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EXHIBIT B

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(12) **United States Patent**
Lenius et al.

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(45) **Date of Patent: Jun. 14, 2016**

(54) **LASER DIODE FIRING SYSTEM**

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(73) Assignee: **Google Inc.**, Mountain View, CA (US)

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(22) Filed: **Dec. 18, 2013**

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(51) **Int. Cl.**

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H01S 5/06	(2006.01)
G01S 17/32	(2006.01)
H01S 5/062	(2006.01)
H05B 33/08	(2006.01)
G01J 1/46	(2006.01)

(52) **U.S. Cl.**
CPC . ***H01S 5/06*** (2013.01); ***G01S 17/32*** (2013.01); *G01J 1/46* (2013.01); *H01S 5/062* (2013.01); *H05B 33/0842* (2013.01); *H05B 33/0845* (2013.01)

(58) **Field of Classification Search**
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USPC 359/4.01
See application file for complete search history.

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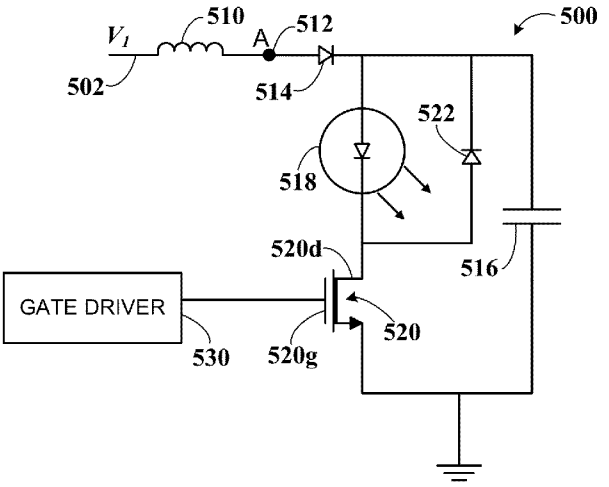
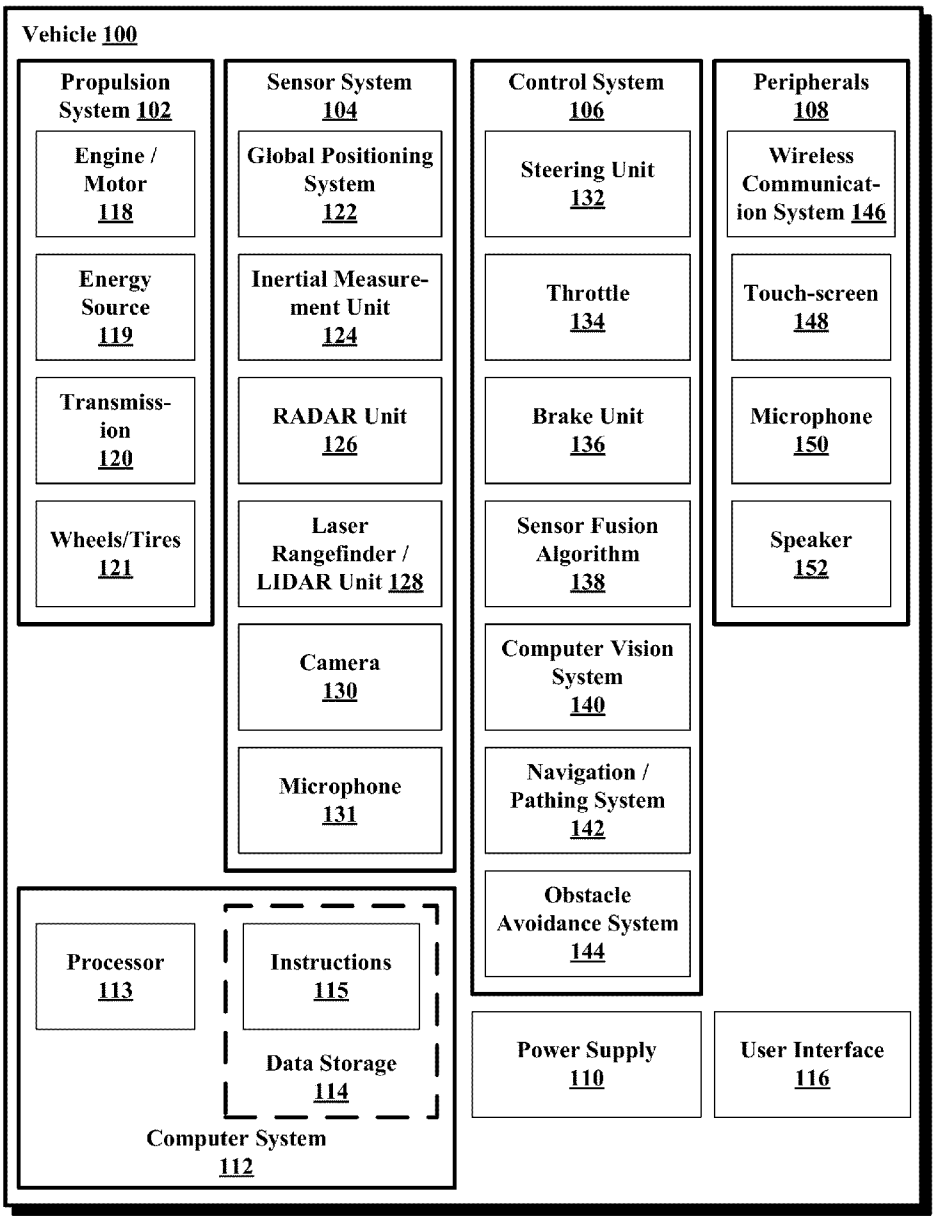
(57) **ABSTRACT**

A laser diode firing circuit for a light detection and ranging device is disclosed. The firing circuit includes a laser diode coupled in series to a transistor, such that current through the laser diode is controlled by the transistor. The laser diode is configured to emit a pulse of light in response to current flowing through the laser diode. The firing circuit includes a capacitor that is configured to charge via a charging path that includes an inductor and to discharge via a discharge path that includes the laser diode. The transistor controlling current through the laser diode can be a Gallium nitride field effect transistor.

20 Claims, 11 Drawing Sheets

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Engine / Motor 118
Energy Source 119
Transmiss-ion 120
Wheels/Tires 121
Sensor System 104
Global Positioning System 122
Inertial Measure-ment Unit 124
RADAR Unit 126
Laser Rangefinder / LIDAR Unit 128
Camera 130
Microphone 131
Control System 106
Steering Unit 132
Throttle 134
Brake Unit 136
Sensor Fusion Algorithm 138
Computer Vision System 140
Navigation / Pathing System 142
Obstacle Avoidance System 144
Peripherals 108
Wireless Communicat-ion System 146
Touch-screen 148
Microphone 150
Speaker 152
Processor 113
Instructions 115
Data Storage 114
Computer System 112
Power Supply 110
User Interface 116

Figure 1

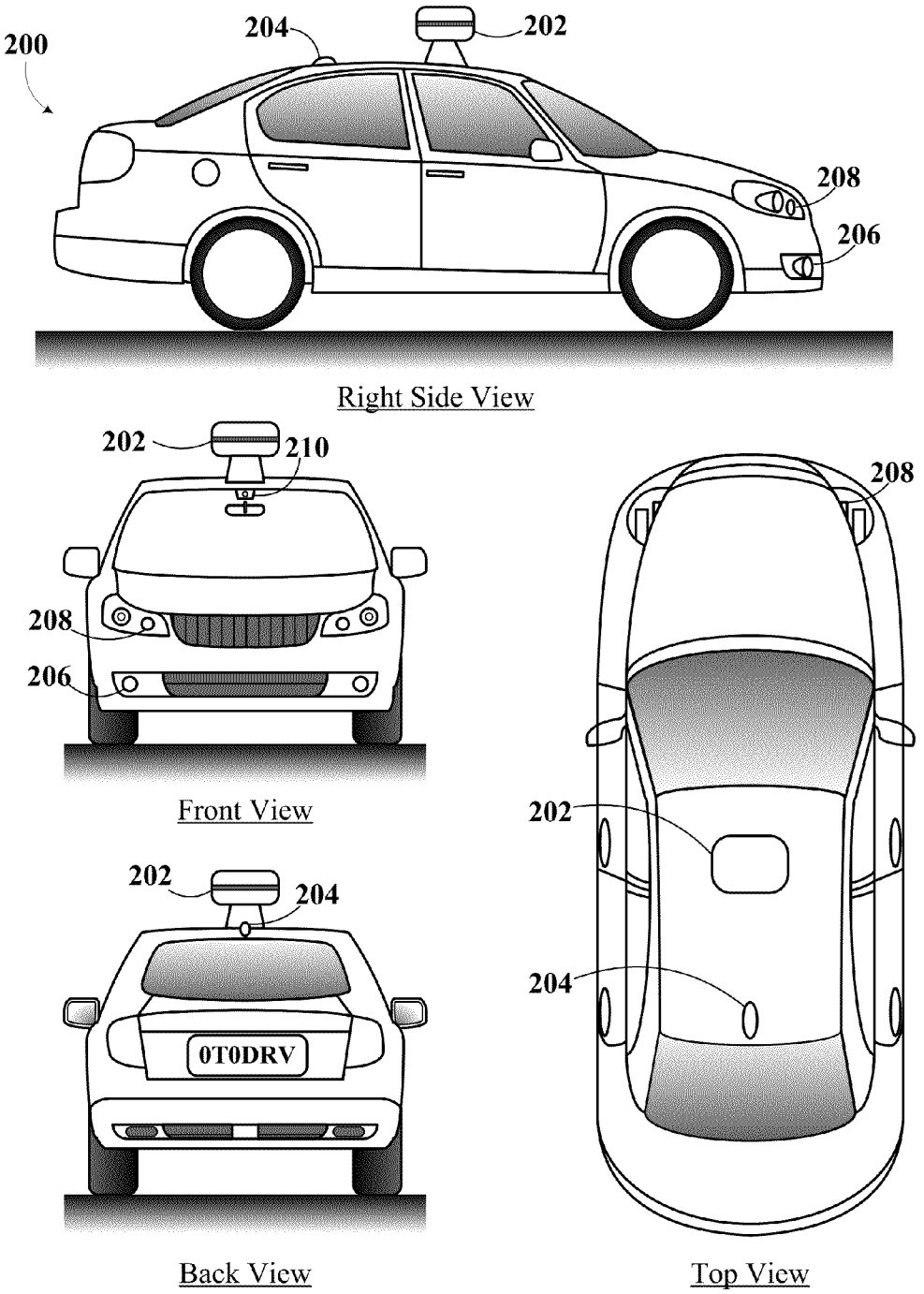

200
204
202
208
206
Right Side View
202
210
208
206
Front View
208
202
204
Top View
202
204
0T0DRV
Back View

Figure 2

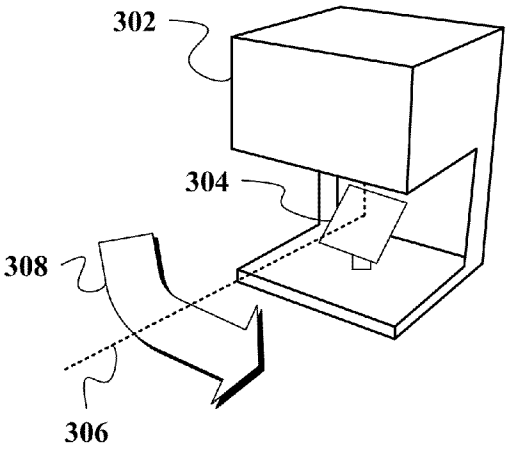


Figure 3A

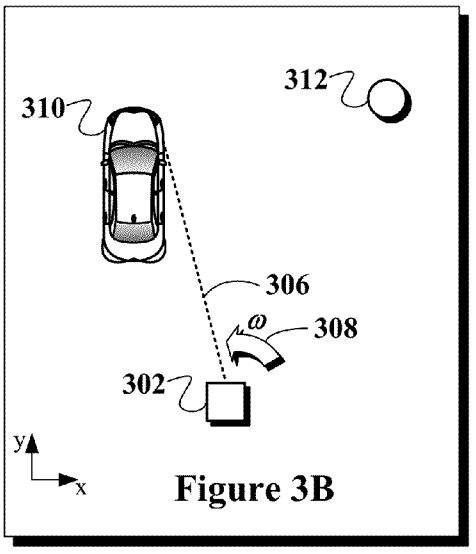


Figure 3B

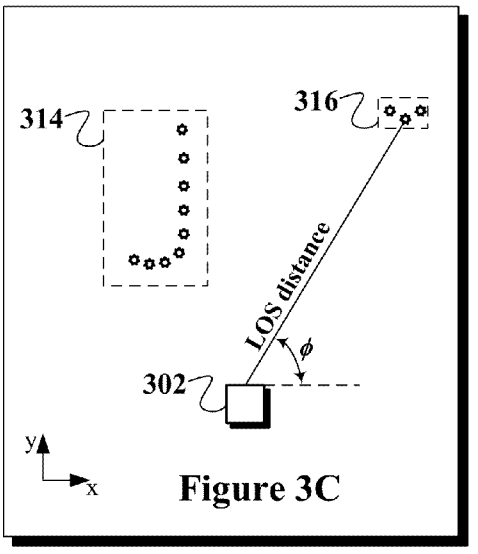


Figure 3C

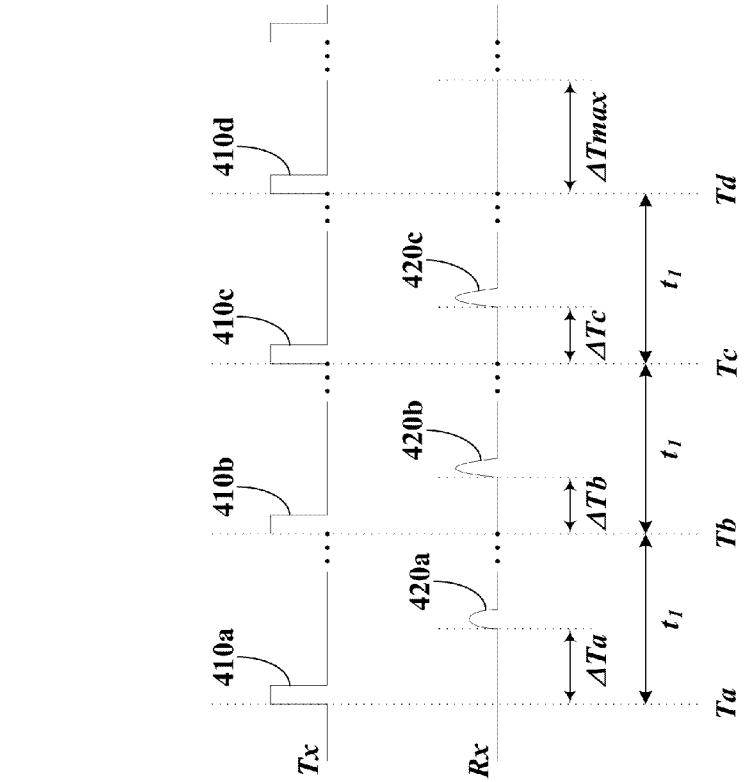


Figure 4B

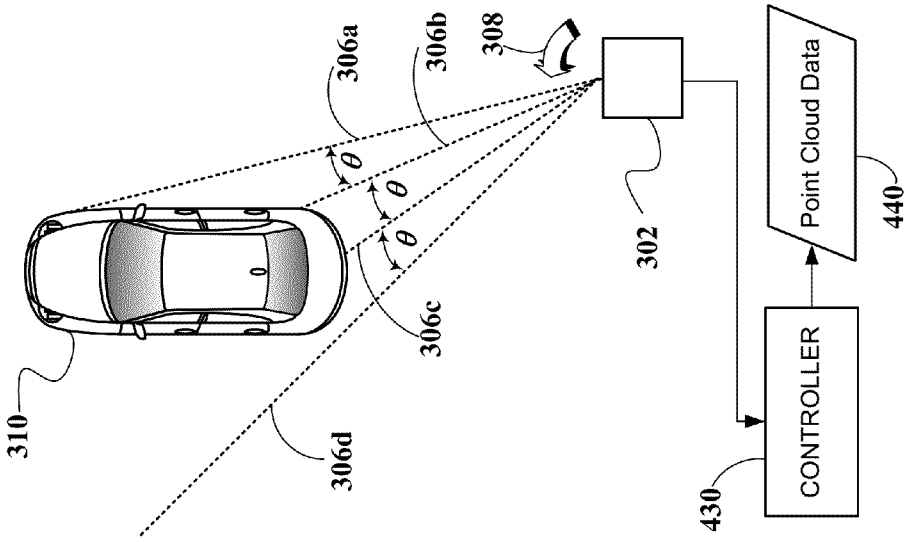


Figure 4A

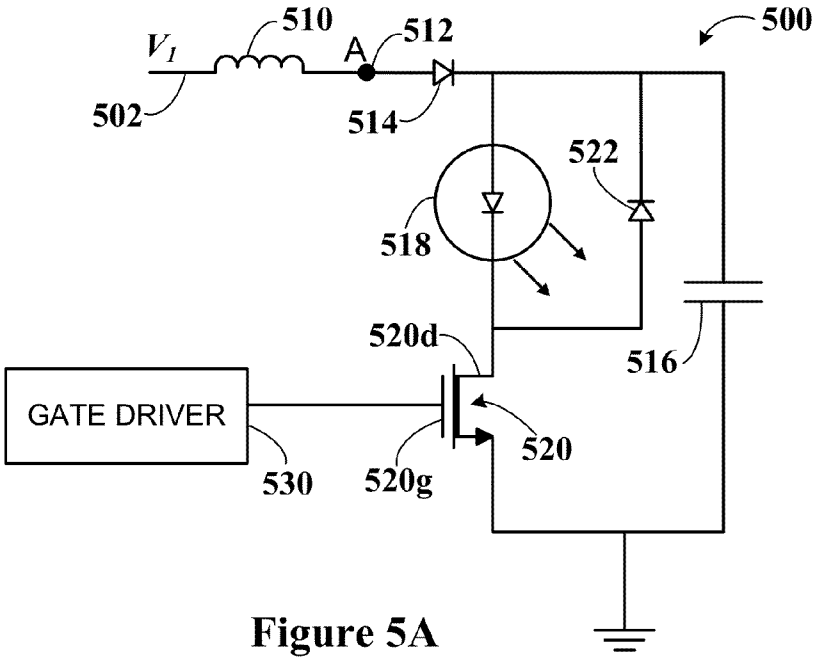


Figure 5A

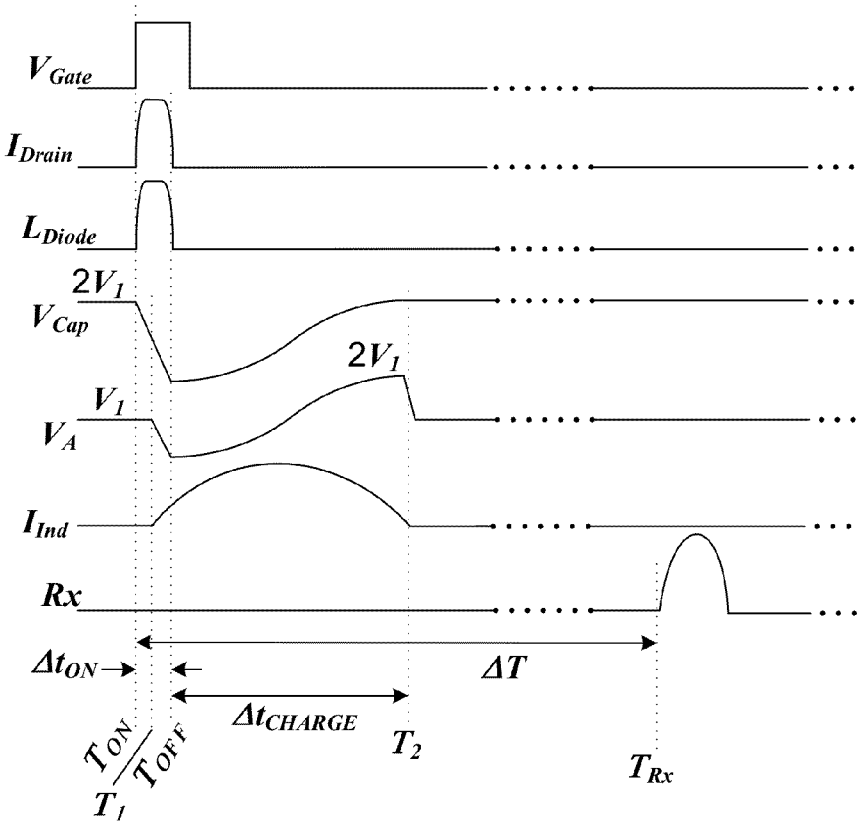


Figure 5B

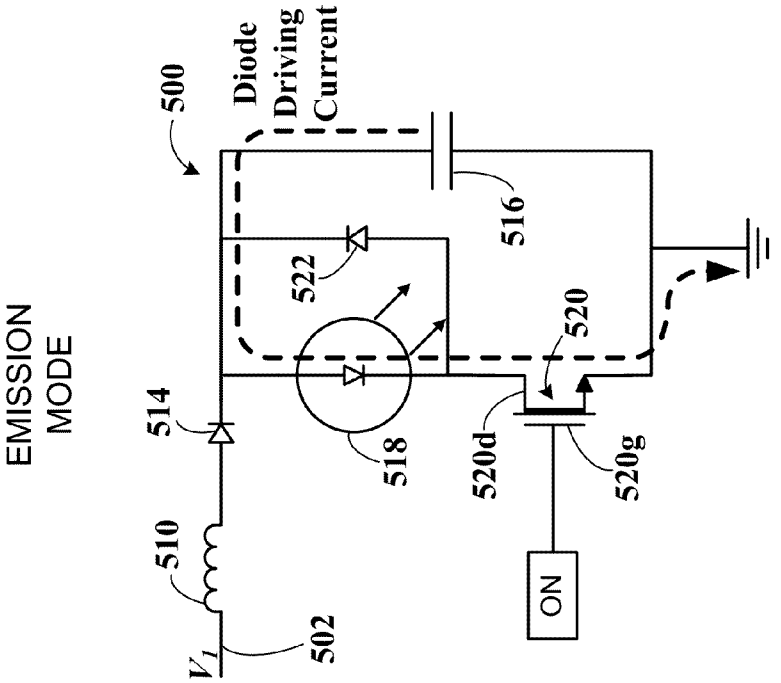


Figure 5D

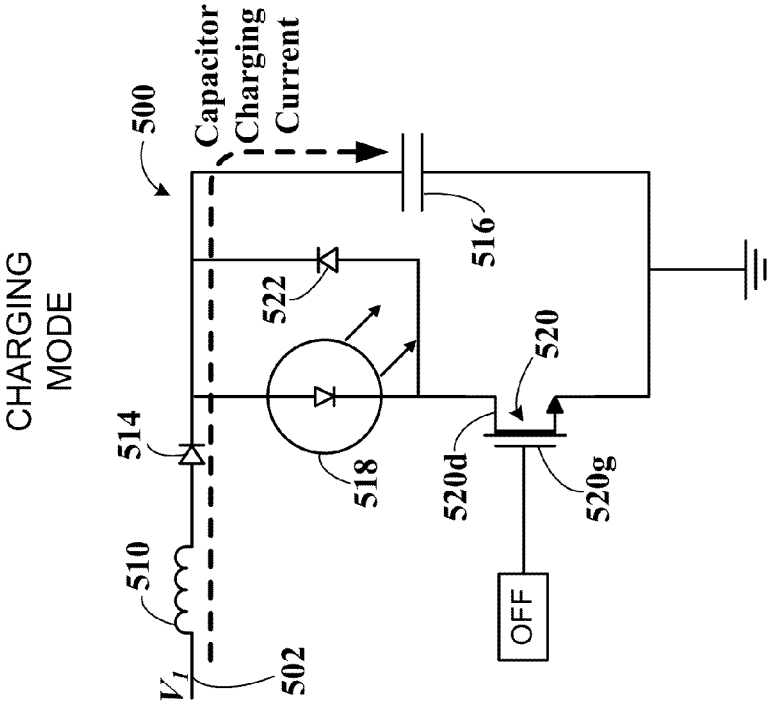
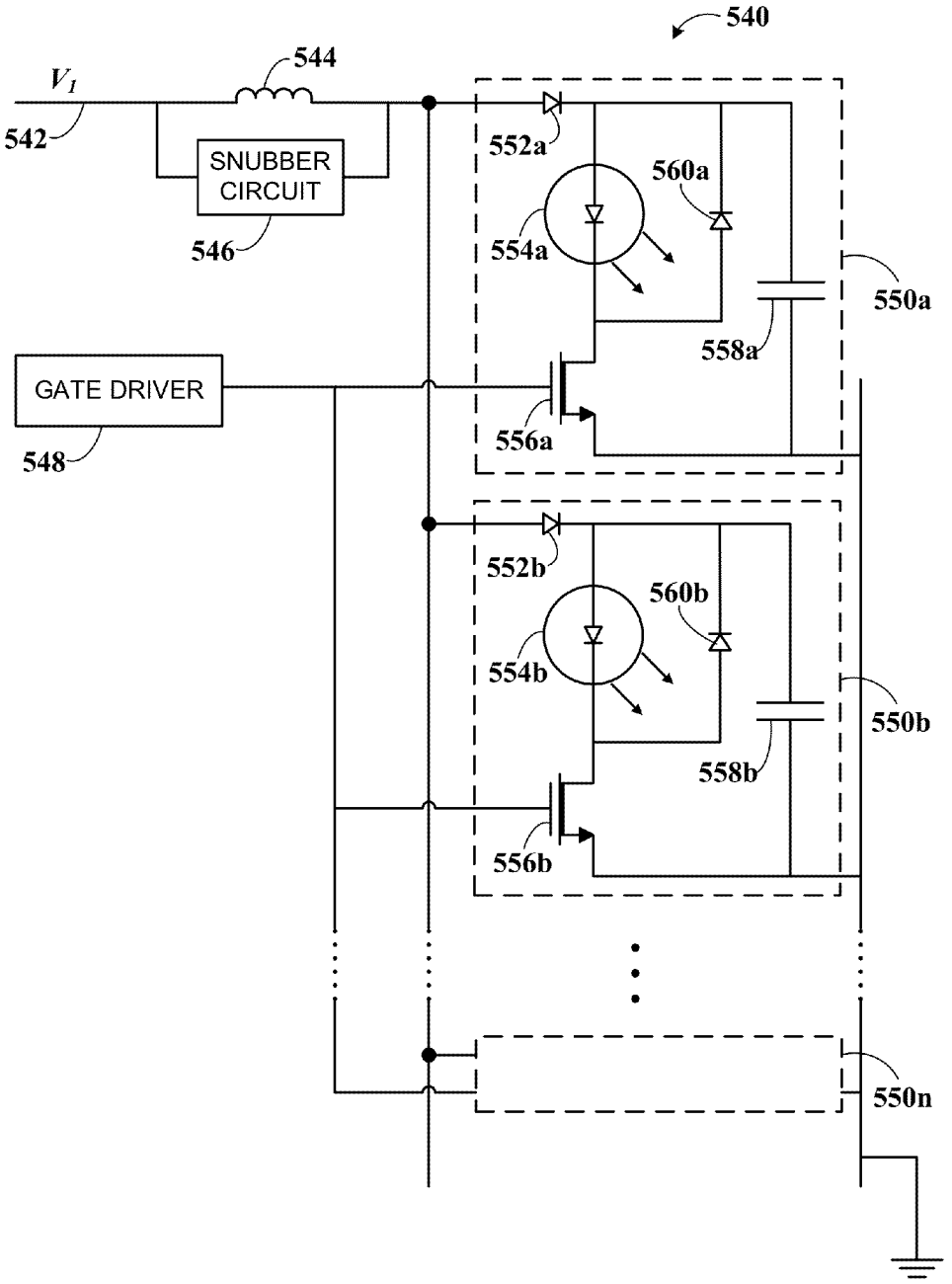


Figure 5C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544
V_1
542
SNUBBER CIRCUIT
546
552a
560a
554a
550a
558a
GATE DRIVER
548
556a
552b
560b
554b
550b
558b
556b
550n

Figure 5E

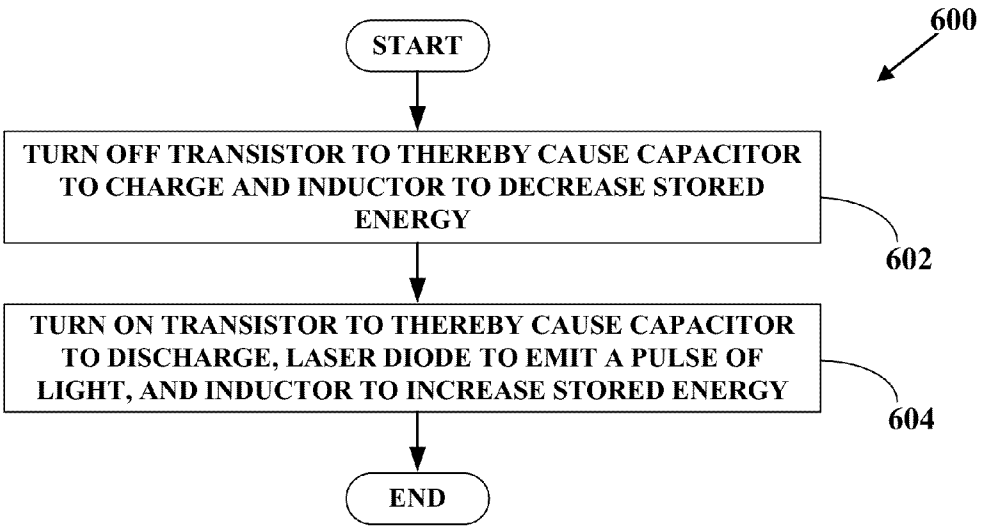
600
START
TURN OFF TRANSISTOR TO THEREBY CAUSE CAPACITOR TO CHARGE AND INDUCTOR TO DECREASE STORED ENERGY
602
TURN ON TRANSISTOR TO THEREBY CAUSE CAPACITOR TO DISCHARGE, LASER DIODE TO EMIT A PULSE OF LIGHT, AND INDUCTOR TO INCREASE STORED ENERGY
604
END

Figure 6A

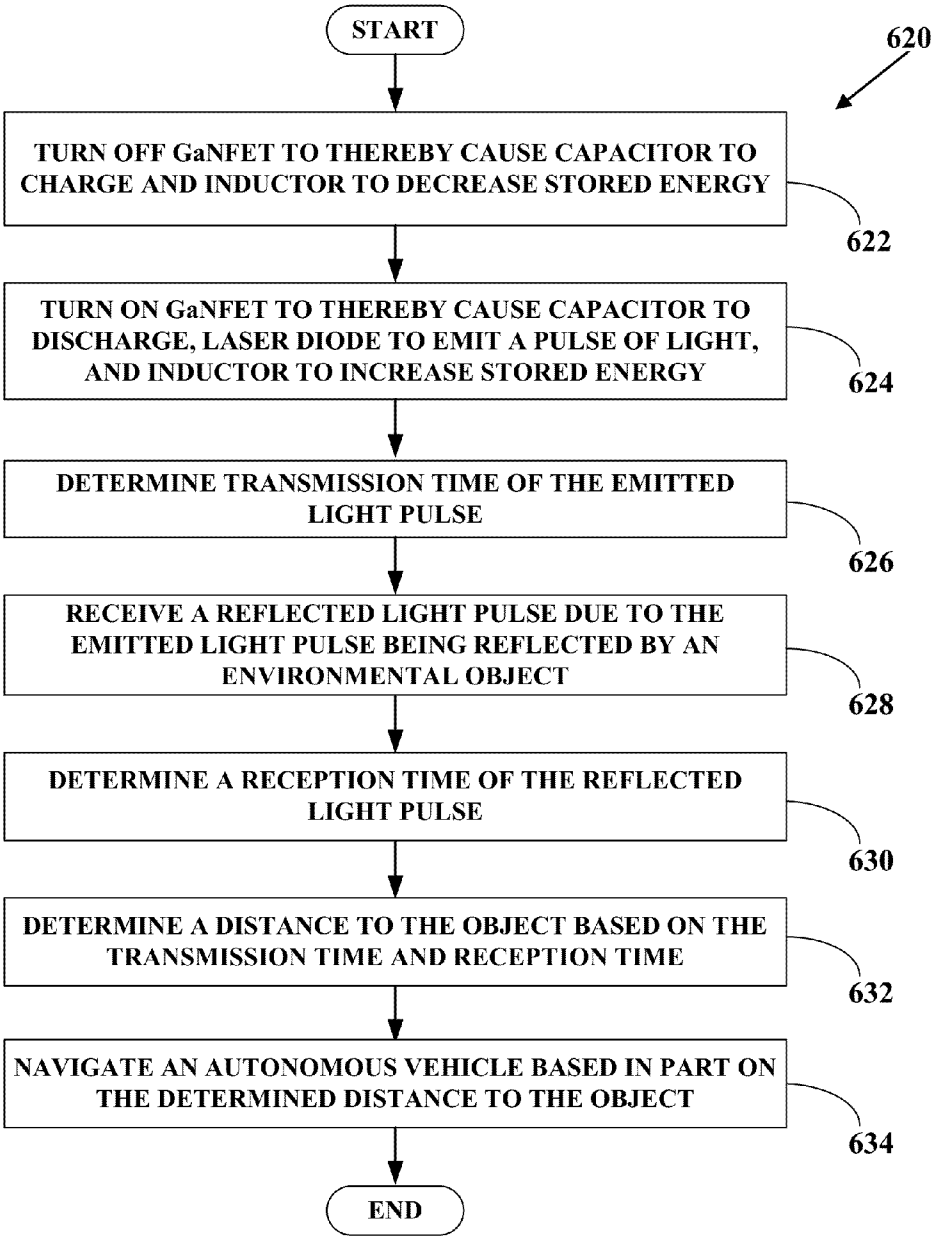
START
620
TURN OFF GaNFET TO THEREBY CAUSE CAPACITOR TO CHARGE AND INDUCTOR TO DECREASE STORED ENERGY
622
TURN ON GaNFET TO THEREBY CAUSE CAPACITOR TO DISCHARGE, LASER DIODE TO EMIT A PULSE OF LIGHT, AND INDUCTOR TO INCREASE STORED ENERGY
624
DETERMINE TRANSMISSION TIME OF THE EMITTED LIGHT PULSE
626
RECEIVE A REFLECTED LIGHT PULSE DUE TO THE EMITTED LIGHT PULSE BEING REFLECTED BY AN ENVIRONMENTAL OBJECT
628
DETERMINE A RECEPTION TIME OF THE REFLECTED LIGHT PULSE
630
DETERMINE A DISTANCE TO THE OBJECT BASED ON THE TRANSMISSION TIME AND RECEPTION TIME
632
NAVIGATE AN AUTONOMOUS VEHICLE BASED IN PART ON THE DETERMINED DISTANCE TO THE OBJECT
634
END

Figure 6B

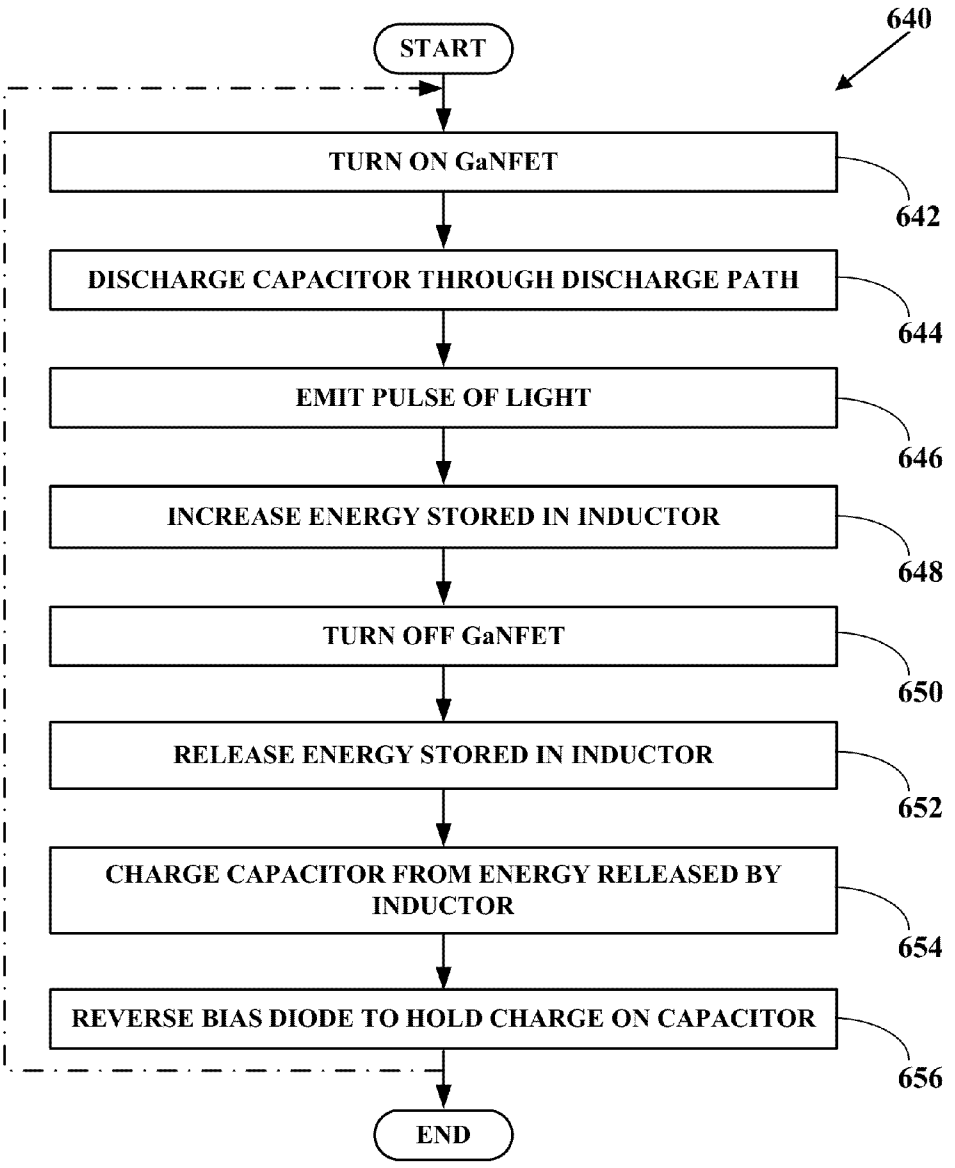
640
START
TURN ON GaNFET
642
DISCHARGE CAPACITOR THROUGH DISCHARGE PATH
644
EMIT PULSE OF LIGHT
646
INCREASE ENERGY STORED IN INDUCTOR
648
TURN OFF GaNFET
650
RELEASE ENERGY STORED IN INDUCTOR
652
CHARGE CAPACITOR FROM ENERGY RELEASED BY INDUCTOR
654
REVERSE BIAS DIODE TO HOLD CHARGE ON CAPACITOR
656
END

Figure 6C

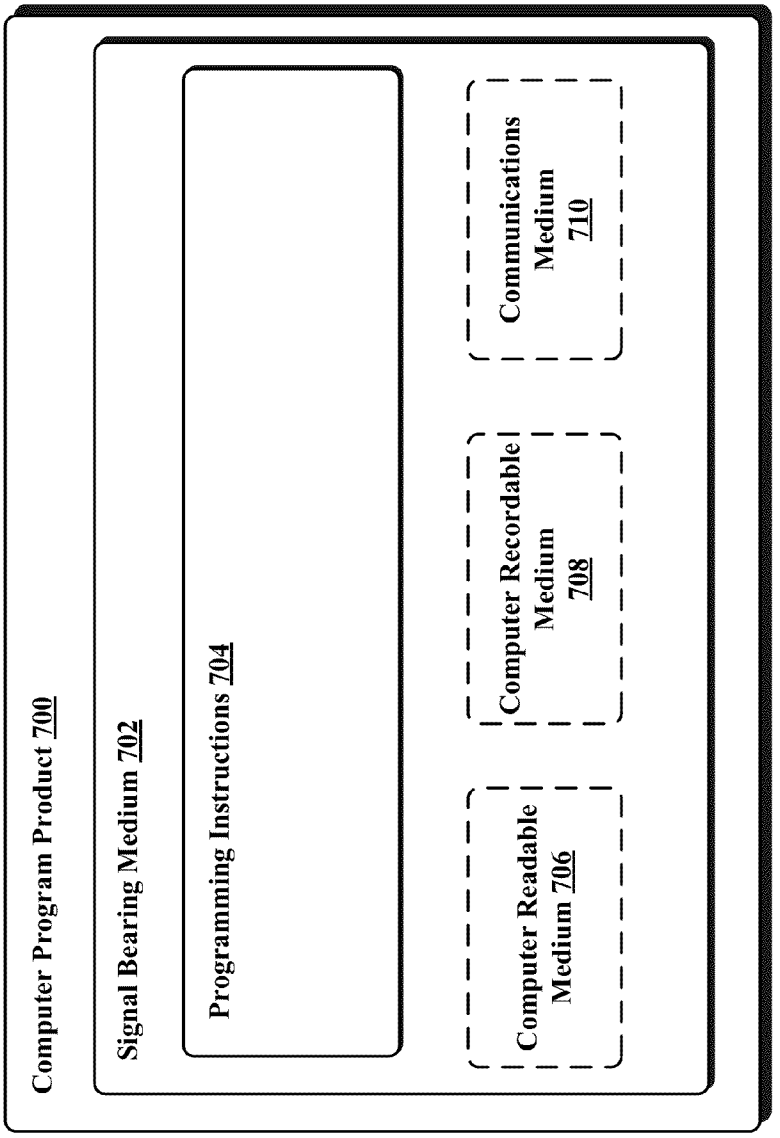
Computer Program Product 700
Signal Bearing Medium 702
Programming Instructions 704
Computer Readable Medium 706
Computer Recordable Medium 708
Communications Medium 710

Figure 7

LASER DIODE FIRING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 61/884,762, filed Sep. 30, 2013, which is incorporated herein by reference in its entirety and for all purposes.

BACKGROUND

Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

Vehicles can be configured to operate in an autonomous mode in which the vehicle navigates through an environment with little or no input from a driver. Such autonomous vehicles can include one or more sensors that are configured to detect information about the environment in which the vehicle operates. The vehicle and its associated computer-implemented controller use the detected information to navigate through the environment. For example, if the sensor(s) detect that the vehicle is approaching an obstacle, as determined by the computer-implemented controller, the controller adjusts the vehicle's directional controls to cause the vehicle to navigate around the obstacle.

One such sensor is a light detection and ranging (LIDAR) device. A LIDAR actively estimates distances to environmental features while scanning through a scene to assemble a cloud of point positions indicative of the three-dimensional shape of the environmental scene. Individual points are measured by generating a laser pulse and detecting a returning pulse, if any, reflected from an environmental object, and determining the distance to the reflective object according to the time delay between the emitted pulse and the reception of the reflected pulse. The laser, or set of lasers, can be rapidly and repeatedly scanned across a scene to provide continuous real-time information on distances to reflective objects in the scene. Combining the measured distances and the orientation of the laser(s) while measuring each distance allows for associating a three-dimensional position with each returning pulse. A three-dimensional map of points of reflective features is generated based on the returning pulses for the entire scanning zone. The three-dimensional point map thereby indicates positions of reflective objects in the scanned scene.

SUMMARY

A laser diode firing circuit for a light detection and ranging (LIDAR) device is disclosed. The firing circuit includes a laser diode coupled in series with a transistor, such that current through the laser diode is controlled by the transistor. The laser diode is configured to emit a pulse of light in response to current flowing through the laser diode. A capacitor is connected across the laser diode and the transistor such that the capacitor discharges through the laser diode when the transistor is turned on. The capacitor is charged by a voltage source via a charging path that includes a diode and an inductor. The inductor has one terminal coupled to the voltage source and another terminal coupled to the anode of the diode, and the cathode of the diode is coupled to the capacitor. As a result, the capacitor is only charged while the diode is forward biased. Upon turning on the transistor, the capacitor discharges through the laser diode and a pulse of light is emitted. Once the capacitor discharges to a voltage level sufficient to forward bias the diode, current begins flowing through the inductor. The increase in inductor current causes the inductor to increase energy stored in its magnetic field, and drives the voltage applied to the anode of the diode lower than the voltage source. Once the transistor is turned off, the laser diode ceases emission, and the current through the inductor is directed to recharge the capacitor, which causes the inductor current to begin decreasing. The sudden change in current through the inductor causes an increase in the voltage applied to the anode of the diode. The capacitor is charged until the voltage of the capacitor approximately matches the voltage at the diode anode, at which point the diode becomes reverse biased. Upon reverse biasing the diode, the current through the inductor goes to zero and the charging cycle is complete. Both the emission and charging operations of the firing circuit can thus be controlled by operation of the single transistor.

Some embodiments of the present disclosure provide an apparatus. The apparatus includes a voltage source, an inductor, a diode, a transistor, a light emitting element, and a capacitor. The inductor can be coupled to the voltage source. The inductor can be configured to store energy in a magnetic field. The diode can be coupled to the voltage source via the inductor. The transistor can be configured to be turned on and turned off by a control signal. The light emitting element can be coupled to the transistor. The capacitor can be coupled to a charging path and a discharge path. The charging path can include the inductor and the diode. The discharge path can include the transistor and the light emitting element. The capacitor can be configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level responsive to the transistor being turned off. The inductor can be configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level responsive to the transistor being turned off. The capacitor can be configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level responsive to the transistor being turned on. The inductor can be configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level responsive to the transistor being turned on.

Some embodiments of the present disclosure provide a method. The method can include turning off a transistor and turning on a transistor. The transistor can be coupled to a light emitting element. Both the transistor and the light emitting element can be included in a discharge path coupled to a capacitor. The capacitor can also be coupled to a charging path including a diode and an inductor. The inductor can be configured to store energy in a magnetic field. The diode can be coupled to a voltage source via the inductor. The capacitor can be configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level responsive to the transistor being turned off. The inductor can be configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level responsive to the transistor being turned off. The capacitor can be configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level responsive to the transistor being turned on. The inductor can be configured to store energy in the magnetic field such that the current

through the inductor increases from the lower current level to the higher current level responsive to the transistor being turned on.

Some embodiments of the present disclosure provide a light detection and ranging (LIDAR) device. The LIDAR device can include a light source, a light sensor, and a controller. The light source can include a voltage source, an inductor, a diode, a transistor, a light emitting element, and a capacitor. The inductor can be coupled to the voltage source. The inductor can be configured to store energy in a magnetic field. The diode can be coupled to the voltage source via the inductor. The transistor can be configured to be turned on and turned off by a control signal. The light emitting element can be coupled to the transistor. The capacitor can be coupled to a charging path and a discharge path. The charging path includes the inductor and the diode. The discharge path includes the transistor and the light emitting element. The capacitor can be configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level responsive to the transistor being turned off. The inductor can be configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level responsive to the transistor being turned off. The capacitor can be configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level responsive to the transistor being turned on. The inductor can be configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level responsive to the transistor being turned on. The light sensor can be configured to detect a reflected light signal comprising light from the emitted light pulse reflected by a reflective object. The controller can be configured to determine a distance to the reflective object based on the reflected light signal.

Some embodiments of the present disclosure provide a means for controlling a laser diode firing circuit to operate in an emission mode and a charging mode using a single transistor. Embodiments may include means turning off a transistor and turning on a transistor. The transistor can be coupled to a light emitting element. Both the transistor and the light emitting element can be included in a discharge path coupled to a capacitor. The capacitor can also be coupled to a charging path including a diode and an inductor. The inductor can be configured to store energy in a magnetic field. The diode can be coupled to a voltage source via the inductor. The capacitor can be configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level responsive to the transistor being turned off. The inductor can be configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level responsive to the transistor being turned off. The capacitor can be configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level responsive to the transistor being turned on. The inductor can be configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level responsive to the transistor being turned on.

These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a functional block diagram depicting aspects of an example autonomous vehicle.

FIG. **2** depicts exterior views of an example autonomous vehicle.

FIG. **3**A provides an example depiction of a LIDAR device including beam steering optics.

FIG. **3**B symbolically illustrates an example in which a LIDAR device scans across an obstacle-filled environmental scene.

FIG. **3**C symbolically illustrates an example point cloud corresponding to the obstacle-filled environmental scene of FIG. **3**B.

FIG. **4**A symbolically illustrates a LIDAR device scanning across an example obstacle-filled environmental scene and using reflected signals to generate a point cloud.

FIG. **4**B is an example timing diagram of transmitted and received pulses for the symbolic illustration of FIG. **4**A.

FIG. **5**A is an example laser diode firing circuit.

FIG. **5**B is a timing diagram that shows operation of the example laser diode firing circuit of FIG. **5**A.

FIG. **5**C shows a current path through the example laser diode firing circuit of FIG. **5**A during a charging mode.

FIG. **5**D shows a current path through the example laser diode firing circuit of FIG. **5**A during an emission mode.

FIG. **5**E illustrates an arrangement in which multiple laser diode firing circuit are charged via a single inductor.

FIG. **6**A is a flowchart of an example process for operating a laser diode firing circuit.

FIG. **6**B is a flowchart of an example process for operating a LIDAR device.

FIG. **6**C is a flowchart of another example process for operating a laser diode firing circuit.

FIG. **7** depicts a non-transitory computer-readable medium configured according to an example embodiment.

DETAILED DESCRIPTION

I. Overview

Example embodiments relate to an autonomous vehicle, such as a driverless automobile, that includes a light detection and ranging (LIDAR) sensor for actively detecting reflective features in the environment surrounding the vehicle. A controller analyzes information from the LIDAR sensor to identify the surroundings of the vehicle. The LIDAR sensor includes a light source that may include one or more laser diodes configured to emit pulses of light that are then directed to illuminate the environment surrounding the vehicle. Circuits for firing a laser diode and determining a pulse emission time from the laser diode are disclosed herein.

According to some embodiments, a LIDAR device includes one or more laser diode firing circuits in which a laser diode is connected in series to a transistor such that current through the laser diode is controlled by the transistor. A capacitor is coupled to a charging path and a discharge path. The discharge path includes the laser diode and the transistor such that turning on the transistor causes the capacitor to discharge through the laser diode, which causes the laser diode to emit a pulse of light.

The capacitor's charging path includes an inductor and a diode. The inductor is configured to store energy in a magnetic field, and is connected between a voltage source and the

diode. An increasing inductor current charges the inductor by increasing the energy stored in the magnetic field of the inductor. The increasing current induces a voltage across the inductor, such that a voltage less than the voltage source is applied to the diode. A decreasing inductor current discharges the inductor by decreasing the energy stored in the magnetic field. The decreasing current induces a voltage across the inductor, such that the voltage applied to the diode exceeds the voltage source. The diode is also connected to the capacitor and is configured to be forward biased when the voltage across the capacitor does not exceed the voltage applied to the diode by the inductor (to thereby charge the capacitor). The diode is also configured to be reverse biased when the voltage across the capacitor exceeds the voltage applied to the diode by the inductor (to thereby prevent the capacitor from discharging).

In some embodiments, the firing circuit disclosed herein is configured to switch between a charging mode and an emission mode based on operation of a single transistor. In response to turning the transistor off, current through the laser diode ceases and emission of a pulse terminates. In response to turning off the transistor, if the charging path diode is forward biased, the capacitor begins recharging through the charging path. As charge accumulates on the capacitor the current through the charging path (and the inductor) decreases, and the decrease in inductor current causes the inductor to release energy stored in its magnetic field. The released energy from the inductor causes the voltage applied to the capacitor through the diode to exceed the voltage of the voltage source, at least transiently. The transient voltage is applied to the capacitor through the diode. The capacitor is therefore charged according to the transient voltage and then holds its charge level when the diode becomes reverse biased. Following a charging interval, the voltage charged across the capacitor can be greater than the voltage of the voltage source.

The laser diode can emit light in the visible spectrum, ultraviolet spectrum, infrared spectrum, near infrared spectrum, and/or infrared spectrum. In one example, the laser diode emits pulses of infrared light with a wavelength of about 905 nm. The transistor can be a Gallium nitride field effect transistor (FET), for example.

II. Example Autonomous Vehicle System

Some aspects of the example methods described herein may be carried out in whole or in part by an autonomous vehicle or components thereof. However, some example methods may also be carried out in whole or in part by a system or systems that are remote from an autonomous vehicle. For instance, an example method could be carried out in part or in full by a server system, which receives information from sensors (e.g., raw sensor data and/or information derived therefrom) of an autonomous vehicle. Other examples are also possible.

Example systems within the scope of the present disclosure will now be described in greater detail. An example system may be implemented in, or may take the form of, an automobile. However, an example system may also be implemented in or take the form of other vehicles, such as cars, trucks, motorcycles, buses, boats, airplanes, helicopters, lawn mowers, earth movers, boats, snowmobiles, aircraft, recreational vehicles, amusement park vehicles, farm equipment, construction equipment, trams, golf carts, trains, and trolleys. Other vehicles are possible as well.

FIG. **1** is a functional block diagram illustrating a vehicle **100** according to an example embodiment. The vehicle **100** is configured to operate fully or partially in an autonomous mode, and thus may be referred to as an "autonomous vehicle." For example, a computer system **112** can control the vehicle **100** while in an autonomous mode via control instructions to a control system **106** for the vehicle **100**. The computer system **112** can receive information from one or more sensor systems **104**, and base one or more control processes (such as setting a heading so as to avoid a detected obstacle) upon the received information in an automated fashion.

The autonomous vehicle **100** can be fully autonomous or partially autonomous. In a partially autonomous vehicle some functions can optionally be manually controlled (e.g., by a driver) some or all of the time. Further, a partially autonomous vehicle can be configured to switch between a fully-manual operation mode and a partially-autonomous and/or a fully-autonomous operation mode.

The vehicle **100** includes a propulsion system **102**, a sensor system **104**, a control system **106**, one or more peripherals **108**, a power supply **110**, a computer system **112**, and a user interface **116**. The vehicle **100** may include more or fewer subsystems and each subsystem can optionally include multiple components. Further, each of the subsystems and components of vehicle **100** can be interconnected and/or in communication. Thus, one or more of the functions of the vehicle **100** described herein can optionally be divided between additional functional or physical components, or combined into fewer functional or physical components. In some further examples, additional functional and/or physical components may be added to the examples illustrated by FIG. **1**.

The propulsion system **102** can include components operable to provide powered motion to the vehicle **100**. In some embodiments the propulsion system **102** includes an engine/motor **118**, an energy source **119**, a transmission **120**, and wheels/tires **121**. The engine/motor **118** converts energy source **119** to mechanical energy. In some embodiments, the propulsion system **102** can optionally include one or both of engines and/or motors. For example, a gas-electric hybrid vehicle can include both a gasoline/diesel engine and an electric motor.

The energy source **119** represents a source of energy, such as electrical and/or chemical energy, that may, in full or in part, power the engine/motor **118**. That is, the engine/motor **118** can be configured to convert the energy source **119** to mechanical energy to operate the transmission. In some embodiments, the energy source **119** can include gasoline, diesel, other petroleum-based fuels, propane, other compressed gas-based fuels, ethanol, solar panels, batteries, capacitors, flywheels, regenerative braking systems, and/or other sources of electrical power, etc. The energy source **119** can also provide energy for other systems of the vehicle **100**.

The transmission **120** includes appropriate gears and/or mechanical elements suitable to convey the mechanical power from the engine/motor **118** to the wheels/tires **121**. In some embodiments, the transmission **120** includes a gearbox, a clutch, a differential, a drive shaft, and/or axle(s), etc.

The wheels/tires **121** are arranged to stably support the vehicle **100** while providing frictional traction with a surface, such as a road, upon which the vehicle **100** moves. Accordingly, the wheels/tires **121** are configured and arranged according to the nature of the vehicle **100**. For example, the wheels/tires can be arranged as a unicycle, bicycle, motorcycle, tricycle, or car/truck four-wheel format. Other wheel/tire geometries are possible, such as those including six or more wheels. Any combination of the wheels/tires **121** of vehicle **100** may be operable to rotate differentially with respect to other wheels/tires **121**. The wheels/tires **121** can optionally include at least one wheel that is rigidly attached to the transmission **120** and at least one tire coupled to a rim of

a corresponding wheel that makes contact with a driving surface. The wheels/tires **121** may include any combination of metal and rubber, and/or other materials or combination of materials.

The sensor system **104** generally includes one or more sensors configured to detect information about the environment surrounding the vehicle **100**. For example, the sensor system **104** can include a Global Positioning System (GPS) **122**, an inertial measurement unit (IMU) **124**, a RADAR unit **126**, a laser rangefinder/LIDAR unit **128**, a camera **130**, and/or a microphone **131**. The sensor system **104** could also include sensors configured to monitor internal systems of the vehicle **100** (e.g., O_2 monitor, fuel gauge, engine oil temperature, wheel speed sensors, etc.). One or more of the sensors included in sensor system **104** could be configured to be actuated separately and/or collectively in order to modify a position and/or an orientation of the one or more sensors.

The GPS **122** is a sensor configured to estimate a geographic location of the vehicle **100**. To this end, GPS **122** can include a transceiver operable to provide information regarding the position of the vehicle **100** with respect to the Earth.

The IMU **124** can include any combination of sensors (e.g., accelerometers and gyroscopes) configured to sense position and orientation changes of the vehicle **100** based on inertial acceleration.

The RADAR unit **126** can represent a system that utilizes radio signals to sense objects within the local environment of the vehicle **100**. In some embodiments, in addition to sensing the objects, the RADAR unit **126** and/or the computer system **112** can additionally be configured to sense the speed and/or heading of the objects.

Similarly, the laser rangefinder or LIDAR unit **128** can be any sensor configured to sense objects in the environment in which the vehicle **100** is located using lasers. The laser rangefinder/LIDAR unit **128** can include one or more laser sources, a laser scanner, and one or more detectors, among other system components. The laser rangefinder/LIDAR unit **128** can be configured to operate in a coherent (e.g., using heterodyne detection) or an incoherent detection mode.

The camera **130** can include one or more devices configured to capture a plurality of images of the environment surrounding the vehicle **100**. The camera **130** can be a still camera or a video camera. In some embodiments, the camera **130** can be mechanically movable such as by rotating and/or tilting a platform to which the camera is mounted. As such, a control process of vehicle **100** may be implemented to control the movement of camera **130**.

The sensor system **104** can also include a microphone **131**. The microphone **131** can be configured to capture sound from the environment surrounding vehicle **100**. In some cases, multiple microphones can be arranged as a microphone array, or possibly as multiple microphone arrays.

The control system **106** is configured to control operation(s) regulating acceleration of the vehicle **100** and its components. To effect acceleration, the control system **106** includes a steering unit **132**, throttle **134**, brake unit **136**, a sensor fusion algorithm **138**, a computer vision system **140**, a navigation/pathing system **142**, and/or an obstacle avoidance system **144**, etc.

The steering unit **132** is operable to adjust the heading of vehicle **100**. For example, the steering unit can adjust the axis (or axes) of one or more of the wheels/tires **121** so as to effect turning of the vehicle. The throttle **134** is configured to control, for instance, the operating speed of the engine/motor **118** and, in turn, adjust forward acceleration of the vehicle **100** via the transmission **120** and wheels/tires **121**. The brake unit **136** decelerates the vehicle **100**. The brake unit **136** can use friction to slow the wheels/tires **121**. In some embodiments, the brake unit **136** inductively decelerates the wheels/tires **121** by a regenerative braking process to convert kinetic energy of the wheels/tires **121** to electric current.

The sensor fusion algorithm **138** is an algorithm (or a computer program product storing an algorithm) configured to accept data from the sensor system **104** as an input. The data may include, for example, data representing information sensed at the sensors of the sensor system **104**. The sensor fusion algorithm **138** can include, for example, a Kalman filter, Bayesian network, etc. The sensor fusion algorithm **138** provides assessments regarding the environment surrounding the vehicle based on the data from sensor system **104**. In some embodiments, the assessments can include evaluations of individual objects and/or features in the environment surrounding vehicle **100**, evaluations of particular situations, and/or evaluations of possible interference between the vehicle **100** and features in the environment (e.g., such as predicting collisions and/or impacts) based on the particular situations.

The computer vision system **140** can process and analyze images captured by camera **130** to identify objects and/or features in the environment surrounding vehicle **100**. The detected features/objects can include traffic signals, road way boundaries, other vehicles, pedestrians, and/or obstacles, etc. The computer vision system **140** can optionally employ an object recognition algorithm, a Structure From Motion (SFM) algorithm, video tracking, and/or available computer vision techniques to effect categorization and/or identification of detected features/objects. In some embodiments, the computer vision system **140** can be additionally configured to map the environment, track perceived objects, estimate the speed of objects, etc.

The navigation and pathing system **142** is configured to determine a driving path for the vehicle **100**. For example, the navigation and pathing system **142** can determine a series of speeds and directional headings to effect movement of the vehicle along a path that substantially avoids perceived obstacles while generally advancing the vehicle along a roadway-based path leading to an ultimate destination, which can be set according to user inputs via the user interface **116**, for example. The navigation and pathing system **142** can additionally be configured to update the driving path dynamically while the vehicle **100** is in operation on the basis of perceived obstacles, traffic patterns, weather/road conditions, etc. In some embodiments, the navigation and pathing system **142** can be configured to incorporate data from the sensor fusion algorithm **138**, the GPS **122**, and one or more predetermined maps so as to determine the driving path for vehicle **100**.

The obstacle avoidance system **144** can represent a control system configured to identify, evaluate, and avoid or otherwise negotiate potential obstacles in the environment surrounding the vehicle **100**. For example, the obstacle avoidance system **144** can effect changes in the navigation of the vehicle by operating one or more subsystems in the control system **106** to undertake swerving maneuvers, turning maneuvers, braking maneuvers, etc. In some embodiments, the obstacle avoidance system **144** is configured to automatically determine feasible ("available") obstacle avoidance maneuvers on the basis of surrounding traffic patterns, road conditions, etc. For example, the obstacle avoidance system **144** can be configured such that a swerving maneuver is not undertaken when other sensor systems detect vehicles, construction barriers, other obstacles, etc. in the region adjacent the vehicle that would be swerved into. In some embodiments, the obstacle avoidance system **144** can automatically select the maneuver that is both available and maximizes

safety of occupants of the vehicle. For example, the obstacle avoidance system **144** can select an avoidance maneuver predicted to cause the least amount of acceleration in a passenger cabin of the vehicle **100**.

The vehicle **100** also includes peripherals **108** configured to allow interaction between the vehicle **100** and external sensors, other vehicles, other computer systems, and/or a user, such as an occupant of the vehicle **100**. For example, the peripherals **108** for receiving information from occupants, external systems, etc. can include a wireless communication system **146**, a touchscreen **148**, a microphone **150**, and/or a speaker **152**.

In some embodiments, the peripherals **108** function to receive inputs for a user of the vehicle **100** to interact with the user interface **116**. To this end, the touchscreen **148** can both provide information to a user of vehicle **100**, and convey information from the user indicated via the touchscreen **148** to the user interface **116**. The touchscreen **148** can be configured to sense both touch positions and touch gestures from a user's finger (or stylus, etc.) via capacitive sensing, resistance sensing, optical sensing, a surface acoustic wave process, etc. The touchscreen **148** can be capable of sensing finger movement in a direction parallel or planar to the touchscreen surface, in a direction normal to the touchscreen surface, or both, and may also be capable of sensing a level of pressure applied to the touchscreen surface. An occupant of the vehicle **100** can also utilize a voice command interface. For example, the microphone **150** can be configured to receive audio (e.g., a voice command or other audio input) from a user of the vehicle **100**. Similarly, the speakers **152** can be configured to output audio to the user of the vehicle **100**.

In some embodiments, the peripherals **108** function to allow communication between the vehicle **100** and external systems, such as devices, sensors, other vehicles, etc. within its surrounding environment and/or controllers, servers, etc., physically located far from the vehicle that provide useful information regarding the vehicle's surroundings, such as traffic information, weather information, etc. For example, the wireless communication system **146** can wirelessly communicate with one or more devices directly or via a communication network. The wireless communication system **146** can optionally use 3G cellular communication, such as CDMA, EVDO, GSM/GPRS, and/or 4G cellular communication, such as WiMAX or LTE. Additionally or alternatively, wireless communication system **146** can communicate with a wireless local area network (WLAN), for example, using WiFi. In some embodiments, wireless communication system **146** could communicate directly with a device, for example, using an infrared link, Bluetooth, and/or ZigBee. The wireless communication system **146** can include one or more dedicated short range communication (DSRC) devices that can include public and/or private data communications between vehicles and/or roadside stations. Other wireless protocols for sending and receiving information embedded in signals, such as various vehicular communication systems, can also be employed by the wireless communication system **146** within the context of the present disclosure.

As noted above, the power supply **110** can provide power to components of vehicle **100**, such as electronics in the peripherals **108**, computer system **112**, sensor system **104**, etc. The power supply **110** can include a rechargeable lithium-ion or lead-acid battery for storing and discharging electrical energy to the various powered components, for example. In some embodiments, one or more banks of batteries can be configured to provide electrical power. In some embodiments, the power supply **110** and energy source **119** can be implemented together, as in some all-electric cars.

Many or all of the functions of vehicle **100** can be controlled via computer system **112** that receives inputs from the sensor system **104**, peripherals **108**, etc., and communicates appropriate control signals to the propulsion system **102**, control system **106**, peripherals, etc. to effect automatic operation of the vehicle **100** based on its surroundings. Computer system **112** includes at least one processor **113** (which can include at least one microprocessor) that executes instructions **115** stored in a non-transitory computer readable medium, such as the data storage **114**. The computer system **112** may also represent a plurality of computing devices that serve to control individual components or subsystems of the vehicle **100** in a distributed fashion.

In some embodiments, data storage **114** contains instructions **115** (e.g., program logic) executable by the processor **113** to execute various functions of vehicle **100**, including those described above in connection with FIG. **1**. Data storage **114** may contain additional instructions as well, including instructions to transmit data to, receive data from, interact with, and/or control one or more of the propulsion system **102**, the sensor system **104**, the control system **106**, and the peripherals **108**.

In addition to the instructions **115**, the data storage **114** may store data such as roadway maps, path information, among other information. Such information may be used by vehicle **100** and computer system **112** during operation of the vehicle **100** in the autonomous, semi-autonomous, and/or manual modes to select available roadways to an ultimate destination, interpret information from the sensor system **104**, etc.

The vehicle **100**, and associated computer system **112**, provides information to and/or receives input from, a user of vehicle **100**, such as an occupant in a passenger cabin of the vehicle **100**. The user interface **116** can accordingly include one or more input/output devices within the set of peripherals **108**, such as the wireless communication system **146**, the touchscreen **148**, the microphone **150**, and/or the speaker **152** to allow communication between the computer system **112** and a vehicle occupant.

The computer system **112** controls the operation of the vehicle **100** based on inputs received from various subsystems indicating vehicle and/or environmental conditions (e.g., propulsion system **102**, sensor system **104**, and/or control system **106**), as well as inputs from the user interface **116**, indicating user preferences. For example, the computer system **112** can utilize input from the control system **106** to control the steering unit **132** to avoid an obstacle detected by the sensor system **104** and the obstacle avoidance system **144**. The computer system **112** can be configured to control many aspects of the vehicle **100** and its subsystems. Generally, however, provisions are made for manually overriding automated controller-driven operation, such as in the event of an emergency, or merely in response to a user-activated override, etc.

The components of vehicle **100** described herein can be configured to work in an interconnected fashion with other components within or outside their respective systems. For example, the camera **130** can capture a plurality of images that represent information about an environment of the vehicle **100** while operating in an autonomous mode. The environment may include other vehicles, traffic lights, traffic signs, road markers, pedestrians, etc. The computer vision system **140** can categorize and/or recognize various aspects in the environment in concert with the sensor fusion algorithm **138**, the computer system **112**, etc. based on object recognition models pre-stored in data storage **114**, and/or by other techniques.

Although the vehicle **100** is described and shown in FIG. **1** as having various components of vehicle **100**, e.g., wireless communication system **146**, computer system **112**, data storage **114**, and user interface **116**, integrated into the vehicle **100**, one or more of these components can optionally be mounted or associated separately from the vehicle **100**. For example, data storage **114** can exist, in part or in full, separate from the vehicle **100**, such as in a cloud-based server, for example. Thus, one or more of the functional elements of the vehicle **100** can be implemented in the form of device elements located separately or together. The functional device elements that make up vehicle **100** can generally be communicatively coupled together in a wired and/or wireless fashion.

FIG. **2** shows an example vehicle **200** that can include some or all of the functions described in connection with vehicle **100** in reference to FIG. **1**. Although vehicle **200** is illustrated in FIG. **2** as a four-wheel sedan-type car for illustrative purposes, the present disclosure is not so limited. For instance, the vehicle **200** can represent a truck, a van, a semi-trailer truck, a motorcycle, a golf cart, an off-road vehicle, or a farm vehicle, etc.

The example vehicle **200** includes a sensor unit **202**, a wireless communication system **204**, a RADAR unit **206**, a laser rangefinder unit **208**, and a camera **210**. Furthermore, the example vehicle **200** can include any of the components described in connection with vehicle **100** of FIG. **1**. The RADAR unit **206** and/or laser rangefinder unit **208** can actively scan the surrounding environment for the presence of potential obstacles and can be similar to the RADAR unit **126** and/or laser rangefinder/LIDAR unit **128** in the vehicle **100**.

The sensor unit **202** is mounted atop the vehicle **200** and includes one or more sensors configured to detect information about an environment surrounding the vehicle **200**, and output indications of the information. For example, sensor unit **202** can include any combination of cameras, RADARs, LIDARs, range finders, and acoustic sensors. The sensor unit **202** can include one or more movable mounts that could be operable to adjust the orientation of one or more sensors in the sensor unit **202**. In one embodiment, the movable mount could include a rotating platform that could scan sensors so as to obtain information from each direction around the vehicle **200**. In another embodiment, the movable mount of the sensor unit **202** could be moveable in a scanning fashion within a particular range of angles and/or azimuths. The sensor unit **202** could be mounted atop the roof of a car, for instance, however other mounting locations are possible. Additionally, the sensors of sensor unit **202** could be distributed in different locations and need not be collocated in a single location. Some possible sensor types and mounting locations include RADAR unit **206** and laser rangefinder unit **208**. Furthermore, each sensor of sensor unit **202** can be configured to be moved or scanned independently of other sensors of sensor unit **202**.

In an example configuration, one or more RADAR scanners (e.g., the RADAR unit **206**) can be located near the front of the vehicle **200**, to actively scan the region in front of the car **200** for the presence of radio-reflective objects. A RADAR scanner can be situated, for example, in a location suitable to illuminate a region including a forward-moving path of the vehicle **200** without occlusion by other features of the vehicle **200**. For example, a RADAR scanner can be situated to be embedded and/or mounted in or near the front bumper, front headlights, cowl, and/or hood, etc. Furthermore, one or more additional RADAR scanning devices can be located to actively scan the side and/or rear of the vehicle **200** for the presence of radio-reflective objects, such as by including such devices in or near the rear bumper, side panels, rocker panels, and/or undercarriage, etc.

The wireless communication system **204** could be located on a roof of the vehicle **200** as depicted in FIG. **2**. Alternatively, the wireless communication system **204** could be located, fully or in part, elsewhere. The wireless communication system **204** may include wireless transmitters and receivers that could be configured to communicate with devices external or internal to the vehicle **200**. Specifically, the wireless communication system **204** could include transceivers configured to communicate with other vehicles and/or computing devices, for instance, in a vehicular communication system or a roadway station. Examples of such vehicular communication systems include dedicated short range communications (DSRC), radio frequency identification (RFID), and other proposed communication standards directed towards intelligent transport systems.

The camera **210** can be a photo-sensitive instrument, such as a still camera, a video camera, etc., that is configured to capture a plurality of images of the environment of the vehicle **200**. To this end, the camera **210** can be configured to detect visible light, and can additionally or alternatively be configured to detect light from other portions of the spectrum, such as infrared or ultraviolet light. The camera **210** can be a two-dimensional detector, and can optionally have a three-dimensional spatial range of sensitivity. In some embodiments, the camera **210** can include, for example, a range detector configured to generate a two-dimensional image indicating distance from the camera **210** to a number of points in the environment. To this end, the camera **210** may use one or more range detecting techniques.

For example, the camera **210** can provide range information by using a structured light technique in which the vehicle **200** illuminates an object in the environment with a predetermined light pattern, such as a grid or checkerboard pattern and uses the camera **210** to detect a reflection of the predetermined light pattern from environmental surroundings. Based on distortions in the reflected light pattern, the vehicle **200** can determine the distance to the points on the object. The predetermined light pattern may comprise infrared light, or radiation at other suitable wavelengths for such measurements.

The camera **210** can be mounted inside a front windshield of the vehicle **200**. Specifically, the camera **210** can be situated to capture images from a forward-looking view with respect to the orientation of the vehicle **200**. Other mounting locations and viewing angles of camera **210** can also be used, either inside or outside the vehicle **200**.

The camera **210** can have associated optics operable to provide an adjustable field of view. Further, the camera **210** can be mounted to vehicle **200** with a movable mount to vary a pointing angle of the camera **210**, such as via a pan/tilt mechanism.

III. Example LIDAR Device

An example light detection and ranging (LIDAR) device operates to estimate positions of reflective objects surrounding the device by illuminating its surrounding environment with pulses of light and measuring the reflected signals. An example LIDAR device may include a light source, beam-steering optics, a light sensor, and a controller. The light source may emit pulses of light toward the beam-steering optics, which directs the pulses of light across a scanning zone. Reflective features in the scanning zone reflect the emitted pulses of light and the reflected light signals can be detected by the light sensor. The controller can regulate the

operation of the light source and beam-steering optics to scan pulses of light across the scanning zone. The controller can also be configured to estimate positions of reflective features in the scanning zone based on the reflected signals detected by the light sensor. For example, the controller can measure the time delay between emission of a pulse of light and reception of a reflected light signal and determine the distance to the reflective feature based on the time of flight of a round trip to the reflective feature. In addition, the controller may use the orientation of the beam-steering optics at the time the pulse of light is emitted to estimate a direction toward the reflective feature. The estimated direction and estimated distance can then be combined to estimate a three-dimensional position of the reflective object relative to the LIDAR device.

FIG. **3**A provides an example depiction of a LIDAR device **302** including beam steering optics **304**. A laser beam **306** is directed to the beam steering optics **304**. In the example illustrated in FIG. **3**A, the beam steering optics **304** is a rotating angled mirror that directs the laser beam **306** to sweep across a scanning zone. The beam steering optics **304** may include a combination of lenses, mirrors, and/or apertures configured to direct the laser beam to sweep across a scanning zone, and are interchangeably described as the rotating angled mirror **304**. The rotating angled mirror **304** rotates about an axis substantially parallel, and roughly in line with, the initial downward path of the laser beam **306**. The rotating angled mirror **304** rotates in the direction indicated by the reference arrow **308** in FIG. **3**A.

Although rangefinder **302** is depicted as having an approximately 180 degree range of rotation for the scanning zone of the laser beam **306** via the rotating angled mirror **304**, this is for purposes of example and explanation only. LIDAR **302** can be configured to have viewing angles (e.g., angular range of available orientations during each sweep), including viewing angles up to and including 360 degrees. Further, although LIDAR **302** is depicted with the single laser beam **306** and a single mirror **304**, this is for purposes of example and explanation only, LIDAR **302** can include multiple laser beams operating simultaneously or sequentially to provide greater sampling coverage of the surrounding environment. The LIDAR **302** also includes, or works in concert with, additional optical sensors (e.g., a photo-detector, not shown) configured to detect the reflection of laser beam **306** from features/objects in the surrounding environment with sufficient temporal sensitivity to determine distances to the reflective features. For example, with reference to the vehicle **200** in FIG. **2**, such optical sensors can optionally be co-located with the top-mounted sensors **204** on the autonomous vehicle **200**.

FIG. **3**B symbolically illustrates the LIDAR device **302** scanning across an obstacle-filled environmental scene. The example vehicular environment depicted in FIG. **3**B includes a car **310** and a tree **312**. In operation, LIDAR **302** rotates according to motion reference arrow **308**. While rotating, the LIDAR **302** regularly (e.g., periodically) emits laser pulses, such as the laser pulse **306**. Objects in the surrounding environment, such as vehicle **310** and tree **312**, reflect the emitted pulses and the resulting reflected signals are then received by suitable sensors. Precisely time-stamping the receipt of the reflected signals allows for associating each reflected signal (if any is received at all) with the most recently emitted laser pulse, and measuring the time delay between emission of the laser pulse and reception of the reflected light. The time delay provides an estimate of the distance to the reflective feature by scaling according to the speed of light in the intervening atmosphere. Combining the distance information for each reflected signal with the orientation of the LIDAR device **302** for the respective pulse emission allows for determining a position of the reflective feature in three-dimensions. For illustrative purposes, the environmental scene in FIG. **3**B is described in the two-dimensional x-y plane in connection with a single sweep of the LIDAR device **302** that estimates positions to a series of points located in the x-y plane. However, it is noted that a more complete three-dimensional sampling is provided by either adjusting the beam steering optics **304** to direct the laser beam **306** up or down from the x-y plane on its next sweep of the scene or by providing additional lasers and associated beam steering optics dedicated to sampling point locations in planes above and below the x-y plane shown in FIG. **3**B, or combinations of these techniques.

FIG. **3**C symbolically illustrates a point cloud corresponding to the obstacle-filled environmental scene of FIG. **3**B. Spatial-point data (represented by stars) are shown from a ground-plane (or aerial) perspective. Even though the individual points are not equally spatially distributed throughout the sampled environment, adjacent sampled points are roughly equally angularly spaced with respect to the LIDAR device **302**. A cluster of points referred to herein as car spatial data **314** corresponds to measured points on the surface of the car **310** with a line of sight to the LIDAR device **302**. Similarly, a cluster of points referred to herein as tree spatial data **316** corresponds to measured points on the surface of the tree **312** visible from the LIDAR device **302**. The absence of points between the car spatial data **314** and the tree spatial data **316** indicates an absence of reflective features along the sampled line of sight paths in the plane illustrated.

Each point in the example point cloud illustrated symbolically in FIG. **3**C can be referenced by an azimuth angle ϕ (e.g. orientation of the LIDAR device **302** while emitting the pulse corresponding to the point, which is determined by the orientation of the rotating angled mirror **304**) and a line-of-sight (LOS) distance (e.g., the distance indicated by the time delay between pulse emission and reflected light reception). For emitted pulses that do not receive a reflected signal, the LOS distance can optionally be set to the maximum distance sensitivity of the LIDAR device **302**. The maximum distance sensitivity can be determined according to the maximum time delay the associated optical sensors wait for a return reflected signal following each pulse emission, which can itself be set according to the anticipated signal strength of a reflected signal at a particular distance given ambient lighting conditions, intensity of the emitted pulse, predicted reflectivity of environmental features, etc. In some examples, the maximum distance can be approximately 60 meters, 80 meters, 100 meters, or 150 meters, but other examples are possible for particular configurations of the LIDAR device **302** and associated optical sensors.

In some embodiments, the sensor fusion algorithm **138**, computer vision system **140**, and/or computer system **112**, can interpret the car spatial data **314** alone and/or in combination with additional sensor-indicated information and/or memory-based pattern-matching point clouds and/or baseline maps of the environment to categorize or identify the group of points **314** as corresponding to the car **310**. Similarly, the tree spatial data **316** can identified as corresponding to the tree **310** in accordance with a suitable object-detection technique. As described further herein, some embodiments of the present disclosure provide for identifying a region of the point cloud for study with enhanced resolution scanning technique on the basis of the already-sampled spatial-points.

FIG. **4**A symbolically illustrates a LIDAR device **302** scanning across an example obstacle-filled environmental scene. The LIDAR device **302** scans the laser beam **306** across the environmental scene via its beam steering optics **304** while its laser light source pulses, such that successive pulses are emit-

ted with an angular separation θ_1. Successive pulses are emitted periodically with a temporal separation t_1. For illustrative purposes, the angular separation θ_1 between adjacent, successively emitted pulses is exaggerated in FIG. **4**A to allow individual pulses to be represented in the drawing. As a result of the rotation of the beam steering optics in the LIDAR device **302**, temporally separated pulses (e.g., pulses emitted at times separated by the time t_1) are directed in respective angular orientations separated by the amount of rotation of the beam steering optics during the interval t_1, (e.g., the angle θ_1). A controller **430** is arranged to receive signals from the LIDAR device **302** and/or associated optical sensors to generate point cloud data **440** indicative of the 3-D positions of reflective features in the environmental scene surrounding the LIDAR device **302**.

FIG. **4**B is a timing diagram of the transmitted and received pulses for the exaggerated symbolic illustration of FIG. **4**A. The timing diagram symbolically illustrates the transmitted pulses (labeled on FIG. **4**B as "Tx") and the corresponding received pulses (labeled on FIG. **4**B as "Rx").

An example operation of the LIDAR device **302** is described in connection with FIGS. **4**A and **4**B. At time Ta, a first pulse **410***a* is emitted from the LIDAR device **302** and directed along laser beam path **306***a* via the beam steering optics. As shown in FIG. **4**A, the beam path **306***a* is reflected from near the front passenger-side region of the car **310**, and a first reflected signal **420***a* is detected at optical signals associated with the LIDAR device **302** (e.g., via optical sensors included in the sensor system **202** mounted on the vehicle **200** in FIG. **2**). The time delay between the emission of pulse **410***a* and reception of the reflected signal **420***a* is indicated by time delay ΔTa. The time delay ΔTa and the orientation of the LIDAR device **302** at time Ta, i.e., the direction of laser beam **306***a*, are combined in the controller **430** to map the 3-D position of the reflective point on the front passenger-side region of the car **310**.

Next, at time Tb, a second pulse **410***b* is emitted from the LIDAR device **302** and directed along laser beam path **306***b*. Time Tb is temporally separated from time Ta by the interval time t**1**, and the direction of the laser beam path **306***b* is angularly separated from the direction of laser beam path **306***a* by angular separation θ_1, due to the change in orientation of the beam steering optics in the LIDAR device during the interval t_1. The laser pulse **310***b* is reflected from near the rear passenger-side region of the car **310**, and a second reflected signal **420***b* is detected with a relative time delay ΔTb from the emission of the second pulse **410***b*. As illustrated in FIG. **4**B, the LIDAR device **302** is generally situated behind the car **310**, and so the reflective point near the rear passenger-side region of the car **310** (responsible for the reflected signal **420***b*) is closer to the LIDAR device **302** than the reflective point near the front passenger-side region of the car **310** (responsible for the reflected signal **420***a*). As a result, the relative time delay ΔTb is shorter than the relative time delay ΔTa, corresponding to the difference in roundtrip travel time at the speed of light between the LIDAR device **302**, and the respective reflective points at the front and rear of the car.

Further, the sensors detecting the reflected signals can optionally be sensitive to the intensity of the reflected signals. For example, the intensity of the reflected signal **420***b* can be perceptibly greater than the intensity of the reflected signal **420***a*, as shown symbolically in FIG. **4**B. The controller **430** maps the 3-D position of the reflective point near the rear passenger-side of the car **310** according to the time delay value ΔTb and the orientation of the LIDAR device **310** at time Tb, i.e., the direction of laser beam **306***b*. The intensity of the reflected signal can also indicate the reflectance of the reflective point, in combination with the distance to the point as indicated by the measured time delay. The reflectance of the reflective point can be employed by software and/or hardware implemented modules in the controller **430** to characterize the reflective features in the environment. For example, traffic indicators such as lane markers, traffic signs, traffic signals, navigational signage, etc., can be indicated in part based on having a relatively high reflectance value, such as associated with a reflective coating applied to traffic and/or navigational signage. In some embodiments, identifying a relatively high reflectance feature can provide a prompt to undertake a further scan of the high reflectance feature with one or more sensors, such as those in the sensing system **104**. Thus, in one example, a reflected signal indicating a high reflectance feature can provide a prompt to image the high reflectance feature with a camera to allow for identifying the high reflectance feature. In some embodiments where the high reflectance feature is a traffic sign, the camera image can allow for reading the sign via character recognition and/or pattern matching, etc. and then optionally adjusting navigational instructions based on the sign (e.g., a sign indicating a construction zone, pedestrian crosswalk, school zone, etc. can prompt the autonomous vehicle to reduce speed).

At time Tc, following the time Tb by the interval t**1**, a third pulse **410***c* is emitted from the LIDAR device **302**. The third pulse **410***c* is directed along a laser beam path **306***c*, which is approximately angularly separated from the beam path **306***b* by the angle θ_1. The pulse **410***c* is reflected from a point near the middle of the rear bumper region of the car **310**, and a resulting reflected signal **420***c* is detected at the LIDAR device **302** (or its associated optical sensors). The controller **430** combines the relative time delay ΔTc between the emission of pulse **410***c* and reception of reflected signal **420***c* and the orientation of the LIDAR device **302** at time Tc, i.e., the direction of beam path **306***c*, to map the 3-D position of the reflective point.

At time Td, following time Tc by the interval t_1, a fourth pulse **410***d* is emitted from the LIDAR device **302**. The fourth pulse **410***d* is directed along a laser beam path **306***d*, which is approximately angularly separated from the beam path **306***c* by the angle θ_1. The beam path **306***d* entirely avoids the car **310**, and all other reflective environmental features within a maximum distance sensitivity of the LIDAR device **302**. As discussed above, the maximum distance sensitivity of the LIDAR device **302** is determined by the sensitivity of the associated optical sensors for detecting reflected signals. The maximum relative time delay ΔTmax corresponds to the maximum distance sensitivity of the LIDAR device (i.e., the time for light signals to make a round trip of the maximum distance). Thus, when the optical sensor associated with the LIDAR device **302** does not receive a reflected signal in the period ΔTmax following time Td, the controller **430** determines that no reflective features are present in the surrounding environment along the laser beam path **306***d*.

The reflective points on the car **310** corresponding to the reflected signals **420***a-c* form a subset of points included in a 3-D point cloud map **440** of the environment surrounding the LIDAR device **302**. In addition, the direction of the laser beam **310***d* is noted in the 3-D point cloud map **440** as being absent of reflective features along the line of sight within the maximum distance sensitivity of the LIDAR device **302**, because no reflected signal was received after the duration ΔTmax following the emission of pulse **410***d* at time Td. The points corresponding to laser beam directions **306***a-d* are combined with points spaced throughout the scanning zone (e.g., the region scanned by the LIDAR device **302**), to create a complete 3-D point cloud map, and the results are output as

fixed resolution point cloud data **440** for further analysis by object detection systems, pattern recognition systems, computer vision systems, etc.

IV. Example Laser Diode Firing Circuit

In order to illuminate a scanning zone with pulses of light, a LIDAR device includes one or more light sources that are triggered to emit pulses of light. The light sources may include light emitting elements such as a laser diode or another emissive light source. A laser diode is a semiconductor device including a p-n junction with an active region in which oppositely polarized, energized charge carriers (e.g., free electrons and/or holes) recombine while current flows through the device across the p-n junction. The recombination results in emission of light due to a change in energy state of the charge carriers. When the active region is heavily populated by such energized pairs (e.g., the active region may have a population inversion of energized states), stimulated emission across the active region may produce a substantially coherent wave front of light that is then emitted from the laser diode. Recombination events, and the resulting light emission, occur in response to current flowing through the device, and so applying a pulse of current to the laser diode results in emission of a pulse of light from the laser diode.

A light pulse with the desired temporal profile can be generated by applying a rapidly switched current to a laser diode (e.g., a current source that rapidly transitions from near zero current to a current sufficient to cause the laser diode to emit light). Circuits configured to convey such currents to laser diodes to cause the laser diodes to fire (e.g., emit a pulse of light) are referred to herein as laser diode firing circuits. One example laser diode firing circuit includes a laser diode connected in series with a transistor capable of switching large currents over brief transition times. Current through the laser diode, and thus emission from the laser diode, can then be controlled by operating the transistor. An example circuit may switch from near zero current through the laser diode, to about 30 amperes, and back to near zero all in a span of about 1-2 nanoseconds.

The firing circuits disclosed herein may include a laser diode configured to emit a pulse of light with a wavelength in the visible spectrum, ultraviolet spectrum, near infrared spectrum, and/or infrared spectrum. In one example, the laser diode is configured to emit a pulse of light in the infrared spectrum with a wavelength of about 905 nanometers.

FIG. **5**A is an example laser diode firing circuit **500**. The firing circuit **500** includes a capacitor **516** connected to a laser diode **518** and a transistor **520**. In some examples, the capacitor **516**, laser diode **518**, and transistor **520** can be connected in series. The capacitor **516** is connected to both a charging path (e.g., FIG. **5**C) and a discharge path (e.g., FIG. **5**D). The capacitor **516** has one terminal coupled to a voltage source **502** (e.g., through inductor **510** and diode **514**) and an anode of the laser diode **518**. The other terminal of the capacitor **516** can be connected to ground, or to another reference voltage sufficient to allow the capacitor **516** to be charged by the voltage source **502**, through the charging path. The cathode of the laser diode **518** is connected to one terminal of the transistor **520**, which has another terminal connected to ground (which may also connect to the capacitor **516**). The transistor **520** acts as a switch to selectively allow current to flow through the laser diode **518** according to a control signal from a gate driver **530**.

A discharge diode **522** is coupled across the laser diode **518**. The discharge diode **522** is configured to allow an internal capacitance of the laser diode **518** to discharge when the transistor **520** is turned off. For example, the discharge diode **522** may have an anode and a cathode; the anode can be connected to the cathode of the laser diode **518**; the cathode can be connected to the anode of the laser diode **518**. As such, charge remaining on an internal capacitance of the laser diode **518** following a firing operation causes the discharge diode **522** to be forward biased, and the internal capacitance is allowed to discharge through the discharge diode **522**. Following such discharge, the discharge diode **522** is no longer forward biased.

To initiate firing, the gate driver **530** causes the transistor **520** to turn on by adjusting the voltage applied to the gate terminal **520***g*, which allows current to flow to the drain terminal **520***d* through the laser diode **518**. The capacitor **516** discharges through a discharge path that includes the laser diode **518** and the transistor **520**. The discharge current from the capacitor **516** causes the laser diode **518** to emit a pulse of light. The transistor **520** is turned back off by adjusting the voltage applied to the gate terminal **520***g* via the gate driver **530**. Upon turning off the transistor **520**, the laser diode **518** ceases emission.

The inductor **510** is connected between the voltage source **502** and the anode of the diode **514**. For convenience in the description and the drawings a point connecting the inductor **510** and the anode of the diode **514** is labeled node A **512**. The cathode of the diode **514** is connected to the capacitor **516** and also to the anode of the laser diode **518**. The capacitor's **516** charging path, which couples the capacitor **516** and the voltage source **502**, includes the inductor **510** and the diode **514**. During charging, the voltage across the inductor **510** varies in accordance with changes in the inductor current, and the diode **514** regulates the voltage applied to the capacitor **516** depending on whether the diode **514** is forward biased or reverse biased. The diode **514** is forward biased (and thus allows the capacitor **516** to charge) when the voltage at node A **512** is greater than the voltage on the capacitor **516**. The diode **514** is reverse based (and thus prevents the capacitor **516** from charging) when the voltage at node A **512** is less than the voltage on the capacitor **516**. Voltage variations at node A **512** due to changes in current through the inductor **510** may result in a voltage being applied to the capacitor **516** that exceeds the voltage of the voltage source **502**.

For example, the voltage source **502** connected to one side of the inductor **510** may have a voltage V_1. The voltage on the other side of the inductor **510**, at node A **512**, varies due to induced voltage across the inductor **510** as the inductor current changes. In particular, during a charging operation to recharge the capacitor **516**, the current through the inductor **510** briefly increases and then decreases. As the inductor current increases, the voltage at node A **512** may decrease to a voltage less than V_1. As the inductor current changes from increasing to decreasing, the voltage at node A **512** may increase to a higher level voltage (e.g., a voltage greater than V_1), before decreasing. The transient higher level voltage at node A **512** (e.g., $>V_1$) is applied to the capacitor **516**, which charges as the voltage at node A **512** decreases due to the inductor current continuing to decrease. The capacitor **516** charges until the voltage on the capacitor **516** approximately equal the voltage at node A **512**. Upon the voltage at node A **512** approximately equaling the voltage on the capacitor **516**, the diode **512** is reverse biased. Upon the diode **514** being reverse biased, the current through the inductor **510** goes to zero and the voltage across the inductor **510** settles at zero, which sets node A to the voltage of the voltage source **502** (e.g., the voltage V_1), but the capacitor **516** may hold a higher voltage (e.g., about 2 V_1).

The transistor **520** may be a field effect transistor (FET) with a channel region including Gallium nitride (i.e., the transistor **520** may be a GaNFET). However, alternative FETs may be employed, such as FETs configured to rapidly switch large current values, such as transistors with carrier mobility (e.g., high electron mobility transistors (HEMTs)). In FIG. **5**A, the transistor **520** is illustrated as a field effect transistor (FET); although it is understood the firing circuit **500** may be implemented with alternative transistors to selectively switch current through the laser diode, such as a bipolar junction transistor, etc. Further, while the transistor **520** is illustrated as an n-type transistor, a complementary circuit may be formed using a p-type transistor.

FIG. **5**B is a timing diagram of a pulse emission operation of the example laser diode firing circuit **500** of FIG. **5**A. Shown in FIG. **5**B is the gate voltage V_{Gate} of the FET **520**, the drain current I_{Drain} of the FET **520**, the luminosity L_{Diode} of the laser diode **518**, the voltage V_{Cap} of the capacitor **516**, the voltage V_A at node A **512**, the current I_{Ind} through the inductor **510**, and the light signal received Rx from a reflected portion of the emitted pulse. For convenience in the description, the time at which an initiating signal is applied to the transistor **520** and a pulse is emitted is referred to herein and in the drawings as the turn on time T_{ON}.

Initially, the capacitor **516** is charged to a voltage set in part by the voltage source **502**. The charge on the capacitor **516** may exceed the voltage V_1 of the voltage source **502** due to transient variations at node A **512** caused by changes in current through the inductor **510**. A voltage that exceeds V_1 may be held on the capacitor **516** after the diode **514** is reverse biased to terminate a charging operation. For example, the capacitor **516** may be initially charged to a voltage level of about 2 V_1. At the turn on time T_{ON}, an initiating signal is applied to the transistor **520** from the gate driver **530**. The initiating signal can be a gate voltage V_{Gate} that transitions from a low level to a high level so as turn on the transistor **520**. The transistor **520** turns on and the drain current I_{Drain} transitions from a current near zero to a current sufficient to drive the laser diode **518**. The laser diode **518** emits a pulse of light, as indicated by the luminosity L_{Diode}. As the drain current I_{Drain} flows through the laser diode **518**, the capacitor **516** discharges to source current to the laser diode **518**. In some examples, during pulse emission, the capacitor **516** and the parasitic capacitance of the laser diode **518** can combine to form a resonant LC tank circuit, which is heavily damped. Discharging the capacitor **516** thus transfers the electrical energy charged on the capacitor **516** to the laser diode **518**, where energy is consumed by current flowing in the laser diode to produce light. Upon completion of a single half-cycle of the damped LC oscillation, there may be almost no energy left to continue to drive current through the laser diode **518**, and remaining voltage, if any, can return to the capacitor **516** via the diode **522** connected in parallel across the laser diode **518**.

In practice then, the energy stored on the capacitor **516** may be consumed, and the laser diode **518** may turn off (at time T_{OFF}), following a single half-cycle of the resonant LC circuit formed by the capacitor **516** and the parasitic inductance of the inductor **518**. The pulse duration Δt_{ON} may be about 20 nanoseconds in some examples. In some cases (and as shown in FIG. **5**B), the laser diode **518** may cease emitting light prior to turning off the transistor **520** (e.g., by adjusting the gate voltage V_{Gate}). Although, in some examples, and depending on the values of the capacitor **516** and the parasitic inductance of the laser diode **518**, the pulse duration Δt_{ON} may continue until the transistor **520** turns off. Thus, in some examples, the transistor **520** can be turned off by adjusting the gate voltage V_{Gate} to a level sufficient to turn off the transistor **520**, which terminates current flowing through the laser diode **518**.

The charging cycle is initiated in response to the transistor **520** firing, which discharges the capacitor **516**. Upon the capacitor voltage V_{Cap} discharging to a voltage level sufficient to forward bias the diode **514**, at time T_1, current begins flowing through the inductor **510** (as indicated by I_{Ind} in FIG. **5**B). In FIG. **5**B, time T_1 is shown during the interval Δt_{ON} (i.e., before T_{OFF}), although in some implementations the diode **514** may not begin conducting current until the transistor **520** has turned off (i.e., after T_{OFF}). The increase in inductor current I_{Ind} causes the voltage at node A **512** to decrease in proportion to the time derivative of the inductor current I_{Ind}, because changes in the inductor current I_{Ind} induce a voltage in the inductor **510** that opposes the direction of any current change. The voltage at node A **512**, and thus the increasing inductor current I_{Ind}, are prevented from changing so rapidly as to reverse bias the diode **514**.

For example, starting at time T_1, the voltage at node A **512** may decrease to a voltage level less than V_1 (as indicated by V_A in FIG. **5**B). At time T_{OFF}, current ceases flowing through the laser diode **518**, and the diode **514** connects the inductor **510** and the capacitor **516**, which form a resonant LC tank circuit. The current from the inductor **510** charges the capacitor **516**, in a sinusoidal oscillatory fashion. At one quarter of the oscillation period, the inductor current I_{Ind} reaches a maximum, and begins to decrease. At that point, the resonant LC circuit divides its stored energy with about half in the capacitor **516** and about half in the inductor **510**. Continuing with the sinusoidal oscillation, current continues to flow to the capacitor **516**, until the mid-point of the oscillation cycle, at time T_2, at which point the current reaches zero and the capacitor **516** stores substantially all of the energy that had been divided between the inductor **510** and the capacitor **516**. Before the energy stored on the capacitor **516** can transfer back to the inductor **510**, the diode **514** becomes reverse biased, which causes the capacitor **516** to remain charged with approximately twice the supply voltage V_1. For example, the supply voltage V_1 may be about 20 volts and the voltage stored on the capacitor **516** following charging may be about 40 volts.

The oscillatory LC circuit described herein efficiently transfers energy between the inductor **510** and the capacitor **516** during the recharge interval Δt_{CHARGE} of the circuit **500**, but the present disclosure is not limited to the use of resonant LC circuits. Generally, the capacitor **516** may be charged to a greater value than the supply voltage V1 based on transient voltages on the inductor **510** caused by changes in current following firing of the circuit **500**. Current through the inductor **510** may change from increasing (e.g., between times T_1 and T_{OFF}) to decreasing (e.g., following time T_{OFF}), and the sudden change in current through the inductor **510** can induce a rapid increase in voltage at node A **512**. For example, at time T_{OFF}, the voltage at node A **512** can go to a voltage greater than V_1, and may be several times V_1. The precise voltage applied to node A **512** depends on the time derivative of the inductor current when transitioning from an increasing current to a decreasing current, but may be several times the voltage of the voltage source **502** (e.g., just after T_{OFF}, $V_A \approx X$ V_1, with X>2).

Following the increase in the voltage at node A **512**, the current through the inductor **510** can continue to decrease as the capacitor **516** becomes charged, and the voltage at node A **512** can therefore decrease. The capacitor **516** may continue charging until the diode **514** becomes reverse biased, at time T_2 in FIG. **5**B. While charging, between times T_{OFF} and T_2, the voltage V_{Cap} across the capacitor **516** increases and the

voltage V_A of node A **512** decreases. The time T_2, at which the charging cycle stops, occurs when the two voltages approximately equal one another (e.g., $V_A \approx V_{Cap}$). In some examples, the voltage at which the two voltages are approximately equal so as to terminate the charging cycle occurs for a voltage of about $2\,V_1$ (e.g., $2\,V_1 \approx V_A \approx V_{Cap}$). The voltage on the capacitor **516** (i.e., V_{Cap}) following the charging cycle may be, for example, about 40 Volts. Upon the diode **514** becoming reverse biased, at time T_2, the charging current stops flowing through the diode **514**, and therefore the current I_{Ind} through the inductor **518** changes quickly to zero. The change in inductor current at time T_2 is therefore accompanied a change in the voltage V_A of node A, to return to the voltage of the voltage source **502** (i.e., the voltage V_1).

The voltage variations across the inductor **510** can be described in terms of energy temporarily stored in a magnetic field of the inductor **510** and then released. Energy stored in an inductor's magnetic field is proportionate to the square of the current flowing through the inductor. When the inductor current I_{Ind} is increased, the inductor **510** increases the energy stored in its magnetic field (e.g., according to the difference in current I_{Ind}). Increasing the inductor current I_{Ind} thus charges the energy stored in the magnetic field of the inductor **510** from a low energy level (e.g., zero) to a high energy level. When the inductor **510** is being charged by an increasing current from the voltage source **502**, the induced voltage across the inductor **510** opposes the change in current and so node A **512** goes to a voltage less than V_1. By contrast, when the inductor current I_{Ind} is decreased, the energy stored in the magnetic field of the inductor **510** is decreased. Decreasing the inductor current I_{Ind} thus discharges the energy stored in the magnetic field of the inductor **510** from high energy level to a low energy level. When the inductor **510** is being discharged by a decreasing current from the voltage source **502**, the induced voltage across the inductor **510** opposes the change in current and so node A **512** goes to a voltage higher than V_1. However, the diode **514** only remains forward biased while the voltage at node A **512** exceeds the voltage across the capacitor **516**.

The diode **514** and inductor **510** can thus combine to cause the capacitor **516** to be charged to a voltage that exceeds the voltage V_1 of the voltage source **502**. For example, the diode **514** is forward biased when the voltage across the capacitor **516** is at a lower level, such as between time times T_{OFF} and T_2 as shown in FIG. **5**B when the capacitor voltage V_{Cap} charges from less than V_1 to about $2\,V_1$. However, the diode **514** is reverse biased when the voltage across the capacitor **516** is at a higher level, such as following time T_2 as shown in FIG. **5**B when the capacitor voltage V_{Cap} remains at about $2\,V_1$ while the voltage V_A at node A **512** decreases to V_1. For example, V_1 may be about 20 Volts and the capacitor voltage V_{Cap} following charging may be about 40 Volts.

In some examples, the firing circuit **500** is operated such that the capacitor **516** is recharged immediately following emission of a pulse of light from the laser diode **518**. As shown in FIG. **5**B, a capacitor recharging interval Δt_{CHARGE} begins at the transistor turn off time T_{OFF} and ends with the reverse biasing of the diode **514**, at time T_2. The capacitor recharging interval Δt_{CHARGE} may be approximately 500 nanoseconds, for example. Moreover, by configuring the firing circuit **500** such that the capacitor **516** is recharged immediately following a pulse emission, the firing circuit **500** can be recharged and ready to emit a subsequent pulse faster than an alternative configuration. If, for example, a recharging operation were to be initiated after some duration following a pulse emission (e.g., using a second transistor other than a transistor controlling current through a laser diode), the additional time would increase the lag time between emission of subsequent pulses and thus reduce the duty cycle of the firing circuit. In some examples, the firing circuit **500** is configured to immediately recharge the capacitor **516** upon emission of a pulse because the recharging operation is initiated in response to operation of the same transistor **520** that initiates emission (e.g., turning on the transistor **520** both causes a pulse to be emitted and, upon sufficient discharge from the capacitor **516**, causes the diode **514** to become forward biased and current to begin flowing through the inductor **510** so as to initiate charging).

The light pulse emitted at time T_{ON} can be reflected from an environmental object, such as an obstacle surrounding an autonomous vehicle, and a light signal from the reflected portion of the emitted pulse is received via a photo detector at reception time T_{Rx}. The time ΔT between the emission time (at time T_{ON}) and the reception time T can then be used to calculate the distance to the reflective object. For example, the round trip travel time ΔT can be multiplied by the speed of light in the surrounding atmosphere to get the round trip distance, which is twice the distance to the reflective object.

In some examples, the emission time of the emitted pulse may be determined using a feedback loop configured to react to the discharge current flowing through the laser diode **518**. For example, a conductive loop may be situated such that a voltage is induced in the loop due to changing magnetic flux through the loop in response to the discharge current flowing through the firing circuit **500**. The voltage across the leads of such a conductive feedback loop can then be detected, and the time at which a pulse is emitted from the firing circuit can be estimated based on the time the voltage is detected. Such a system can be used to reduce timing uncertainty in the firing time due to delays between application of the turn on signal (e.g., the gate voltage V_{Gate}) and the firing of the laser diode **518**, which may involve some non-zero random and/or systematic timing delay and/or timing jitter.

FIG. **5**C shows a current path through the example laser diode firing circuit **500** of FIG. **5**A during a charging mode. During charging, the voltage across the capacitor **516** is less than the voltage at the node between the inductor **510** and diode **514** such that the diode **514** is forward biased. In addition, the transistor **520** is turned off (as indicated by the OFF block coupled to the gate terminal **520***g* in FIG. **5**C). As such, current does not flow through the laser diode **518**, and instead flows to accumulate charge across the capacitor **516**. The dashed arrow in FIG. **5**C illustrates such a charging current path, which flows from the voltage source **502** (which may have a voltage V_1), through the biasing diode **514**, toward the capacitor **516**. In some examples, following a discharge, the capacitor **516** can be recharged in preparation for a subsequent discharge (and associated pulse emission) event in about 500 nanoseconds.

FIG. **5**D shows a current path through the example laser diode firing circuit **500** of FIG. **5**A during an emission mode. During emission, the transistor **520** is turned on (as indicated by the ON block coupled to the gate terminal **520***g* in FIG. **5**D). As such, the capacitor **516** is connected across the laser diode **518** (via the turned on transistor **520**), and so the charge on the capacitor **516** rapidly discharges through the laser diode **518** and the transistor **520**. The dashed arrow in FIG. **5**D illustrates such a discharge current path, which flows from the capacitor **516**, through the laser diode **518** and the transistor **520** toward ground. Upon the transistor **520** being turned on, the discharge current flows rapidly to discharge the capacitor **516** and the resulting change in current (e.g., increase in current) causes the laser diode **518** to emit a pulse of light.

The current paths shown in FIGS. **5**C and **5**D illustrate two operation modes of the firing circuit **500**: a charging mode (FIG. **5**C) and an emission mode (FIG. **5**D). In some examples, the firing circuit **500** switches between the charging mode and the emission mode based solely on whether the transistor **520** is turned on or turned off. In the charging mode, the transistor **520** is turned off and current flows from the voltage source **502** to the capacitor **516** via the charging path (e.g., the current path including the inductor **510** and diode **514**) until the diode **514** is reverse biased. In the emission mode, the transistor **520** is turned on and current flows from the charged capacitor **516** through the laser diode **518** and the transistor **520** until the transistor **520** is turned off again.

FIG. **5**E illustrates an arrangement **540** in which multiple laser diode firing circuits **550***a-n* are connected to be charged via a single inductor **544**. The inductor **544** has one terminal connected to a voltage source **542** (labeled V_1), and a second terminal that connects to the firing circuits **550***a-n* so as to be included in a charging path of the respective firing circuits **550***a-n*. Each of the firing circuits **550***a-n* can be similar to the firing circuit **500** described above in connection with FIGS. **5**A-**5**D. For example, the first firing circuit **550***a* includes a capacitor **558***a* connected to a laser diode **554***a* and a transistor **556***a*. The capacitor **558***a*, laser diode **554***a*, and transistor **556***a* can be connected in series such that turning on the transistor **556***a* causes the capacitor **558***a* to discharge through the laser diode **554***a*, which causes the laser diode to emit a pulse of light. A discharge diode **560***a* can be connected across the laser diode **554***a* to discharge the internal capacitance of the laser diode **554***a*. The first firing circuit **550***a* also includes a diode **552***a* that connects the firing circuit **550***a* to the inductor **544** and the voltage source **542**. The diode **552***a* can function similarly to the diode **514** described above in connection with FIGS. **5**A-**5**D. For example, the diode **552***a* can become forward biased and draw current through the inductor **544** to charge the capacitor **558***a* following a firing event (and associated discharge of the capacitor **558***a*). Upon the capacitor **558***a* being recharged, the diode **552***a* can then become reverse biased and thereby cause the capacitor **558***a* to maintain its stored charge.

The second firing circuit **550***b* is similarly connected to the inductor **544** via a diode **552***b* and includes a capacitor **558***b*, laser diode **554***b*, transistor **556***b*, discharge diode **560***b*. One or more additional firing circuits can also be similarly connected in parallel with the inductor **544** to the "nth" firing circuit **550***n*. In some cases, the arrangement **540** includes 16 individual laser diode firing circuits **550***a-n* connected to the single inductor **544**.

Similar to the operation of the firing circuit described above in connection with FIGS. **5**A-**5**D, the firing circuits **550***a-n* are turned on and off by operation of their respective transistors **556***a-n*, which are controlled by the respective gate voltages applied by the gate driver **548**. For example, the gate driver **548** can be used to turn on all of the firing circuits **550***a-n* at substantially the same time by setting the gate voltage high (or otherwise manipulating the gate voltage to turn the respective transistors on). The discharging capacitors **558***a-n* cause current to begin flowing through the inductor **544**. Upon the transistors **556***a-n* in the firing circuits **550***a-n* being turned back off (by the gate driver **548**), the voltage across the inductor rises to begin recharging the capacitors **558***a-n* in the firing circuits **550***a-n* until the respective diodes **552***a-n* are reverse biased, at which point recharging terminates.

Additionally, the firing circuit arrangement **540** shown in FIG. **5**E also illustrates a snubber circuit **546** connected across the inductor **544**. The snubber circuit **546** provides an alternative current path during rapid current switching through the inductor **544** to regulate and/or smooth the resulting variations across the inductor **544**. The snubber circuit **546** may include a resistor and/or capacitor connected in parallel across the inductor **544**, for example. The snubber circuit **546** may additionally or alternatively include one or more diodes and/or solid state components configured to limit and/or regulate the maximum voltage and/or maximum voltage rate across the inductor **544**. Thus, the snubber circuit **546** may operate actively and/or passively to modify transient voltage variations across the inductor **544**. In some cases, the snubber circuit **544** may be used to prevent transient voltage variations from exceeding a predetermined threshold and thereby prevent damage to circuit components. While illustrated in FIG. **5**E, the snubber circuit **544** may (or may not) be included in particular implementations of the arrangement **540** shown in FIG. **5**E. Moreover, a snubber circuit may (or may not) be included across the charging path inductor in a particular implementation of the single firing circuit arrangement described above in connection with FIG. **5**A-**5**D.

V. Example Operations

FIGS. **6**A through **6**C present flowcharts describing processes employed separately or in combination in some embodiments of the present disclosure. The methods and processes described herein are generally described by way of example as being carried out by an autonomous vehicle, such as the autonomous vehicles **100**, **200** described above in connection with FIGS. **1** and **2**. For example, the processes described herein can be carried out by the LIDAR sensor **128** mounted to an autonomous vehicle in communication with the computer system **112**, sensor fusion algorithm module **138**, and/or computer vision system **140**.

Furthermore, it is noted that the functionality described in connection with the flowcharts described herein can be implemented as special-function and/or configured general-function hardware modules, portions of program code executed by a processor (e.g., the processor **113** in the computer system **112**) for achieving specific logical functions, determinations, and/or steps described in connection with the flowcharts. Where used, program code can be stored on any type of computer readable medium (e.g., computer readable storage medium or non-transitory media, such as data storage **114** described above with respect to computer system **112**), for example, such as a storage device including a disk or hard drive. In addition, each block of the flowcharts can represent circuitry that is wired to perform the specific logical functions in the process. Unless specifically indicated, functions in the flowcharts can be executed out of order from that shown or discussed, including substantially concurrent execution of separately described functions, or even in reverse order in some examples, depending on the functionality involved, so long as the overall functionality of the described method is maintained. Furthermore, similar combinations of hardware and/or software elements can be employed to implement the methods described in connection with other flowcharts provided in the present disclosure.

FIG. **6**A is a flowchart of an example process **600** for operating a laser diode firing circuit. The laser diode firing circuit may be the laser diode firing circuit **500** described above in connection with FIG. **5**. The laser diode firing circuit may therefore include a capacitor connected to a charging path and a discharge path. The discharge path can include a laser diode and a transistor, and the charging path can include an inductor and a diode. At block **602**, the transistor is turned off, which causes the capacitor to charge via the charging

path. The current through the charging path can flow through the inductor and the diode. As charge builds on the capacitor, the current through charging path (and the inductor) decreases. The decrease in current through the inductor causes the inductor to discharge energy stored in its magnetic field. For example, the energy stored in the magnetic field of the inductor may transition from a higher energy level to a lower energy level in response to the transistor being turned off. At block **604**, the transistor can be turned on, which causes the capacitor to discharge via the discharge path. The current through the discharge path can flow through the laser diode and the transistor, which causes the laser diode to emit a pulse of light. The voltage stored on the capacitor can discharge until the diode is forward biased, which causes the current through the charging path (and the inductor) to increase. The increase in current through the inductor causes the inductor to charge energy stored in its magnetic field. For example, the energy stored in the magnetic field of the inductor may transition from a lower energy level to a higher energy level in response to the transistor being turned on.

In some embodiments, the operation of the transistor in blocks **602** and **604** provides for operation of a laser diode firing circuit to emit pulses of light and recharge by manipulating only a single transistor. In particular, turning the transistor on (block **604**) can cause the circuit to both emit a pulse of light (by discharging the capacitor through the laser diode) and initiate a recharge cycle (by the voltage on the capacitor discharging to a level sufficient to forward bias the diode in the charging path). The recharge cycle is then terminated in response to turning off the transistor (block **602**), which directs the current conveyed via the charging path to the capacitor (rather than through the laser diode).

FIG. **6**B is a flowchart of an example process **620** for operating a light detection and ranging (LIDAR) device. The LIDAR device includes a light source having a laser diode firing circuit similar to the firing circuit **500** described above in connection with FIG. **5**. For example, the laser diode firing circuit may include a laser diode activated by current through a discharge path of a capacitor. A transistor in the discharge path is configured to control such discharge events by turning on and turning off. The capacitor is also connected to a charging path that includes an inductor and a diode. The transistor may be, for example, a Gallium nitride field effect transistor (GaNFET). At block **622**, the GaNFET is turned off to thereby cause the capacitor to charge (via the charging path) and the inductor (in the charging path) to decrease its stored energy. The inductor can release stored energy as current through the inductor decreases. At block **624**, the GaNFET is turned on to thereby cause the capacitor to discharge (via the discharge path), which causes the laser diode to emit a pulse of light. The inductor charges to an increased stored energy level due to increasing current through the inductor, which occurs once the diode is forward biased. At block **626**, the transmission time of the emitted pulse (e.g., the pulse emission time) is determined. The pulse emission time may be determined based on the time at which the transistor is turned on to initiate the discharge current and/or based on the time an induced voltage is detected in a conductive feedback loop configured to react to changes in the discharge current path. At block **628**, a reflected light pulse is received. The reflected light pulse can include at least a portion of the light pulse emitted in block **624** that is reflected from a reflective object in an environment surrounding the LIDAR device. At block **630**, a reception time of the reflected light pulse is determined. At block **632**, a distance to the reflective object is determined based on both the time of reception determined in block **630** of the reflected light signal and the transmission time determined in block **624**. For example, the distance can be determined based on computing the round trip travel time to the reflective object from the difference of the reception time and emission time, multiplying by the speed of light in the surrounding environment and dividing by 2. At block **634**, the autonomous vehicle is navigated based at least in part on the determined distance to the reflective object. In some examples, one or more of the control systems **106** of the autonomous vehicle **100** described in connection with FIG. **1** may control the autonomous vehicle to avoid obstacles (e.g., the reflective object), navigate toward a predetermined destination, etc.

FIG. **6**C is a flowchart of another example process **640** for operating a laser diode firing circuit. The laser diode firing circuit may be similar to the firing circuit **500** described above in connection with FIG. **5**. For example, the laser diode firing circuit may include a laser diode activated by current through a discharge path of a capacitor. A transistor in the discharge path is configured to control such discharge events by turning on and turning off. The capacitor is also connected to a charging path that includes an inductor and a diode. The transistor may be, for example, a Gallium nitride field effect transistor (GaNFET). At block **642**, the GaNFET is turned on. At block **644**, the capacitor discharges through the discharge path. At block **646**, a pulse of light is emitted from the laser diode due to the discharge current. At block **648**, energy stored in the inductor included in the charging path is increased. For example, upon the diode in the charging path becoming forward biased, the current through the inductor can be increased, which causes energy to be stored in the magnetic field of the inductor. At block **650**, the GaNFET is turned off. At block **652**, energy stored in the inductor is released as the inductor current decreases. At block **654**, the capacitor is charged from energy released by the inductor. For example, following turning off the GaNFET, current through the inductor is conveyed to the capacitor via the charging path. The inductor current can transition from increasing (while the transistor is on) to decreasing (once the transistor is off and current no longer flows through the laser diode). The decrease in inductor current causes the inductor to release its stored energy, and that released energy can be transferred, at least in part, to the capacitor. At block **656**, the charging path diode can become reverse biased, which causes the capacitor to hold charge due to the released energy from the inductor. For example, while the inductor releases its stored energy, the voltage conveyed to the capacitor via the diode can transiently exceed the voltage of the voltage source connected to the inductor. The capacitor charges until the capacitor voltage approximately equals the voltage applied to the diode, at which point the diode is reverse biased. The capacitor holds a voltage due in part to the transient voltage while the voltage applied to the diode settles to the voltage of the voltage source (e.g., upon the inductor current reaching zero).

As indicated by the dashed arrow in FIG. **6**C, the process **640** can be repeated to cause the firing circuit to repeatedly emit pulses of light, and be recharged immediately following each firing event. Moreover, the firing circuit may be operated such that the voltage charged on the capacitor following a given firing event is not sufficient to forward bias the diode in the charging path. In such an example, the firing circuit is not recharged and the firing circuit is re-activated by discharging the charge remaining on the capacitor to generate current through the laser diode and transistor. If the voltage on the capacitor discharges to a level sufficient to forward bias the diode in the charging current path following such a second

firing (or third firing, etc.), the firing circuit can then undergo the charging mode with the capacitor recharging via the charging path.

FIG. **7** depicts a computer-readable medium configured according to an example embodiment. In example embodiments, the example system can include one or more processors, one or more forms of memory, one or more input devices/interfaces, one or more output devices/interfaces, and machine-readable instructions that when executed by the one or more processors cause the system to carry out the various functions, tasks, capabilities, etc., described above, such as the processes discussed in connection with FIGS. **6**A through **6**C above.

As noted above, in some embodiments, the disclosed techniques can be implemented by computer program instructions encoded on a non-transitory computer-readable storage media in a machine-readable format, or on other non-transitory media or articles of manufacture (e.g., the instructions **115** stored on the data storage **114** of the computer system **112** of vehicle **100**). FIG. **7** is a schematic illustrating a conceptual partial view of an example computer program product **700** that includes a computer program for executing a computer process on a computing device, arranged according to at least some embodiments presented herein.

In one embodiment, the example computer program product **700** is provided using a signal bearing medium **702**. The signal bearing medium **702** may include one or more programming instructions **704** that, when executed by one or more processors may provide functionality or portions of the functionality described above with respect to FIGS. **1**-**6**. In some examples, the signal bearing medium **702** can be a non-transitory computer-readable medium **706**, such as, but not limited to, a hard disk drive, a Compact Disc (CD), a Digital Video Disk (DVD), a digital tape, memory, etc. In some implementations, the signal bearing medium **702** can be a computer recordable medium **708**, such as, but not limited to, memory, read/write (R/W) CDs, R/W DVDs, etc. In some implementations, the signal bearing medium **702** can be a communications medium **710**, such as, but not limited to, a digital and/or an analog communication medium (e.g., a fiber optic cable, a waveguide, a wired communications link, a wireless communication link, etc.). Thus, for example, the signal bearing medium **702** can be conveyed by a wireless form of the communications medium **710**.

The one or more programming instructions **704** can be, for example, computer executable and/or logic implemented instructions. In some examples, a computing device such as the computer system **112** of FIG. **1** is configured to provide various operations, functions, or actions in response to the programming instructions **704** conveyed to the computer system **112** by one or more of the computer readable medium **706**, the computer recordable medium **708**, and/or the communications medium **710**.

The non-transitory computer readable medium could also be distributed among multiple data storage elements, which could be remotely located from each other. The computing device that executes some or all of the stored instructions could be a vehicle, such as the vehicle **200** illustrated in FIG. **2**. Alternatively, the computing device that executes some or all of the stored instructions could be another computing device, such as a server.

While various example aspects and example embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various example aspects and example embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

1. An apparatus, comprising:

a voltage source;

an inductor coupled to the voltage source, wherein the inductor is configured to store energy in a magnetic field;

a diode coupled to the voltage source via the inductor;

a transistor configured to be turned on and turned off by a control signal;

a light emitting element coupled to the transistor;

a capacitor coupled to a charging path and a discharge path, wherein the charging path includes the inductor and the diode, and wherein the discharge path includes the transistor and the light emitting element;

wherein, responsive to the transistor being turned off, the capacitor is configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level and the inductor is configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level; and

wherein, responsive to the transistor being turned on, the capacitor is configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level and the inductor is configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level.

2. The apparatus of claim **1**, wherein the lower current level is approximately zero.

3. The apparatus of claim **1**, wherein the capacitor is charged immediately following emission of a pulse of light from the light emitting element.

4. The apparatus of claim **1**, wherein the higher voltage level is greater than a voltage of the voltage source, and wherein the diode has an anode coupled to the voltage source via the inductor and a cathode coupled to the capacitor, such that the diode is forward biased when the voltage across the capacitor is at the lower voltage level and the diode is reverse biased when the voltage across the capacitor is at the higher voltage level.

5. The apparatus of claim **1**, wherein the transistor is a Gallium nitride field effect transistor (GaNFET).

6. The apparatus of claim **5**, wherein the control signal applies voltage to a gate of the GaNFET to selectively turn the GaNFET on and off.

7. The apparatus of claim **1**, wherein the light emitting element is a laser diode.

8. The apparatus of claim **7**, further comprising a drain diode coupled across the laser diode, wherein the drain diode is configured to discharge an internal capacitance of the laser diode through the drain diode when the transistor is off.

9. A method, comprising:

turning off a transistor, wherein the transistor is coupled to a light emitting element, wherein both the transistor and the light emitting element are included in a discharge path coupled to a capacitor, wherein the capacitor is also coupled to a charging path including a diode and an inductor, wherein the inductor is configured to store energy in a magnetic field, wherein the diode is coupled to a voltage source via the inductor, and wherein, responsive to the transistor being turned off, the capaci-

tor is configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level and the inductor is configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level; and

turning on the transistor, wherein responsive to the transistor being turned on, the capacitor is configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level and the inductor is configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level.

10. The method of claim **9**, wherein the lower current level is approximately zero.

11. The method of claim **9**, wherein the capacitor is charged immediately following emission of a pulse of light from the light emitting element.

12. The method of claim **9**, wherein the higher voltage level is greater than a voltage of the voltage source, and wherein the diode has an anode coupled to the voltage source via the inductor and a cathode coupled to the capacitor, such that the diode is forward biased when the voltage across the capacitor is at the lower voltage level and the diode is reverse biased when the voltage across the capacitor is at the higher voltage level.

13. The method of claim **9**, wherein the charging of the capacitor is carried out in about 500 nanoseconds.

14. The method of claim **9**, wherein the light emitting element is a laser diode.

15. The method of claim **14**, further comprising:

when the transistor is off, discharging an internal capacitance of the laser diode via a drain diode coupled across the laser diode.

16. The method of claim **9**, wherein the transistor comprises a Gallium nitride field effect transistor (GaNFET), wherein the GaNFET is turned on and turned off by applying a control signal to a gate of the GaNFET.

17. A light detection and ranging (LIDAR) device comprising:

a light source including:

a voltage source;

an inductor coupled to the voltage source, wherein the inductor is configured to store energy in a magnetic field;

a diode coupled to the voltage source via the inductor;

a transistor configured to be turned on and turned off by a control signal;

a light emitting element coupled to the transistor;

a capacitor coupled to a charging path and a discharge path, wherein the charging path includes the inductor and the diode, and wherein the discharge path includes the transistor and the light emitting element;

wherein, responsive to the transistor being turned off, the capacitor is configured to charge via the charging path such that a voltage across the capacitor increases from a lower voltage level to a higher voltage level and the inductor is configured to release energy stored in the magnetic field such that a current through the inductor decreases from a higher current level to a lower current level; and

wherein, responsive to the transistor being turned on, the capacitor is configured to discharge through the discharge path such that the light emitting element emits a pulse of light and the voltage across the capacitor decreases from the higher voltage level to the lower voltage level and the inductor is configured to store energy in the magnetic field such that the current through the inductor increases from the lower current level to the higher current level;

a light sensor configured to detect a reflected light signal comprising light from the emitted light pulse reflected by a reflective object; and

a controller configured to determine a distance to the reflective object based on the reflected light signal.

18. The LIDAR device of claim **17**, wherein the lower current level is approximately zero.

19. The LIDAR device of claim **17**, wherein the capacitor is charged immediately following emission of a pulse of light from the light emitting element.

20. The LIDAR device of claim **17**, wherein the transistor is a Gallium nitride field effect transistor (GaNFET).

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