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(54) **Title**: METHODS AND DEVICES FOR GENERATING BIPOLAR SIGNALS FROM UNIPOLAR SIGNALS

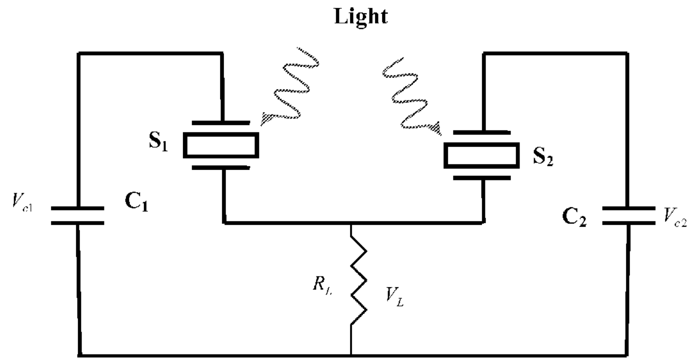


FIG. 6(A)

(57) **Abstract**: Methods, circuits and systems are provides to produce a bipolar signal across a load from two or more unipolar signals. In a circuit that includes a first and a second energy source, as well as a first and a second photonic switch, a first unipolar signal is generated from a first current flow across the load upon activation of the first switch. A second unipolar signal is generated from a second current flow across the load upon activation of the second switch. The bipolar signal with any desired spectral and amplitude characteristics is produced across the load by controlling the relative delay between the activation of the first and second photonic switches. Spectral content and shape of the bipolar signal can be adjusted by controlling the current flows from the one or more energy sources through, for example, modulation of the optical beams incident on the photonic switches.

WO 2012/162702 A2

METHODS AND DEVICES FOR GENERATING BIPOLAR SIGNALS FROM UNIPOLAR SIGNALS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional Application No. 61/490,523, filed on May 26, 2011, the entire contents of which are hereby incorporated by reference.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] The United States Government has rights in this invention pursuant to Contract No. DE-AC52-07NA27344 between the United States Department of Energy and Lawrence Livermore National Security, LLC for the operation of Lawrence Livermore National Laboratory.

TECHNICAL FIELD

[0003] The present application generally relates to methods and devices for generating bipolar waveforms.

BACKGROUND

[0004] Generating signals of various shapes, frequencies and amplitudes has numerous applications that include driving motors and antennas to modulating various optical, acoustical and electrical components to enable communication of coded data from one location to another location, to transfer energy from one location to another, and the like.

[0005] A unipolar waveform corresponds to a signal, such as a voltage or current signal, that is either entirely negative valued, or entirely positive valued. In some instances, a unipolar waveform may have a non-zero initial bias value and, therefore, the positive or negative amplitudes of such unipolar values are measured relative to the initial bias value. Bipolar waveforms, on the other hand, correspond to signals that are both positive and negative valued. It should be noted that in practical implementations of devices, some unipolar signals can include a small proportion of signals with an opposite polarity due to, for example, finite frequency responses of the components that generate and/or transmit these signals. Such substantially unipolar signals may or may not be construed as unipolar signals, depending on the application of the signals, the proportion of residual signals with opposite polarity, the frequency and/or amplitude of the residual signals, and the like.

[0006] Due to the presence of a direct current (DC) component in unipolar signals it is sometimes preferable to utilize bipolar waveforms to reduce signal transmission errors, to increase the dynamic range of signaling, and to control frequency characteristics of the transmitted signals. Further, having the ability to produce bipolar signals in various forms and shapes allows the generation of signals with particular spectral contents, as may be needed for particular applications. For example, bipolar signals are needed to enable driving typical antenna structures with a passband that does not include the DC component.

SUMMARY

[0007] The disclosed embodiments relate to methods, circuits and systems for generating bipolar signals from unipolar signals. One aspect of the disclosed embodiments relates to a circuit that includes a first energy source, a second energy source, and a first photonic switch coupled to the first energy source and configured to allow a first current flow from the first energy source through the first photonic switch upon activation of the first photonic switch at a first time instant. The circuit further includes a second photonic switch coupled to the second energy source and configured to allow a second current flow from the second energy source through the second photonic switch upon activation of the second photonic switch at a second time instant, and a load coupled to the first and second energy sources to allow generation of a bipolar signal across the load from a unipolar signal generated across the load due to the first current flow and a unipolar signal generated across the load due to the second current flow.

[0008] In one exemplary embodiment, each of the first and the second energy sources includes a capacitor. In another exemplary embodiment, each of the first and the second energy sources comprises an energy storage element. In still another exemplary embodiment, voltage level associated with the first energy source has a polarity opposite to voltage level associated with the second energy source, while in another embodiment, voltage levels associated with the first and the second energy sources have the same polarity. In another exemplary embodiment, the above noted circuit further comprises a delay element configured to delay the activation of the second photonic switch relative to the activation of the first photonic switch. The delay element can, for example, be tunable so as to provide a variable time delay. The circuit can additionally include a timing and synchronization circuit coupled to the delay element to control the delay in the activation of the second photonic switch relative to the activation of the first photonic switch.

[0009] In another exemplary embodiment, at least one of the first photonic switch and the second photonic switch is configured to allow the corresponding first current flow and the second current flow to be proportional to an intensity and/or modulation of a corresponding optical signal(s) incident thereupon. In one particular example embodiment, the bipolar signal has a selected shape and a selected spectral content. In another exemplary embodiment, the bipolar signal has a wideband spectral content ranging from direct current (DC) to at least 1 GHz .

[0010] According to one exemplary embodiment, the circuit further includes one or more additional energy sources, as well as one or more additional photonic switches coupled to the corresponding one or more additional energy sources and configured to allow one or more additional current flows through the corresponding additional photonic switch upon activation of the corresponding additional photonic switch. In yet another exemplary embodiment, the circuit further includes a radio frequency (RF) antenna coupled to receive and to be driven by the bipolar signal.

[0011] Another aspect of the disclosed embodiments relates to a method for generating a bipolar signal across a load that includes: at a first time instant, providing a first optical signal to a first photonic switch coupled to a first energy source to generate a first unipolar signal across the load due to a first current flow from the first energy source, and, at a second time instant, providing a second optical signal to a second photonic switch coupled to a second energy source to generate a second unipolar signal, having an opposite polarity with respect to the first unipolar signal, across the load due to a second current flow from the second energy source. The above method further includes controlling timing of the first and second time instants to generate a bipolar signal across the load from the first and second unipolar signals.

[0012] In one exemplary embodiment, the method further includes adjusting one or more power supplies to set voltage values associated with the first and second energy sources. In another exemplary embodiment, providing the second optical signal comprises using a delay element to delay the activation of the second photonic switch relative to the activation of the first photonic switch. In a particular embodiment, the delay element provides a tunable time delay. In one exemplary embodiment, the above method includes reducing or eliminating the first current flow at the second time instant, and reducing or eliminating the second current flow at a third time instant that occurs at a later time than the second time instant.

[0013] Another aspect of the disclosed embodiments relates to a system that includes a load comprising a first and a second terminal and configured to be driven by a signal, a first energy source configured to provide a first voltage value and coupled to the load, and a second energy source configured provide a second voltage value and coupled to the load. The system also includes a first photonic switch coupled to the first energy source and to the first terminal of the load, where the first photonic switch is configured to control supply of a first current flow to the load in response to a first optical signal to generate a first unipolar signal across the load. The system further includes a a second photonic switch coupled to the second energy source and to the second terminal of the load, where the second photonic switch is configured to control supply of a second current flow to the load in response to a second optical signal to generate a second unipolar signal across the load. The system additionally includes a timing and synchronization circuit configured to control a relative delay in generation of the first and second unipolar signals across the load so as to produce a bipolar signal across the load from the first unipolar signal and the second unipolar signal.

[0014] In one exemplary embodiment, the above noted system further includes a laser that produces the first and the second optical signals that are directed to the first and second photonic switches, respectively, to activate the first and second photonic switches, as well as an optical delay element in a path of one of the first and second optical signals under control of the timing and synchronization circuit, where the optical delay element is configured to control a relative delay between the first and second optical signals in activating the first and second photonic switches, respectively. In another exemplary embodiment, the above system includes a second optical delay element in a path of another of the first and second optical signals under control of the timing and synchronization circuit, where the second optical delay element is configured to control the relative delay between the first and second optical signals in activating the first and second photonic switches, respectively.

[0015] According to another exemplary embodiment, the above system further includes one or more modulators configured to modulate one or both of the first and the second optical signals. In a particular example, the one or more modulators are configured to produce one or more of an amplitude-modulated laser beam(s), a frequency modulated laser beam(s), and a pulse-width modulated laser beam(s). In yet another embodiment, the load comprises a third terminal that is connected to a common terminal of both the first energy source and the second energy source.

[0016] Another aspect of the disclosed embodiments relates to a circuit for generating a bipolar signal that includes a first energy storage element, a second energy storage element, a first photonic switch coupled to the first energy storage element and configured to allow a first current flow from the first energy storage element through the first photonic switch upon activation of the first photonic switch at a first time instant. The circuit also includes a second photonic switch coupled to the second energy storage element and configured to allow a second current flow from the second energy storage element through the second photonic switch upon activation of the second photonic switch at a second time instant, where the combination of the first current flow and the second current flow produces the bipolar signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] FIG. 1 illustrates a circuit that can be used for generating a bipolar waveform in accordance with an exemplary embodiment.

[0018] FIG. 2(A) illustrates an ideal bipolar waveform output from the circuit in FIG. 1 in accordance with an exemplary embodiment.

[0019] FIG. 2(B) illustrates a non-ideal pulse charge current associated with the circuit of FIG. 1 in accordance with an exemplary embodiment.

[0020] FIG. 2(C) illustrates a bipolar waveform output from the circuit in FIG. 1 in accordance with an exemplary embodiment.

[0021] FIG. 3 illustrates a configuration for operating photonic switches in accordance with an exemplary embodiment.

[0022] FIG. 4(A) illustrates a circuit for producing a bipolar waveform in accordance with an exemplary embodiment.

[0023] FIG. 4(B) illustrates an antenna that is driven by the circuit in FIG. 4(A) in accordance with an exemplary embodiment.

[0024] FIG. 5(A) illustrates laser induced conductivities as a function of time for photonic switches in accordance with an exemplary embodiment.

[0025] FIG. 5(B) is a plot of voltage across a resistive load as a function of time in accordance with an exemplary embodiment.

[0026] FIG. 6(A) illustrates a circuit diagram for generating a bipolar signal in accordance with an exemplary embodiment.

[0027] FIG. 6(B) is a simplified block diagram of a signal generating circuit.

[0028] FIG. 7(A) illustrates a configuration for combining bipolar voltages in accordance with an exemplary embodiment.

[0029] FIG. 7(B) illustrates voltage combining through an inductive voltage adder configuration in accordance with an exemplary embodiment.

[0030] FIG. 8(A) illustrates a configuration for combining currents in accordance with an exemplary embodiment.

[0031] FIG. 8(B) illustrates a configuration for combining currents using a direct coaxial cable adder in accordance with an exemplary embodiment.

[0032] FIG. 9 illustrates a circuit that can be used for generating a bipolar waveform in accordance with another exemplary embodiment.

[0033] FIG. 10(A) illustrates an exemplary lumped capacitive system.

[0034] FIG. 10(B) illustrates a distributed capacitive system in accordance with an exemplary embodiment.

[0035] FIG. 10(C) is plot comparing the frequency response of lumped and distributed switch systems.

[0036] FIG. 11 illustrates a set of operations that can be carried out to generate a bipolar signal in accordance with an exemplary embodiment.

[0037] FIG. 12 illustrates a simplified diagram of a device that can be used to control the operations of the components of the disclosed embodiments.

DETAILED DESCRIPTION

[0038] Unipolar signals can be generated using capacitor discharge-like technology. However, attempting to combine two signed unipolar waveforms, phased to produce a bipolar waveform, has been a difficult task due, in-part, to strict phasing requirements (timing requirements) associated with combining such unipolar waveforms.

[0039] The disclosed embodiments relate to the generation of bipolar waveforms that are constructed by combining at least two unipolar waveforms. In some embodiments, optically controlled unipolar pulse sources are synchronized to generate a bipolar waveform. For example, two unipolar pulses, or a modulated train of unipolar pulses, are combined to yield a bipolar waveform of one or more cycles. The phasing between the unipolar sources is controlled optically by using, for example, controlling a relative optical delay (e.g., at least one tunable optical delay line) that achieves the correct phasing between the combined sources to produce the bipolar waveform(s). Additionally, or alternatively, the unipolar sources themselves can be controlled optically. The waveforms that are generated using the disclosed embodiments are not limited to digital signals (i.e., not limited to digital ones and zeroes) but can take on continuous, or almost continuous, range of values. Further, waveforms of different shapes and spectral contents can be produced, including waveforms with narrowband or broadband/wideband spectral characteristics. The unipolar waveform shape and spectral content can be selected to achieve a final bipolar waveform with a desired shape and spectral content based on the selected shapes and spectral contents of the two or more unipolar waveform signals that are combined.

[0040] In some embodiments, a bipolar signal is generated using a push-pull configuration where two sources with opposite polarity are provided along with a switching mechanism to allow alternate selection of the sources. The alternate selection can be implemented in the form of an on/off switching of the sources. Additionally or alternatively, the switching mechanism can control or adjust the contribution of each source in continuous or step-wise manner. For example, rather than switching the first source off and the second source on, the contribution from the first source can be decreased while the contribution from the second source is increased.

[0041] FIG. 1 illustrates a circuit 100 for generating a bipolar waveform in accordance with an exemplary embodiment. The circuit 100 includes a first current source 110, I_1, and a second current source 120, I_2, that provide currents in opposite polarity to charge capacitors 112 (C_1) and 122 (C_2), respectively. Synchronized operation of switches 114 (S_1) and 124 (S_2) generates a bipolar waveform V_{out} across a load 130, R_{load}. The bipolar waveform can be used to apply to the load 130 which can be, for example, an antenna configured to transmit electromagnetic radiation, or a transducer or any other load that can operate using RF signals.

[0042] One exemplary operation of the circuit 100 of FIG. 1 is described with the help of the timing diagram of FIG. 2(A) in the following manner. Both switches S_1 and S_2 are left in an open position (i.e., the position depicted in FIG. 1) to allow capacitors C_1 and C_2 to charge to particular (e.g., maximum) voltage values, V_1 and V_2 respectively. At time T_1, switch S_1 is closed, while switch S_2 remains open. As a result the output voltage, V_{out}, becomes equal to V_1. At time T_2, switch S_1 is opened and simultaneously switch S_2 is closed. As a result the output voltage, V_{out}, becomes equal to V_2. At time T_3, switch S_2 is opened while switch S_1 remains open. The output unipolar voltage, V_{out}, that is generated as a result of the above exemplary synchronized operation of switches S_1 and S_2 is illustrated in FIG. 2(A). For a symmetrical output signal, $V_1 = - V_2$. Non-symmetrical output signals can also be generated if the magnitude of V_1 is different from that of V_2. It should be noted that the ideal waveform in FIG. 2(A) is provided to illustrate the principles of push-pull operation of circuit 100. It is, however, understood that, in practical implementations of circuit 100, the output waveform is not a perfect square due to, for example, a finite time constant and non-ideal spectral characteristics of circuit components. To this end, FIGS. 2(B) and 2(C) depict non-ideal pulse charge current and capacitor voltages, respectively, associated with an exemplary implementation of circuit 100 of FIG. 1.

[0043] The operations of switches and/or sources can be controlled using photonic switches, e.g., switches based on photoconductive structures). Photonic switches have the ability to control electrical current flow using an optical waveform (e.g. a laser pulse). When a photonic switch is coupled to a power source such as an energy storage device (e.g. a capacitor), it allows current flow similar to how a voltage controlled diode operates. The result is a unipolar waveform, which is the superposition of the main energy store and the applied optical waveform. Note that the photonic switch can act as a mixer between the source voltage and the gate optical waveform. An exemplary photoconductive switch is described in U.S. Patent No. 7,893,541, titled "Optically-initiated silicon carbide high voltage switch," the entire contents of which is herby incorporated by reference. The switches can be operated in a fashion where conductance is directly controlled via the optical pulse (i.e. laser pulse) that is delivered to the switches. This way, one switch cannot directly drive other switches due to the phasing of the driving optical pulse. In addition, precise optical control and amplitude control can be effectuated. Stability can be achieved in photonic switches since the conduction current in the switch directly follows the optical pulse. Therefore, unlike a transistor where the gate terminal controls the flow of current, the optical pulse enables the flow of current directly by creating the charge carriers. Without this enabling optical pulse, the current flow is limited to the dark current.

[0044] Additionally, the configurations of the disclosed embodiments do not suffer from limitations that are produced due to feedback. Such feedback, which is present in typical amplifier designs, produces unwanted oscillations that result in system instability. The configuration of the disclosed embodiments do not produce self-oscillatory modes since oscillations can only be produced when an optical pulse is directly coupled to the corresponding switches. As such, the configurations of the present application do not break into spontaneous oscillations, even when two or more switches are simultaneously turned on. In this regard, it should be noted that, unlike the exemplary plot in FIG. 2(A), switches S_1 and S_2 can be simultaneously closed to, for example, allow at least some current flow from both the first energy storage element and the second energy storage element for a particular duration of time. As will be described in the sections that follow, photonic switches that are utilized in accordance with the disclosed embodiments can operate in both an "on-off" mode of operation, where a particular switch is completely turned on or turned off, or in a continuous mode of operation, where the current flow through the switch can be increased or decreased in a linear or stepwise fashion.

[0045] The photonic switches that are used in accordance with the disclosed embodiments can be wide bandgap photonic switches that achieve a function similar to that of a voltage controlled switch. Such switches can include wide band-gap photonic crystals such as GaN, SiC, ZnO, AIN, and the like. The source voltage is unipolar and has a constant or a slow decay. The energy storage component or element (e.g., a capacitor) is unipolar and has a constant or slow decay. The energy storage elements may be a separate component that is connected to the switch using, for example, a transmission line or cable. Alternatively, the energy storage element may be integral with the switch. In embodiments where the switch appears as a capacitor (i.e., two metalized electrodes with a dielectric between them), switches may be included in transmission lines or Blumleins.

[0046] In some embodiments, to achieve a bipolar waveform desirable for use with, for example, an antenna that is configured to transmit electromagnetic radiation, two or more unipolar circuit legs are combined into a push-pull configuration. An exemplary configuration that uses two adjoined unipolar circuits is shown in FIG. 1. The synchronization and timing between the two unipolar circuits is controlled, at least in part, using optical techniques that, for example, control a relative optical delay in the timing of optically switching on or off the switches to provide precise and tunable time delays. The waveform in each unipolar circuit can be fed the same optical waveform (e.g., via a beam splitter or similar technique) with the appropriate delay. The delay can be a fixed or variable.

[0047] FIG. 3 illustrates a configuration 300 for operating switch 310 (Switch 1) and switch 312 (Switch 2) in accordance with an exemplary embodiment. A laser 302 is used to generate optical pulses that control operations of switch 310 and switch 312. The laser beam of laser pulses output from the laser 302 is directed to a beam splitter 304 which splits the laser beam into first and second laser beams. The first laser beam (e.g., the transmitted portion of the laser beam) is directed to a first delay 306 component that can introduce a delay in the optical path of the first laser beam. The first laser beam that is output by the first delay element 306 is directed to the photonic switch 310 to control the switch 310. The second laser beam output by the beam splitter 304 (e.g., the portion reflected from the beam splitter 304) is directed to a second delay element 308 and subsequently on the photonic switch 312. A timing and synchronization circuit 314 is used to control the delay elements 306, 308 and the laser 302 to synchronize the timing of the switching status of switches 310 and 312. In this example, the timing and synchronization circuit 314 controls the delay elements 306, 308 in the different paths of the two laser beams to control relative timing of switches 310 and 312. In other embodiments, one of the delay elements 306, 308 can be eliminated so only one delay element is used to control the relative timing of the switches 310 and 312. The amount of the relative delay in the two laser beams for operating switches 310 and 312 can be precisely controlled to provide a range of different relative delays (including zero or no delay). The timing and synchronization circuit 314 can be implemented, at least in-part, using a processor, e.g., microprocessor, controller, digital signal processor (DSP), etc., that is coupled to a memory.

[0048] Additional components (not depicted in FIG. 3) may be included to provide focusing, attenuation and other beam shaping and beam steering operations. For example, optical filters or attenuators may be included in one or both of optical paths that lead to switches 310 and 312 in order to selectively attenuate the optical beam in the corresponding path and/or to provide wavelength selectivity in each optical path. As noted earlier, each of the switches 310 and 2 312 can be configured to operate in an on-off mode of operation, as well as in a continuous mode of operation where the switch can operate in, for example, a linear region allowing a portion of the maximum current to flow to the load. In some embodiments, the delivery of optical beams from the laser to the switches 310 and 312 can be carried out, fully or in-part, using fiber optics. In some embodiments, optical beams are propagated through free space. Additionally, mirrors, beam splitters, stops, apertures and other common optical components may be used to effect necessary beam shaping and beam steering operations.

[0049] In some embodiments, modulators are used to manipulate the optical output of the laser, which are then used to trigger the photonic switches. For example, with reference to FIG. 3, one or more electro-optic or acousto-optic modulators can be used to modulate the laser beam prior to reaching the switch 310 and switch 312. Electro-optic modulators are electrically controlled devices, which use an electrical trigger pulse to control an optical output pulse. Acousto-optic modulators operate based on the principle that the refractive index of a medium can be changed (modulated) due to the presence of sound waves in that medium. Modulated optical beams can be amplitude (or intensity) modulated beams, pulse-width modulated beams and/or frequency-modulated beams.

[0050] While FIG. 3 illustrates only two photonic switches for combining two unipolar waveform signals, it is understood that additional switches in connection with additional unipolar waveform signals may be added to control the shape of the output waveform. Due to the consistency of optical pulses, arrays with a vast number of photonic switches can be constructed while maintaining a low jitter when the output of the associated sources are combined. Experimental results for having more than two switches by combining more than two unipolar waveform signals indicate better than 98% coherent addition of the multiple unipolar waveforms.

[0051] One of the advantages of utilizing photonic switches as part of the disclosed embodiments is their capability to operate at high voltage values (e.g., at hundreds of kilovolts) with breakdown levels in the 200-300 MV/m regime. In comparison, many silicon electrical switches with a comparable thickness can only operate at voltage levels of up to about 800 volts (8kV/cm) in the modulation mode. The over 250-fold difference in achievable voltage levels (i.e., 200 MV/m divided by 8kV/cm) between the photonic switches and electrical switches can open up substantial new areas for application of the disclosed embodiments. For instance, large radar systems, transmitters, and other RF equipment can be miniaturized. Traditionally, high power electron-based vacuum tubes have allowed for large power levels. However, these systems employ vacuum systems, typically use confining magnetic fields, and have concerns for potential X-ray shielding requirements. The solid state photonic switch configurations that are used in the disclosed embodiments eliminate all of those concerns. As such, vastly simplified circuit configurations of the present application lead to circuit layouts that are more compact, cost effective, and can be readily manufactured.

[0052] FIG. 4(A) illustrates an exemplary configuration for producing a bipolar signal in accordance with an exemplary embodiment. The configuration of FIG. 4(A) is similar to that in FIG. 1. The charging supplies 402 provide electrical current that charges storage capacitors 404, 406. Switch 408 (Switch 1) and switch 410 (Switch 2) enable the switching of storage capacitors to allow a first current to flow to the resistive load 412 through switch 408 and a second current to flow to the resistive load 412 through switch 410.

[0053] FIG. 4(B) shows an Archimedean spiral 414 antenna that is connected to the circuit of FIG. 4(A) in place of the resistive load 412 for an antenna transmitter device. The Archimedean spiral 414 antenna is compact and rugged, and produces circular polarization over particular frequency bands of interest.

[0054] FIG. 5(A) illustrates the laser induced conductivities for switch 408 (solid line) and switch 410 (dashed line) of FIG. 4(A). The two switches 408 and 410 are driven 180 degrees out of phase. The plot is characterized as having 400 picoseconds (ps) full-with-half-maximum (FWHM), at 1 GHz and 100 ps rise/fall times. FIG. 5(B) illustrates the voltage across the resistive load as a function of time. As illustrated in FIG. 5(B), the voltage is in the form of a bipolar waveform with plus and minus peak values of approximately 1 KV. This peak voltage value was selected for demonstration purposes. However, as noted earlier, the circuit configurations of the disclosed embodiments are capable of producing voltages in the range of several hundreds of kilovolts.

[0055] FIG. 6(A) illustrates a configuration similar to that in FIG. 1, in which the charging current sources I_1 and I_2 are not shown for simplicity. In the configuration of FIG. 6(A), the voltages across capacitor C_1 and C_2 have opposite but generally unequal amplitudes, V_{C1} and V_{C2}, respectively. It should be noted that the voltages and/or currents that are supplied to the load can be provided using one or more energy sources. Such energy sources can include power supplies and storage elements (such as capacitors). As such, in some example embodiments, the energy source can include both an energy storage element (such as a capacitor) and a power supply (e.g., a voltage/current supply) used to charge the storage element, while in other exemplary embodiments, the power supply may be used to directly provide the necessary voltages/currents to the load through a photonic switch. Referring back to FIG. 6(A), the light incident on switches S_1 and S_2 can enable an on-off switching operation or provide an incremental (or linear) change in the switch conductivity. Such an incremental or linear change can, for example, be effectuated by varying the modulation (e.g., amplitude-, pulsewidth- and/or frequency-modulation) of the incident light pulse. Further, the intensity and spectral contents of the modulated light incident on each switch can differ from one switch to another. Combining the unipolar voltages that is produced from each of the left and right legs of the circuit in FIG. 6(A) in a synchronized fashion (i.e., with the proper time offset) allows the generation of an arbitrary waveform (i.e., arbitrary amplitude and spectral content). For example, output waveforms can be constructed in the Giga Hertz (GHz) range. FIG. 6(B) provides a generic block diagram in the form of module that represents the circuit of FIG. 6(A) (as well as other circuit configurations of the present application), in which the load is removed. For instance, a load having two terminals can be connected to terminals A and B of the Module in FIG. 6(B).

[0056] FIG. 7(A) illustrates a configuration 700 for combining bipolar voltages in accordance with an exemplary embodiment. In the configuration 700 of FIG. 7(A), modules

1 through *n* are connected in series to produce a combined output voltage Vout. In some embodiments, each of the modules 1 through *n* can have an identical output voltage signal such that the configuration 700 operates as a signal multiplier. In other embodiments, the modules 1 through *n* can have dissimilar output signals. Each module 1 through *n* may have a similar configuration as the circuit depicted in FIG. 6(A). However, in some embodiments, at least one of the modules 1 through *n* has a configuration that is different from that in FIG. 6(A). For example, fewer or additional switches, energy sources and energy storage elements may be used compared to the configuration of FIG. 6(A). Under synchronized control of the switches through the use of tuneable delays (e.g., as shown in FIG. 3), Vout can be construed by combining output signals produced by modules 1 through *n* with the proper timing offset. As a result, such an output can be arbitrarily shaped to contain any desired spectral characteristics, with peak voltage values of up to several hundreds of kilovolts. In one exemplary embodiment, combining of the voltages is carried out in an inductive voltage adder configuration, as shown in FIG. 7(B).

[0057] FIG. 8(A) illustrates a configuration 800 for combining currents in accordance with an exemplary embodiment. In the configuration of FIG. 8(A), modules 1 through *k* are connected in parallel to deliver a combined output current at an output voltage value Vout. Similar to the configuration in FIG. 7, modules 1 through *k* can have identical or different output voltage and current values. In one exemplary embodiment, combining of the currents is carried via a direct coaxial cable driven with the modules 1 through k, as shown in FIG. 8(B).

[0058] FIG. 9 illustrates a circuit 900 for generating a bipolar waveform across a load in accordance with an exemplary embodiment. In the exemplary configuration of FIG. 9, the load (e.g., a three terminal RF network such as an RF delay line) is connected to switches S_1 and S_2 through terminals A, B, and C respectively. In the exemplary diagram of FIG. 9, the third terminal, C, (e.g., ground) is connected to the common terminal of storage elements C_1 and C_2. In the configuration of FIG. 9, the voltages V_{C1} and V_{C2} across the storage elements C_1 and C_2 may have the same polarity. In one example embodiment, the circuit 900 can be configured to operate as follows. Assuming that the storage elements C_1 and C_2 are fully charged, the operation starts when S_1 is closed while S_2 remains open. As a result, the current flows through the load from the left hand side of the circuit 900 and is dissipated by the load. Next, S_1 is opened and S_2 is closed. This time, the current flows through the load from the right hand side of the circuit 900 and is dissipated by the load. Under the above operating conditions, the current through the load flows in opposite directions, depending on the state of switches S_1 and S_2. As a result, a bipolar signal across the load is generated from two unipolar signals associated with the two oppositely flowing currents. This operation can continue, as needed, to drive the load alternatively from the storage elements C_1 and C_2. One of the advantages of the configuration in FIG. 9 is that the switches S_1 and S_2 are decoupled from one another (through the load), which operates to reduce or eliminate interference between the switches.

[0059] The modules that are illustrated in FIGS. 7(A), 7(B), 8(A) and 8(B) correspond to bipolar signal generating circuits, such as the circuits that are depicted in FIGS. 6(A) and 9. In some embodiments, however, the modules that are illustrated in FIGS. 7(A), 7(B), 8(A) and 8(B) can include circuits that are capable of producing bipolar signals and/or circuits that are capable of producing unipolar signals. As such, a plurality of bipolar and/or unipolar signal generating circuits can be connected in cascade or in parallel to collectively produce an output signal with the desired amplitude and spectral characteristics. For example, in order to obtain specific spectral characteristics, certain modules can be added or removed to obtain the desired output waveform.

[0060] FIGS. 10(A) through 10(C) illustrate an improved frequency response associated with an optically triggered switch in accordance with an exemplary embodiment. FIG. 10(A) depicts an exemplary lumped capacitive system that comprises a single switch, S, in a circuit that is used to drive a load (e.g., an antenna). It should be noted that only one switch is shown in FIG. 10(A) to facilitate understanding of the underlying concepts. However, similar principles are applicable when more than one switch is used to, for example, produce a bipolar waveform. FIG. 10(B) shows an exemplary distributed capacitive system that comprises a plurality of optically triggered switches S_A, S_B, S_C, etc. instead of a single lumped capacitance of the switch. Since the opto-electical propagation time from point A to point B for all switches in FIG. 10(B) is constant, the distributed configuration of FIG. 10(B) produces a better frequency response due to reduced switch capacitance. FIG. 10(C) is a frequency response plot that compares the performance of the distributed system and two different lumped systems. As evident from FIG. 10(C), the useful range of frequencies can be extended by using a distributed system.

[0061] FIG. 11 illustrates a set of operations 1100 that can be carried out to generate a bipolar signal in accordance with an exemplary embodiment. At 1102, at a first time instant, a first optical signal is provided to a first photonic switch coupled to a first energy source to generate a first unipolar signal across the load due to a first current flow from the first energy source. At 1104, at a second time instant, a second optical signal is provided to a second photonic switch that is coupled to a second energy source to generate a second unipolar signal, having an opposite polarity with respect to the first unipolar signal, across the load due to a second current flow from the second energy source. At 1106, the bipolar signal is generated across the load from the first and second unipolar signal by controlling timing of the first and second time instants.

[0062] In some exemplary embodiments, some or all of the operations that are described in connection with FIG. 11 can be carried out using a system for producing bipolar waveforms from unipolar waveforms that includes a first voltage source and a second voltage source of opposite polarity to the first voltage source. Such a system further includes a first photoconductive switch connected to gate the first voltage source to produce a unipolar waveform at a load, as well as a second photoconductive switch connected to gate the second voltage source to produce a unipolar waveform at the load that has an opposite polarity to the unipolar waveform produced by the first photoconductive switch. The above noted system further also includes means for optically activating the switches so that the two opposite polarity unipolar waveforms arrive staggered at the load as a bipolar waveform. Example means for optically activating the switch include optical and acoustical modulators, as well as fiber optics, lenses, mirrors, optical delay units and other components that can be used to shape and/or direct the optical beams such that they are incident upon the switches with proper timing and synchronization. In a particular embodiment, the method for operating such a system for producing bipolar waveforms from unipolar waveforms includes providing a first photoconductive switch connected to gate a first voltage source to produce a unipolar waveform at a load, and a second photoconductive switch connected to gate a second voltage source to produce a unipolar waveform at the load that has an opposite polarity to the unipolar waveform produced by the first photoconductive switch. This method further includes timing the activation of the first photoconductive switch relative to the second photoconductive switch so that a bipolar waveform is produced at the load from the staggered arrival of the opposite polarity first and second unipolar waveforms.

[0063] It is understood that the various embodiments of the present disclosure may be implemented individually, or collectively, in devices comprised of various hardware and/or software modules and components. In describing the disclosed embodiments, sometimes separate components have been illustrated as being configured to carry out one or more operations. It is understood, however, that two or more of such components can be combined together and/or each component may comprise sub-components that are not depicted. Further, the operations that are described in the form of the flow chart in FIG. 11 may include additional steps that may be used to carry out the various disclosed operations.

[0064] In some examples, the devices that are described in the present application can comprise a processor, a memory unit and an interface that are communicatively connected to each other. For example, FIG. 12 illustrates a block diagram of a device 1200 that can be utilized as part of the synchronization and timing 314 components of FIG. 3, or may be communicatively connected to one or more of the components of FIG. 3. The device 1200 comprises at least one processor 1202 and/or controller, at least one memory 1204 unit that is in communication with the processor 1202, and at least one communication unit 1206 that enables the exchange of data and information, directly or indirectly, through the communication link 1208 with other entities, devices, databases and networks. The communication unit 1206 may provide wired and/or wireless communication capabilities in accordance with one or more communication protocols, and therefore it may comprise the proper transmitter/receiver antennas, circuitry and ports, as well as the encoding/decoding capabilities that may be necessary for proper transmission and/or reception of data and other information.

[0065] Various embodiments described herein are described in the general context of methods or processes, which may be implemented in one embodiment by a computer program product, embodied in a computer-readable medium, including computer-executable instructions, such as program code, executed by computers in networked environments. A computer-readable medium may include removable and non-removable storage devices including, but not limited to, Read Only Memory (ROM), Random Access Memory (RAM), compact discs (CDs), digital versatile discs (DVD), Blu-ray Discs, etc. Therefore, the computer-readable media described in the present application include non-transitory storage media. Generally, program modules may include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Computer-executable instructions, associated data structures, and program modules represent examples of program code for executing steps of the methods disclosed herein. The particular sequence of such executable instructions or associated data structures represents examples of corresponding acts for implementing the functions described in such steps or processes.

[0066] The foregoing description of embodiments has been presented for purposes of illustration and description. The foregoing description is not intended to be exhaustive or to limit embodiments of the present invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of various embodiments. The embodiments discussed herein were chosen and described in order to explain the principles and the nature of various embodiments and its practical application to enable one skilled in the art to utilize the present invention in various embodiments and with various modifications as are suited to the particular use contemplated. For example, the exemplary embodiments have been described in the context of proton beams. It is, however, understood that the disclosed principals can be applied to other charged particle beams. Moreover, the generation of extremely short charged particle pulses that are carried out in accordance with certain embodiments may be used in a variety of applications that range from radiation for cancer treatment, probes for spherical nuclear material detection or plasma compression, or in acceleration experiments. The features of the embodiments described herein may be combined in all possible combinations of methods, apparatus, modules, systems, and computer program products.

CLAIMS

WHAT IS CLAIMED IS:

1. A circuit, comprising:

a first energy source;

a second energy source;

a first photonic switch coupled to the first energy source and configured to allow a first current flow from the first energy source through the first photonic switch upon activation of the first photonic switch at a first time instant;

a second photonic switch coupled to the second energy source and configured to allow a second current flow from the second energy source through the second photonic switch upon activation of the second photonic switch at a second time instant; and

a load coupled to the first and second energy sources to allow generation of a bipolar signal across the load from a unipolar signal generated across the load due to the first current flow and a unipolar signal generated across the load due to the second current flow.

2. The circuit of claim 1, wherein each of the first and the second energy sources includes a capacitor.

3. The circuit of claim 1, wherein each of the first and the second energy sources comprises an energy storage element. .

4. The circuit of claim 1, wherein voltage level associated with the first energy source has a polarity opposite to voltage level associated with the second energy source.

5. The circuit of claim 1, wherein voltage levels associated with the first and the second energy sources have the same polarity.

6. The circuit of claim 1, further comprising a delay element configured to delay the activation of the second photonic switch relative to the activation of the first photonic switch.

7. The circuit of claim 6, wherein the delay element is tunable so as to provide a variable time delay.

8. The circuit of claim 6, further comprising a timing and synchronization circuit coupled to the delay element to control the delay in the activation of the second photonic switch relative to the activation of the first photonic switch.

9. The circuit of claim 1, wherein at least one of the first photonic switch and the second photonic switch is configured to allow the corresponding first current flow and the second current flow to be proportional to an intensity and/or modulation of a corresponding optical signal(s) incident thereupon.

10. The circuit of claim 9, wherein the bipolar signal has a selected shape and a selected spectral content.

11. The circuit of claim 1, wherein the bipolar signal has a wideband spectral content ranging from direct current (DC) to at least 1 GHz.

12. The circuit of claim 1, further comprising:

one or more additional energy sources; and

one or more additional photonic switches coupled to the corresponding one or more additional energy sources and configured to allow one or more additional current flows through the corresponding additional photonic switch upon activation of the corresponding additional photonic switch.

13. The circuit of claim 1, further comprising a radio frequency (RF) antenna coupled to receive and to be driven by the bipolar signal.

14. A method for generating a bipolar signal across a load, comprising:

at a first time instant providing a first optical signal to a first photonic switch coupled to a first energy source to generate a first unipolar signal across the load due to a first current flow from the first energy source;

at a second time instant providing a second optical signal to a second photonic switch coupled to a second energy source to generate a second unipolar signal, having an opposite polarity with respect to the first unipolar signal, across the load due to a second current flow from the second energy source; and

controlling timing of the first and second time instants to generate a bipolar signal across the load from the first and second unipolar signals.

15. The method of claim 14, further comprising adjusting one or more power supplies to set voltage values associated with the first and second energy sources.

16. The method of claim 14, wherein voltage level associated with the first energy source has a polarity opposite to voltage level associated with the second energy source.

17. The method of claim 14, wherein voltage level associated with the first and the second energy sources have the same polarity.

18. The method of claim 14, wherein providing the second optical signal comprises using a delay element to delay the activation of the second photonic switch relative to the activation of the first photonic switch.

19. The method of claim 18, wherein the delay element provides a tunable time delay.

20. The method of claim 14, wherein at least one of the first and the second current flows is proportional to an intensity and/or modulation of a corresponding optical signal incident thereupon.

21. The method of claim 14, comprising:

reducing or eliminating the first current flow at the second time instant; and reducing or eliminating the second current flow at a third time instant that occurs at a later time than the second time instant.

22. A system, comprising:

a load comprising a first and a second terminal and configured to be driven by a signal;

a first energy source configured to provide a first voltage value and coupled to the load;

a second energy source configured provide a second voltage value and coupled to the load;

a first photonic switch coupled to the first energy source and to the first terminal of the load, the first photonic switch configured to control supply of a first current flow to the load in response to a first optical signal to generate a first unipolar signal across the load;

a second photonic switch coupled to the second energy source and to the second terminal of the load, the second photonic switch configured to control supply of a second current flow to the load in response to a second optical signal to generate a second unipolar signal across the load; and

a timing and synchronization circuit configured to control a relative delay in generation of the first and second unipolar signals across the load so as to produce a bipolar signal across the load from the first unipolar signal and the second unipolar signal.

23. The system of claim 22, further comprising:

a laser that produces the first and the second optical signals that are directed to the first and second photonic switches, respectively, to activate the first and second photonic switches; and

an optical delay element in a path of one of the first and second optical signals under control of the timing and synchronization circuit, the optical delay element configured to control a relative delay between the first and second optical signals in activating the first and second photonic switches, respectively.

24. The system of claim 23, comprising:

a second optical delay element in a path of another of the first and second optical signals under control of the timing and synchronization circuit, the second optical delay element configured to control the relative delay between the first and second optical signals in activating the first and second photonic switches, respectively.

25. The system of claim 23, further comprising one or more modulators configured to modulate one or both of the first and the second optical signals.

26. The system of claim 25, wherein the one or more modulators are configured to produce one or more of an amplitude-modulated laser beam(s), a frequency modulated laser beam(s), and a pulse-width modulated laser beam(s).

27. The system of claim 22, wherein the load comprises a third terminal that is connected to a common terminal of both the first energy source and the second energy source.

28. A circuit for generating a bipolar signal, comprising:

a first energy storage element;

a second energy storage element;

a first photonic switch coupled to the first energy storage element and configured to allow a first current flow from the first energy storage element through the first photonic switch upon activation of the first photonic switch at a first time instant;

a second photonic switch coupled to the second energy storage element and configured to allow a second current flow from the second energy storage element through the second photonic switch upon activation of the second photonic switch at a second time instant, wherein the combination of the first current flow and the second current flow produces the bipolar signal.

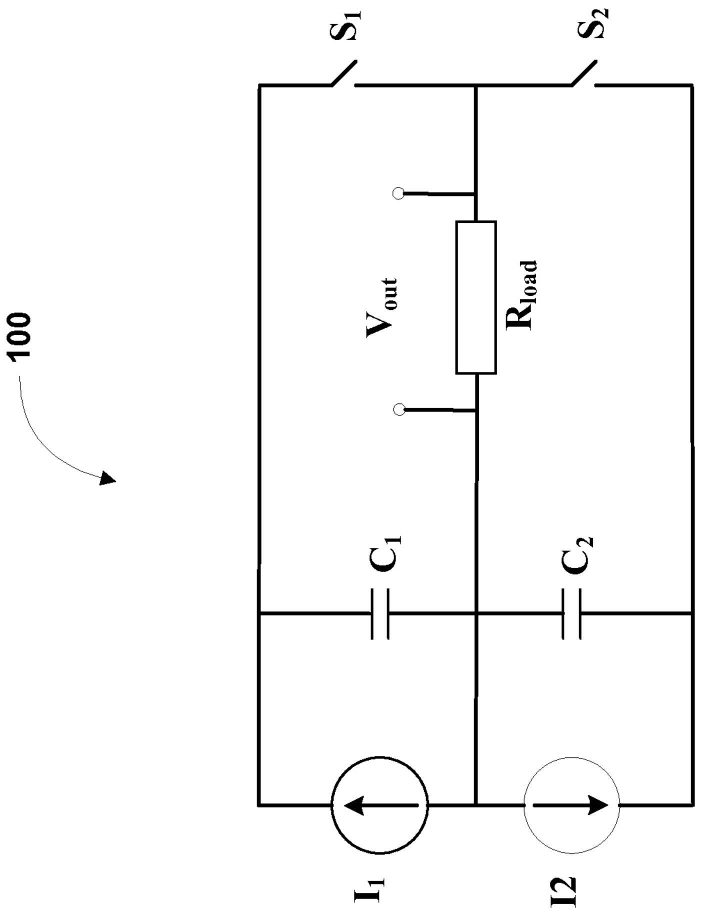


FIG. 1

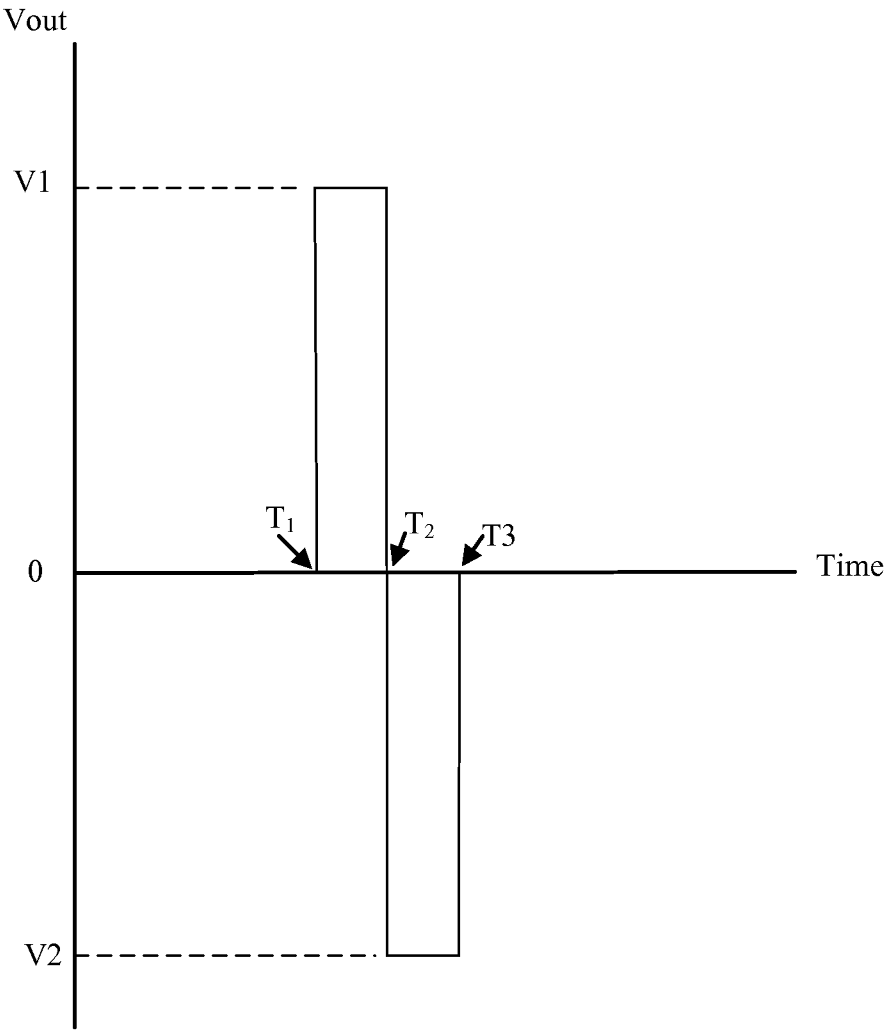


FIG. 2(A)

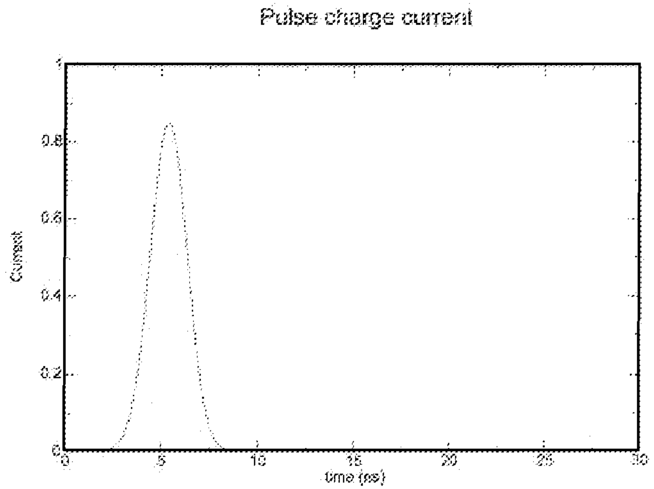

Pulse charge current
Current
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
time (ps)

FIG. 2(B)

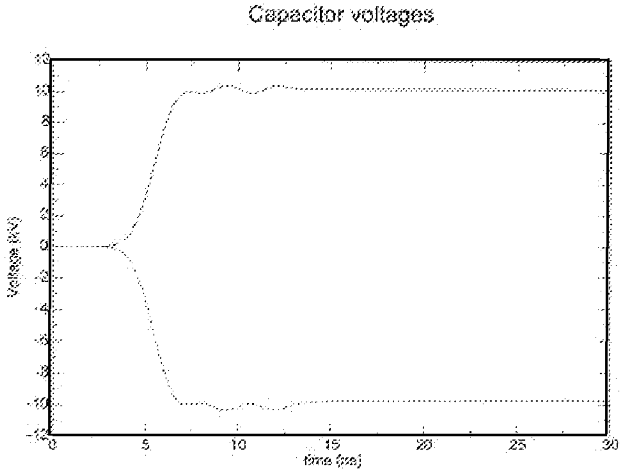

Capacitor voltages
Voltage (kV)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
0
5
10
15
20
25
30
time (ps)

FIG. 2(C)

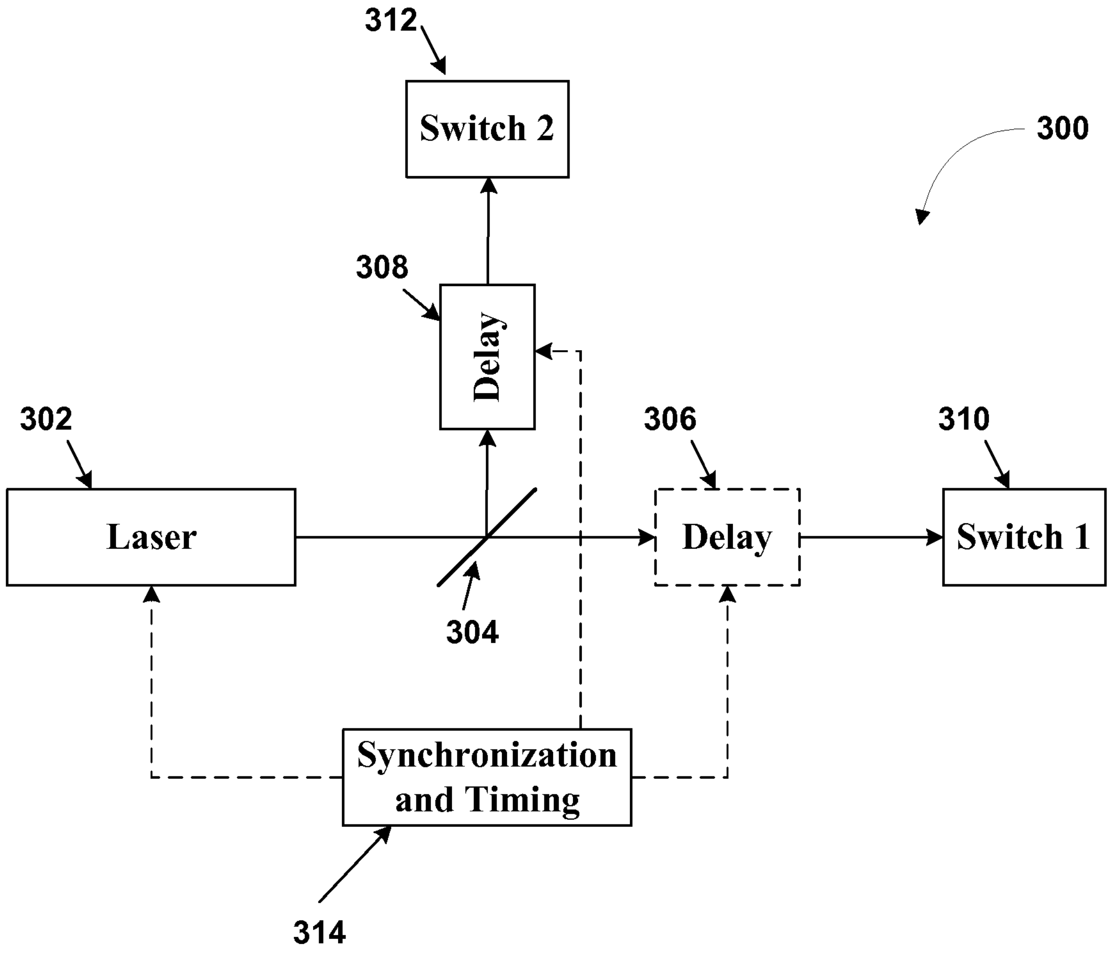

312
Switch 2
300
308
Delay
302
Laser
306
Delay
310
Switch 1
304
Synchronization
and Timing
314

FIG. 3

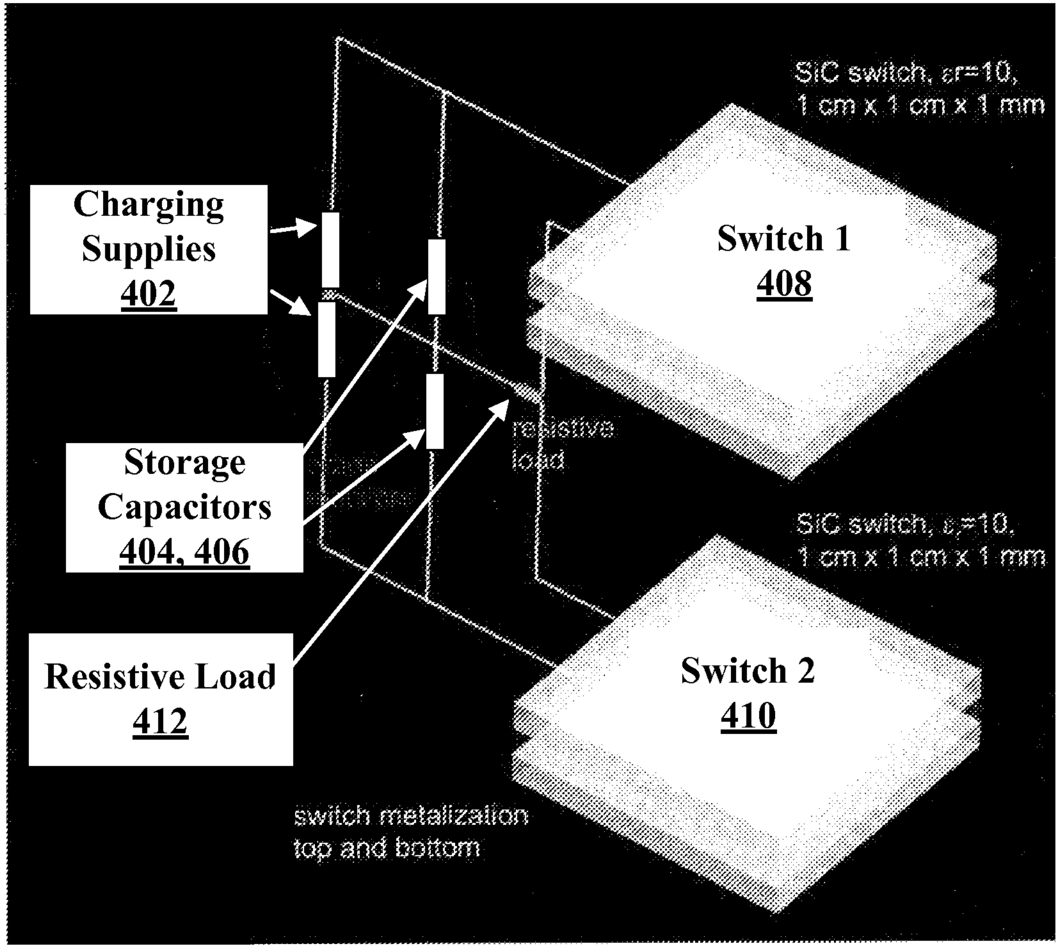

Charging Supplies 402
Storage Capacitors 404, 406
Resistive Load 412
Switch 1 408
Switch 2 410
SiC switch, ε_r=10, 1 cm x 1 cm x 1 mm
SiC switch, ε_r=10, 1 cm x 1 cm x 1 mm
resistive load
switch metalization top and bottom

FIG. 4(A)

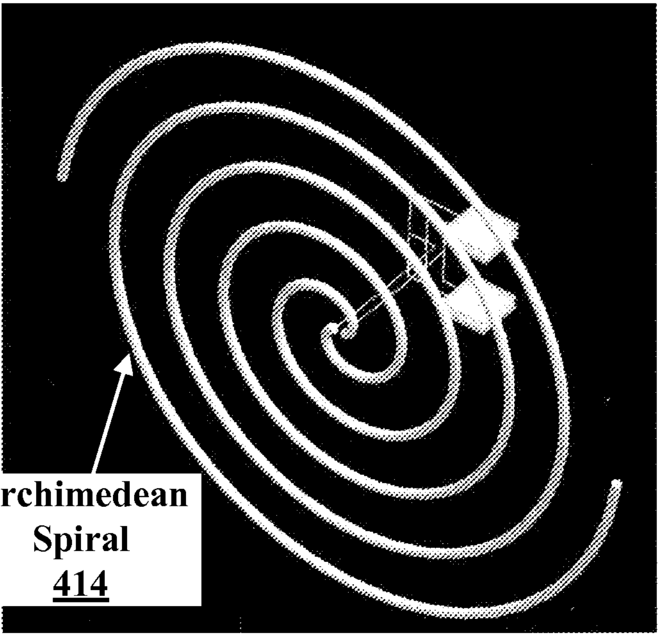

Archimedean Spiral 414

FIG. 4(B)

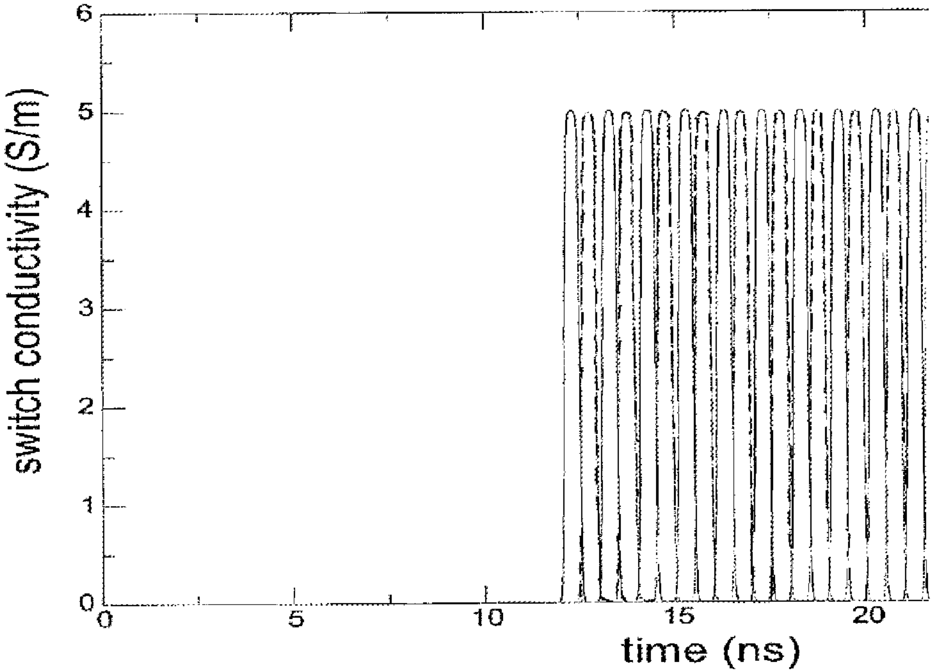
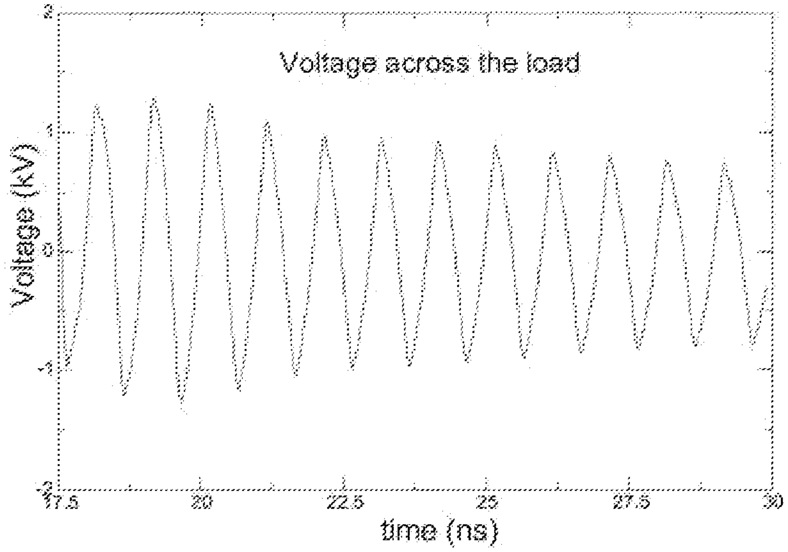

switch conductivity (S/m)
6
5
4
3
2
1
0
0
5
10
15
20
time (ns)

FIG. 5(A)

FIG. 5(B)


Voltage across the load
Voltage (kV)
2
1
0
-1
-2
17.5
20
22.5
25
27.5
30
time (ns)

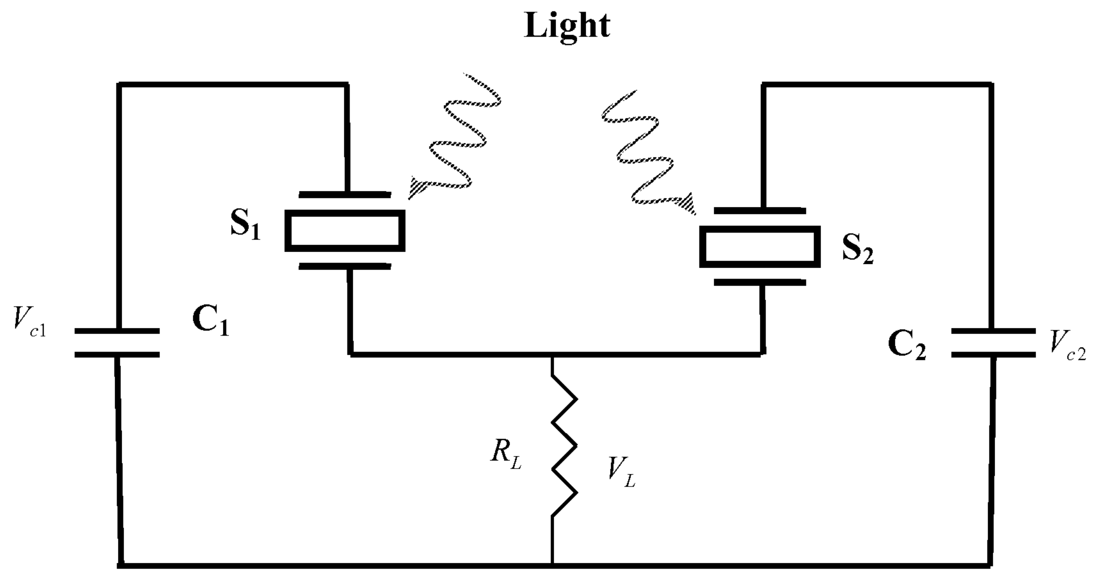


FIG. 6(A)

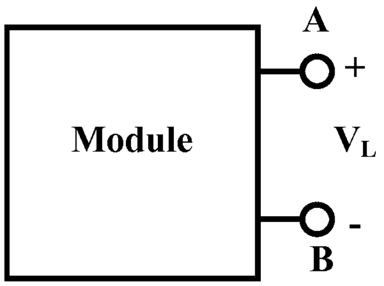


FIG. 6(B)

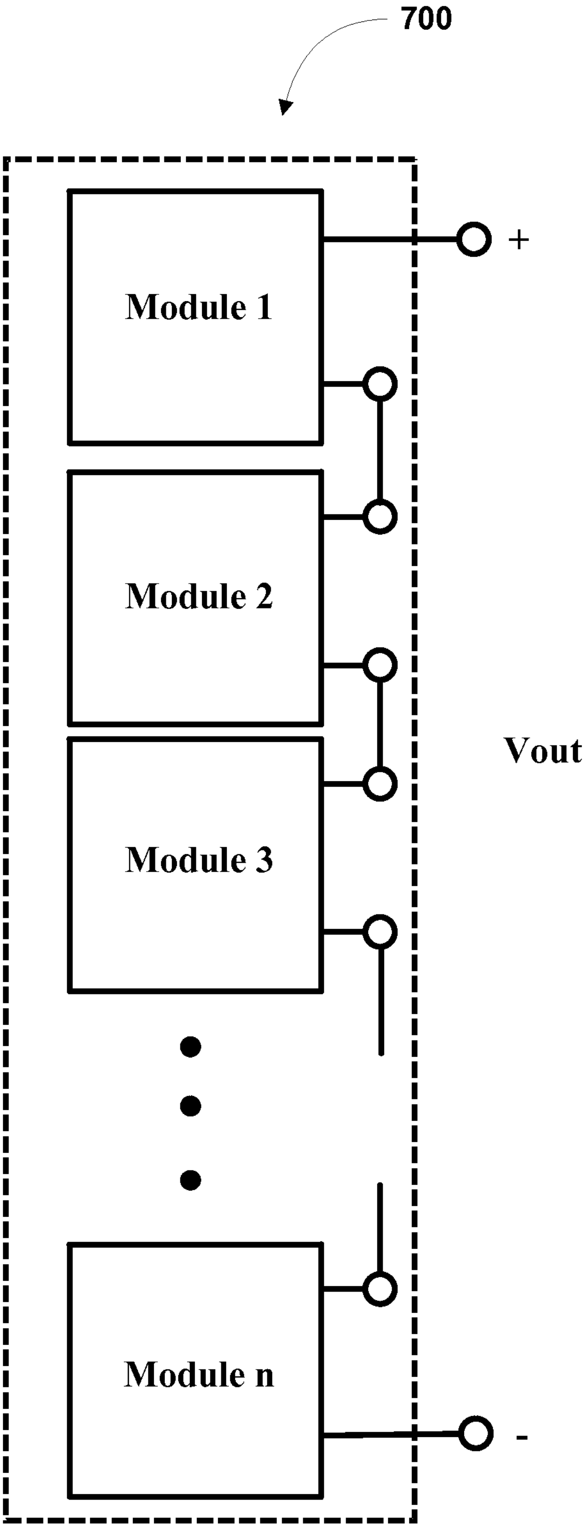

700
Module 1
Module 2
Module 3
Module n
+
-
Vout

FIG. 7(A)

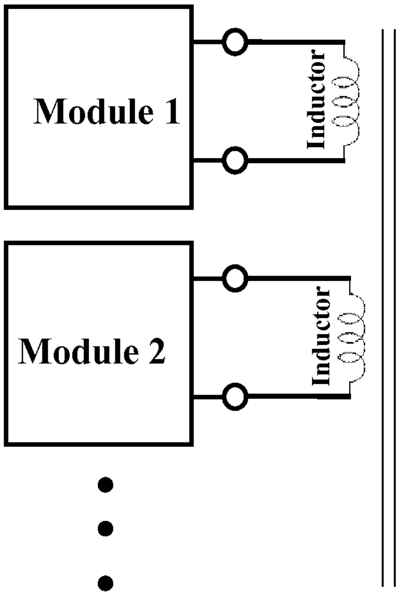

Module 1
Inductor
Module 2
Inductor

FIG. 7(B)

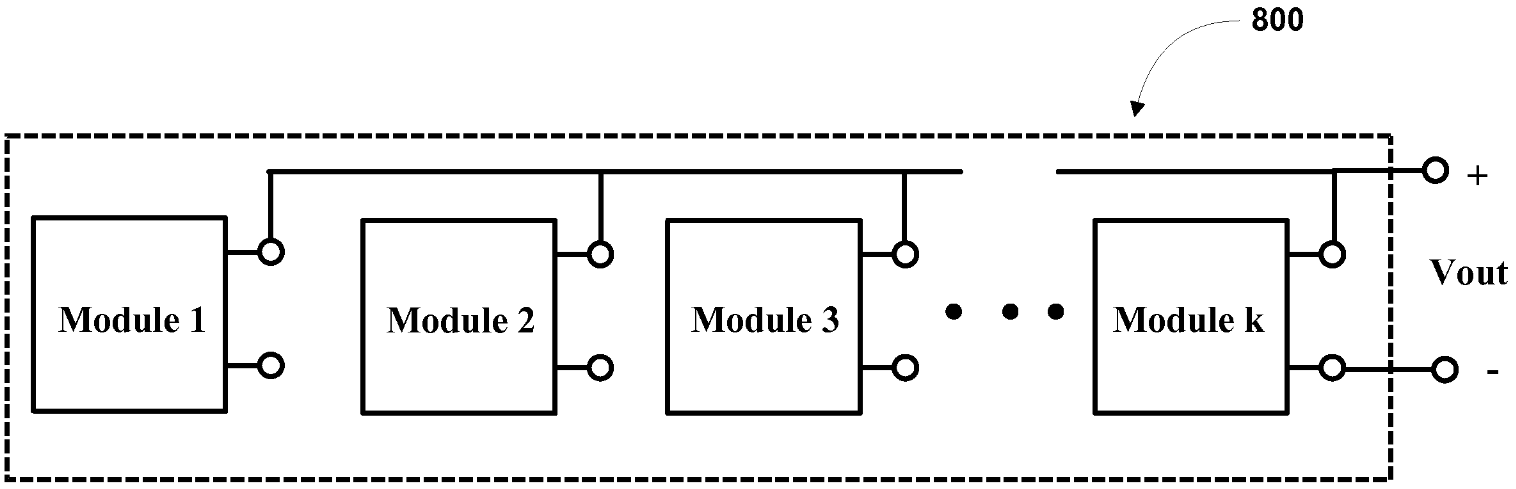

800
Module 1
Module 2
Module 3
Module k
+
Vout
-

FIG. 8(A)

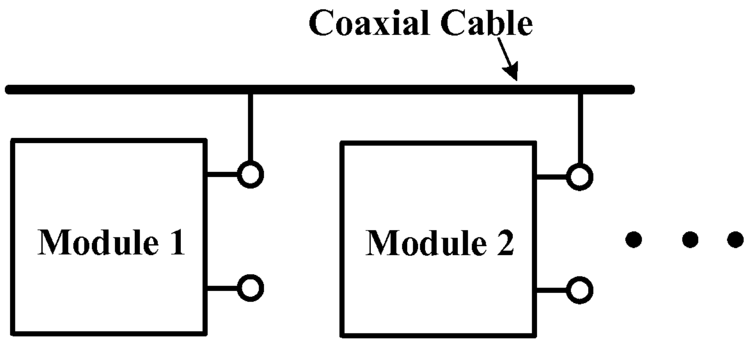

Coaxial Cable
Module 1
Module 2

FIG. 8(B)

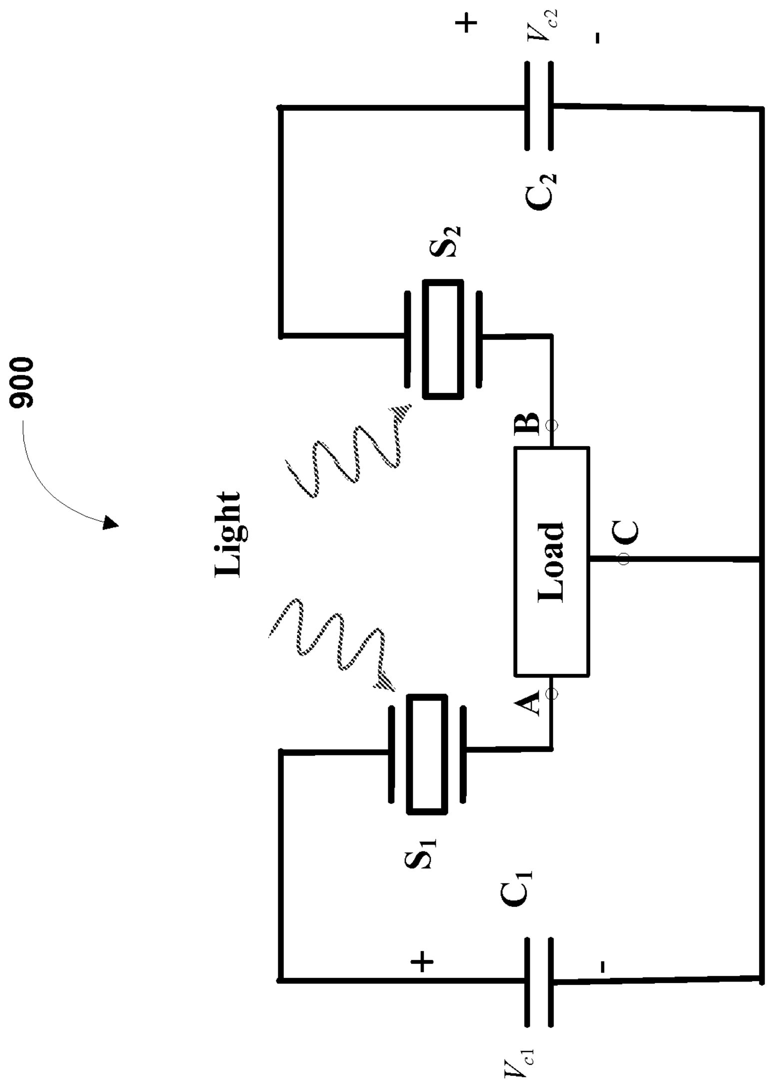


FIG. 9

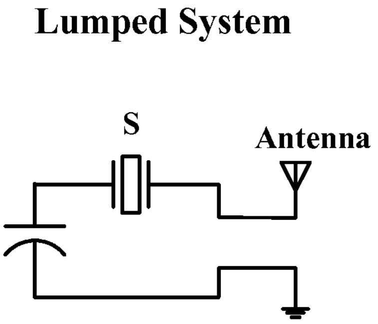


FIG. 10 (A)

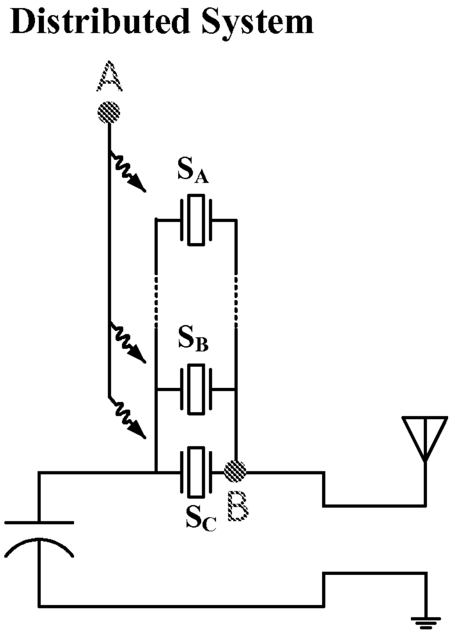


FIG. 10 (B)

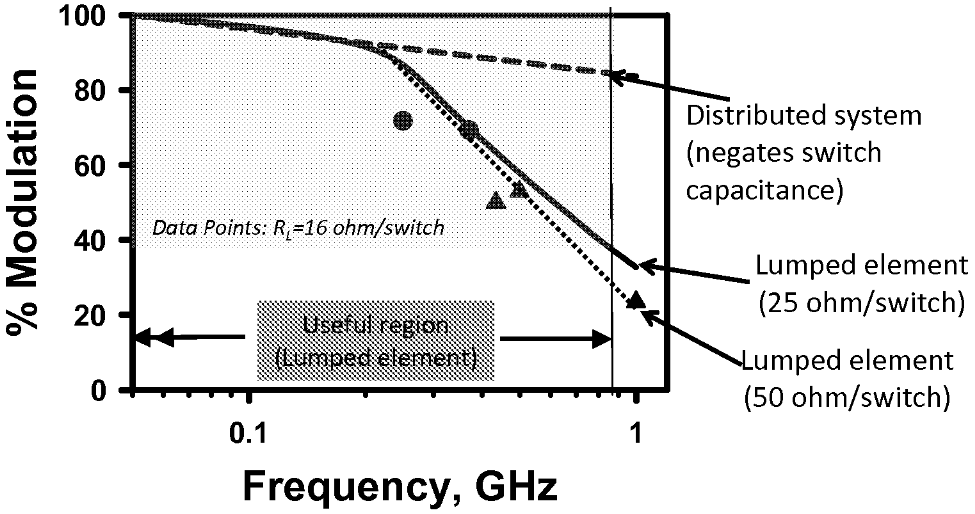


FIG. 10 (C)

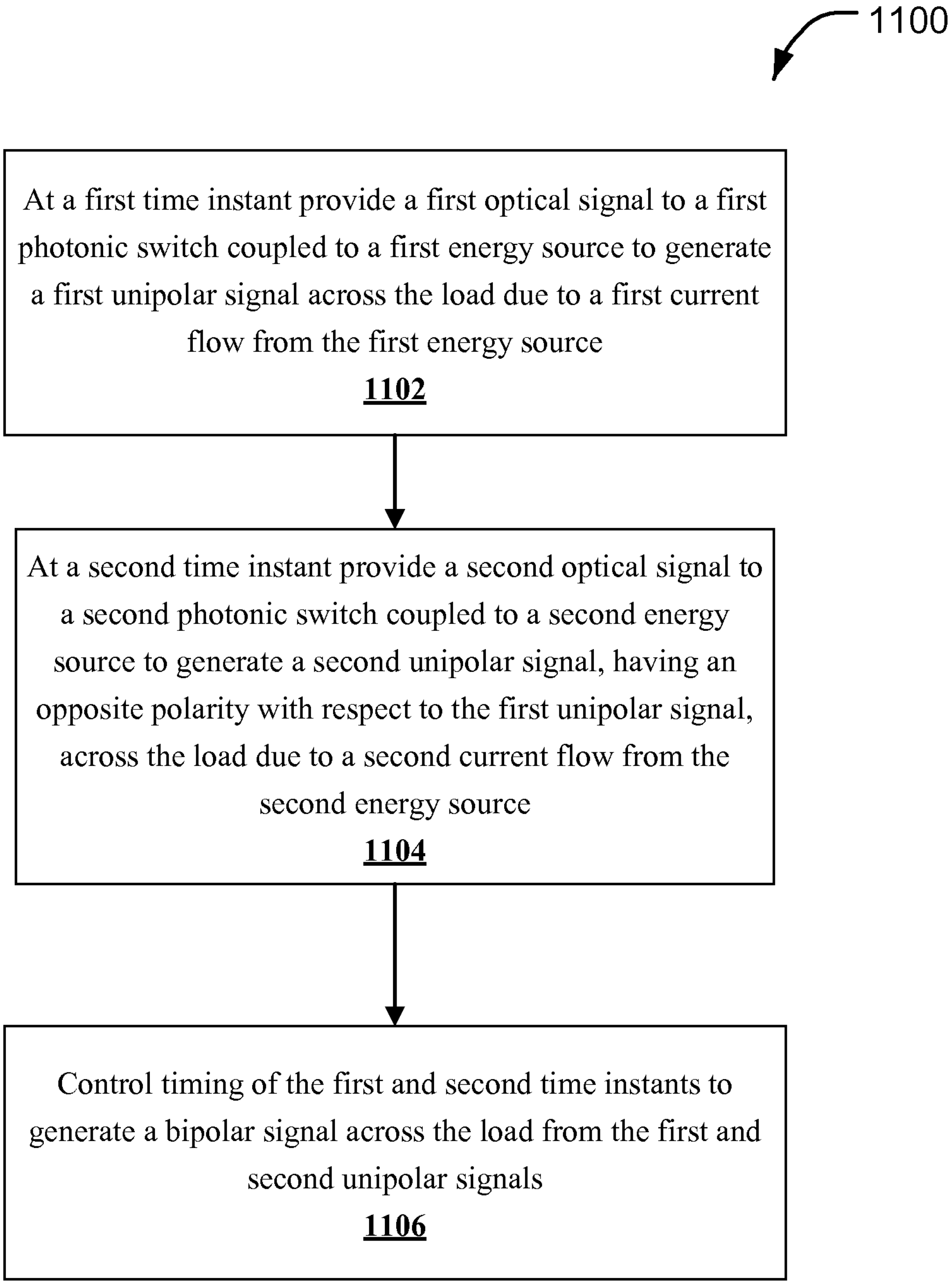

1100
At a first time instant provide a first optical signal to a first photonic switch coupled to a first energy source to generate a first unipolar signal across the load due to a first current flow from the first energy source
1102
At a second time instant provide a second optical signal to a second photonic switch coupled to a second energy source to generate a second unipolar signal, having an opposite polarity with respect to the first unipolar signal, across the load due to a second current flow from the second energy source
1104
Control timing of the first and second time instants to generate a bipolar signal across the load from the first and second unipolar signals
1106

FIG. 11

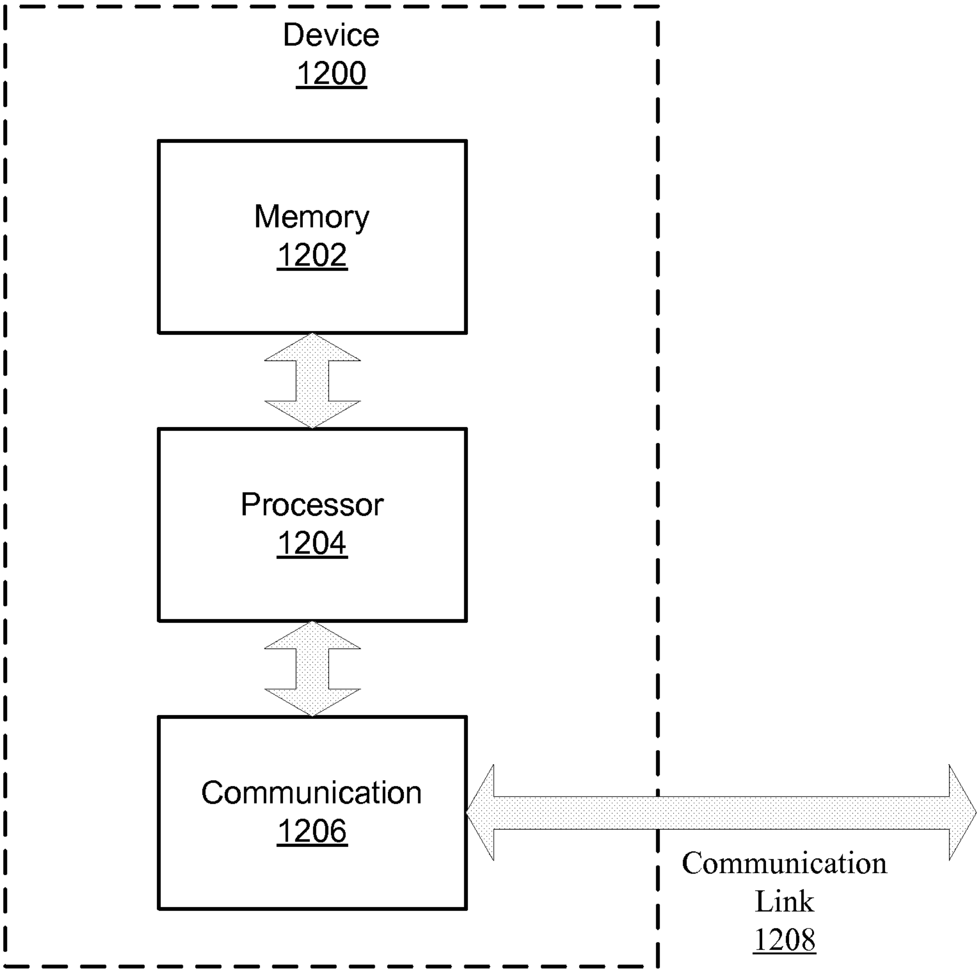

Device
1200
Memory
1202
Processor
1204
Communication
1206
Communication
Link
1208

FIG. 12