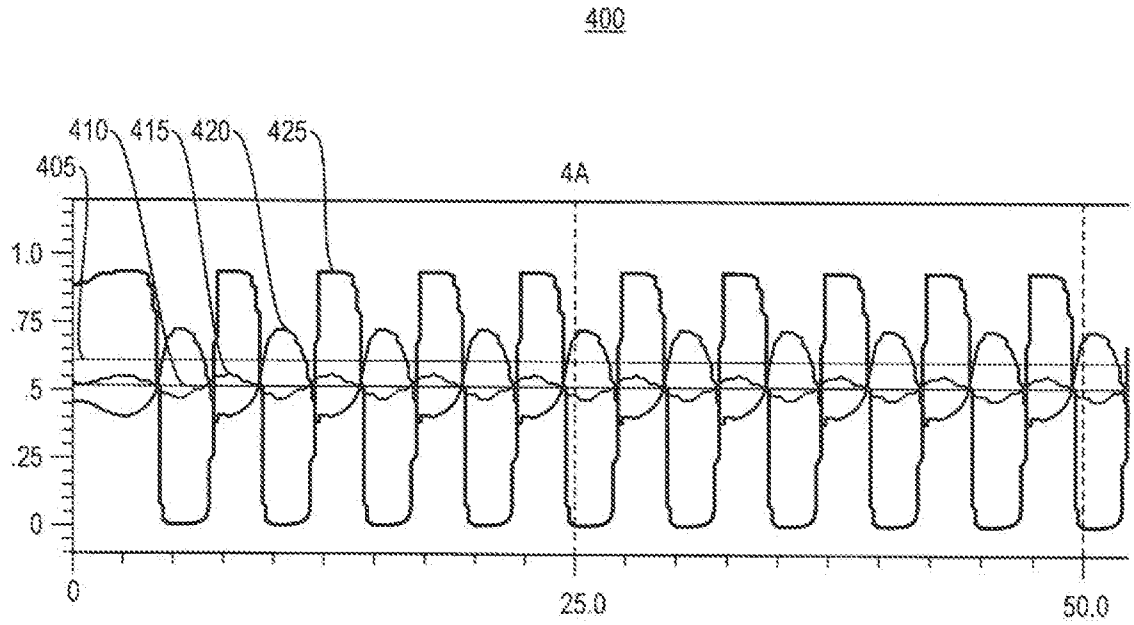
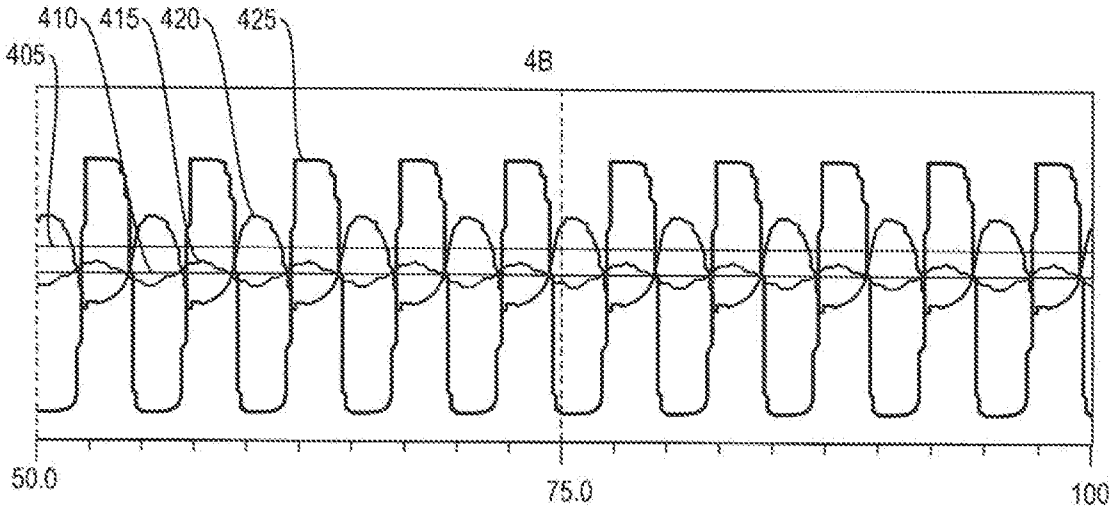


FIG. 4A



TRANSIENT ANALYSIS

FIG. 4B

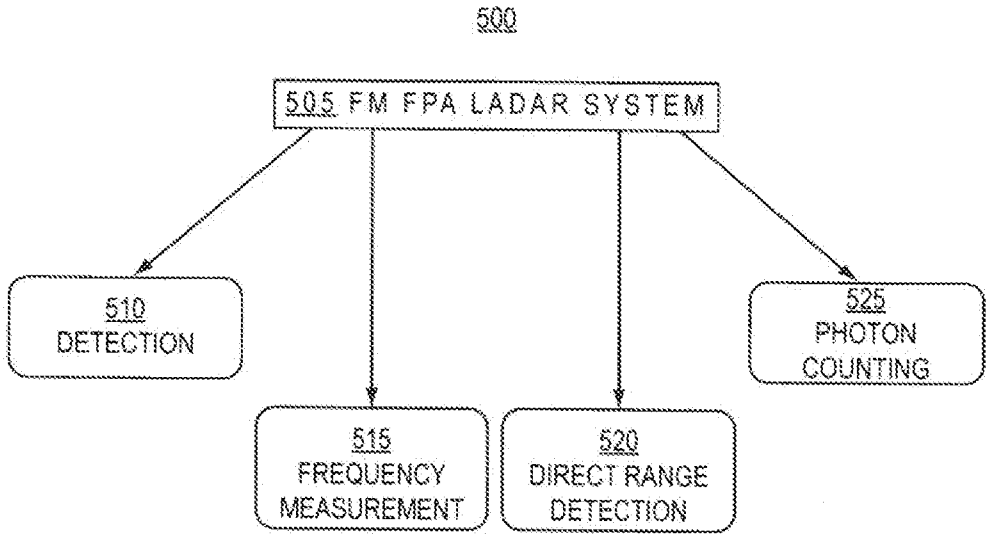
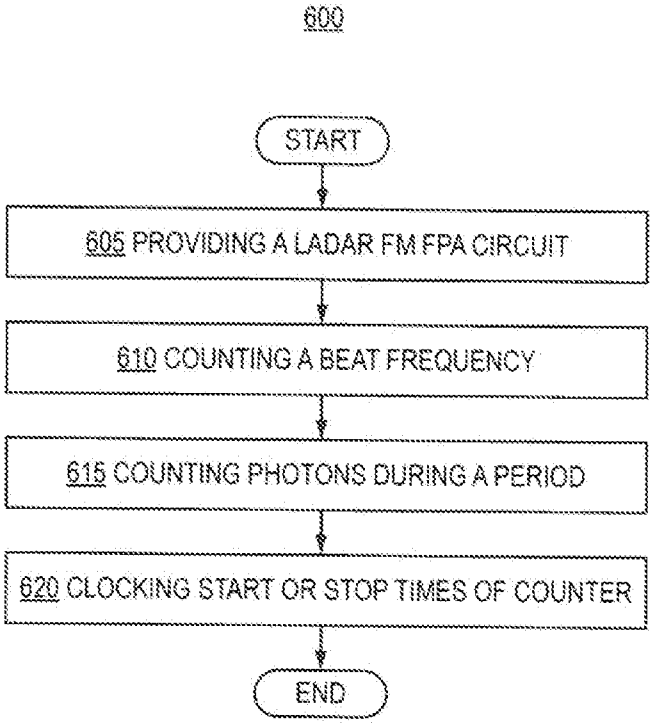

500
505 FM FPA LADAR SYSTEM
510
DETECTION
515
FREQUENCY
MEASUREMENT
520
DIRECT RANGE
DETECTION
525
PHOTON
COUNTING
METHODS OF OPERATION

FIG. 5



OPERATION FLOW CHART

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/041971

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01C 3/08; G01B 9/02; G01C 3/02 (2016.01)
CPC - G01C 3/08; G01B 9/02; G01S 7/487; G01S 17/936 (2016.08)
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)
IPC - G01C 3/08; G01B 9/02; G01C 3/02
CPC - G01C 3/08; G01B 9/02; G01S 7/487; G01S 17/936

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 356/2, 3, 4.1, 5.1, 486, 487 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Orbit, Google Patents, Google Scholar
Search terms used: heterodyne laser radar, frequency, counter, detector, latch, measuring, ac coupled, bit counter, focal plane, photon counting, array, pixel gain, 100, 30

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2005/0088644 A1 (MORCOM) 28 April 2005 (28.04.2005) entire document	1-9, 20
Y	US 2003/0010128 A1 (BUELL et al) 16 January 2003 (16.01.2003) entire document	1-9, 20
Y	US 5,461,235 A (COTTRELL et al) 24 October 1995 (24.10.1995) entire document	2
Y	US 5,159,396 A (YUHAS) 27 October 1992 (27.10.1992) entire document	6
Y	US 2006/0197938 A1 (HALMOS et al) 07 September 2006 (07.09.2006) entire document	7
Y	US 2010/0226495 A1 (KELLY et al) 09 September 2010 (09.09.2010) entire document	8
Y	US 4,928,152 A (GERARDIN) 22 May 1990 (22.05.1990) entire document	9
Y	US 8,829,452 B1 (BROWN) 09 September 2014 (09.09.2014) entire document	20
Y	US 2006/0267054 A1 (MARTIN et al) 30 November 2006 (30.11.2006) entire document	20
A	US 8,426,797 B2 (AULL et al) 23 April 2013 (23.04.2013) entire document	1-9, 20
A	US 2014/0340487 A1 (GILLILAND et al) 20 November 2014 (20.11.2014) entire document	1-9, 20

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"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)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"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
"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
"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
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 October 2016	16 NOV 2016
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/041971

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See supplemental page

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-9, 20

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.