

Aug. 22, 1961

J. F. VIZE
BISTABLE ELECTRO-OPTICAL NETWORK

2,997,596

Filed Dec. 27, 1957

3 Sheets-Sheet 1

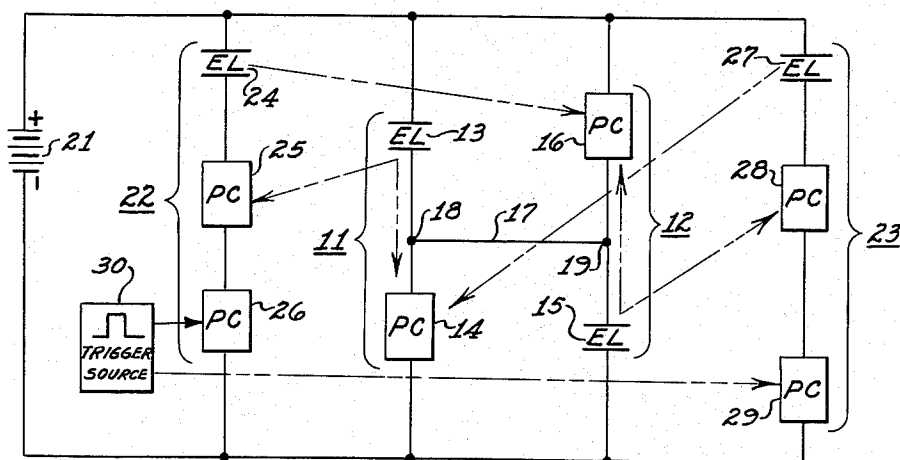


Fig. 1

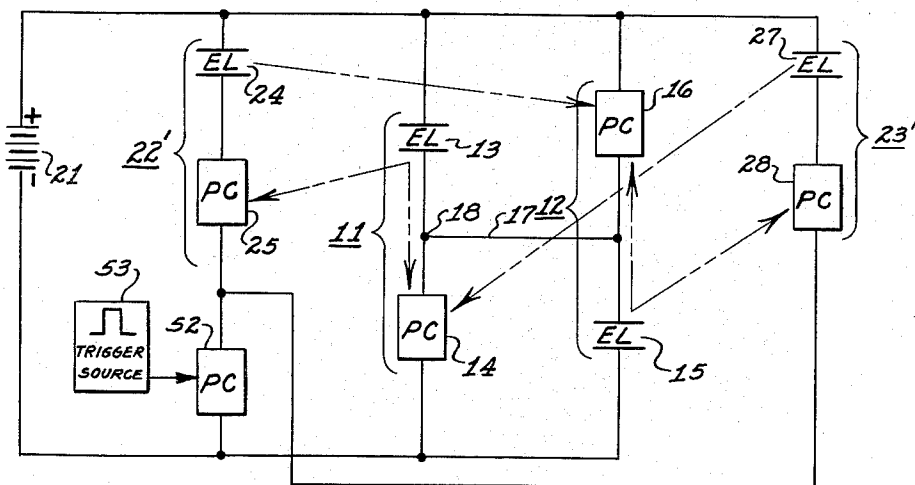
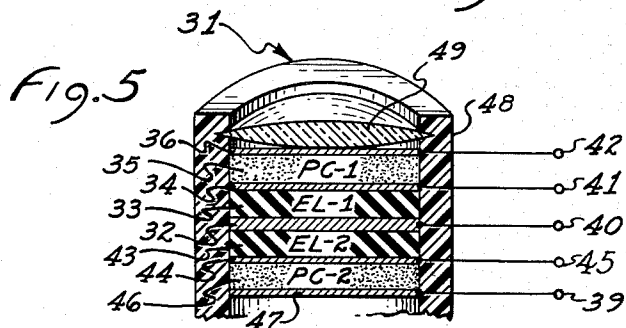


Fig. 2



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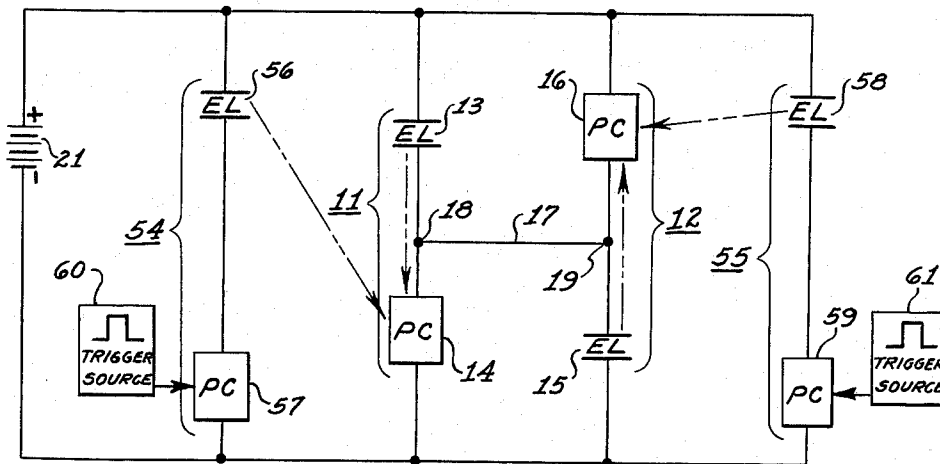


Fig. 3

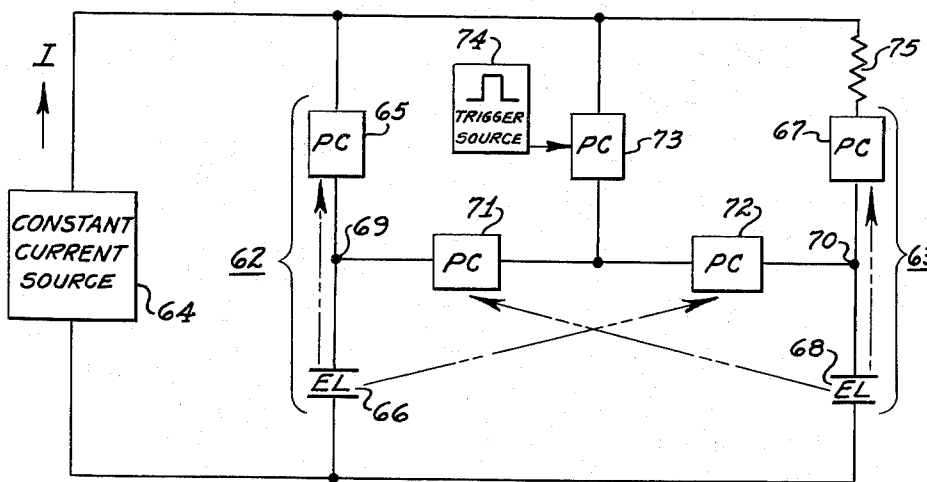


Fig. 4

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3 Sheets-Sheet 3

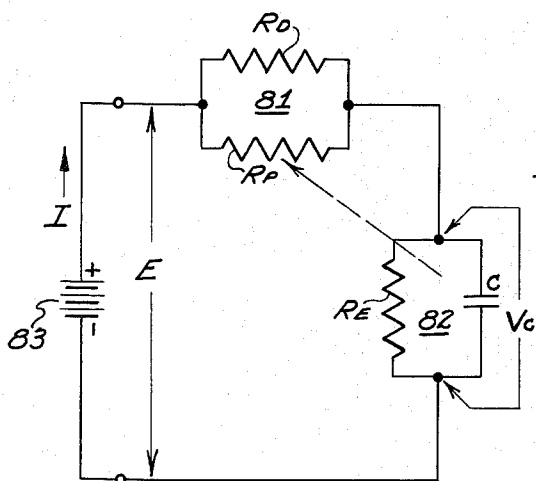


Fig. 6

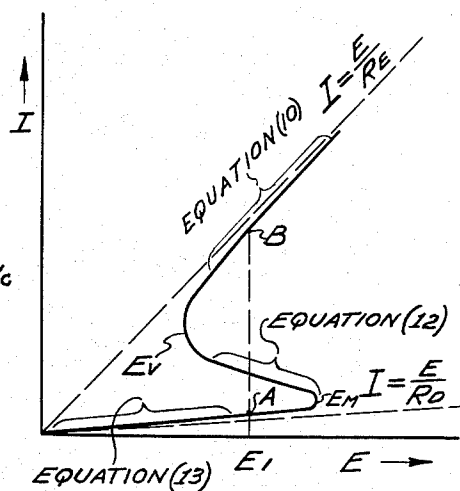


Fig. 7

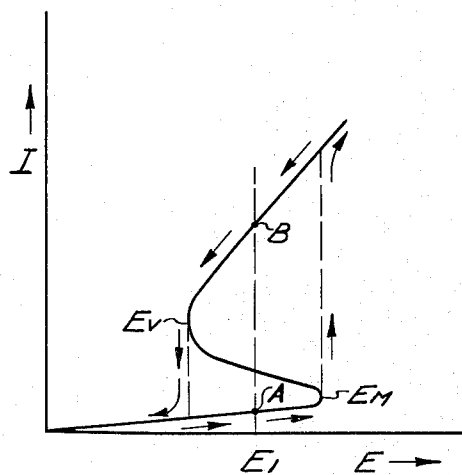


Fig. 8

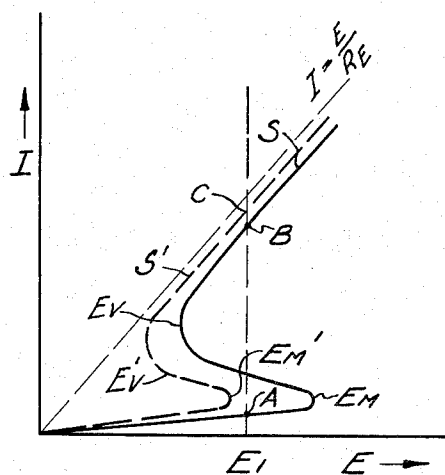


Fig. 9

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2,997,596

BISTABLE ELECTRO-OPTICAL NETWORK**James F. Vize, Auburn, N.Y., assignor to General Electric Company, a corporation of New York**

Filed Dec. 27, 1957, Ser. No. 705,680

2 Claims. (Cl. 250—209)

This invention relates to bistable electro-optical networks, and more particularly to electrical networks including electroluminescent phosphors and photoconductors as elements thereof and adapted to operate in either one of two stable states.

The phenomenon of electroluminescence upon which the operation of the networks of the present invention in part depends is the process by which certain semiconducting materials, known as phosphors, emit radiation under the primary stimulus of an applied electrical field or potential. For a survey and bibliography on the subject of electroluminescence, reference is made to an article by G. Destriau and H. F. Ivey, "Electroluminescence and Related Topics," Proceedings of the Institute of Radio Engineers, vol. 43 (1955), pp. 1911—1940.

As noted in the above article electroluminescent phosphors have in the past been used as light sources in devices frequently called electroluminescent capacitors or electroluminescent cells. Such devices often resemble a flat plate capacitor and may comprise two parallel planar electrodes which have sandwiched between them, in one form or another, an electroluminescent phosphor. The phosphor may be in the form of microcrystals suspended in a transparent plastic or dielectric binder. Alternatively, the phosphor may be in the form of a continuous, transparent crystalline layer such as that disclosed in U.S. Patent No. 2,709,765 to L. R. Koller, or in the form of single crystals as disclosed in U.S. Patent No. 2,721,950 to Piper and Johnson. In general the microcrystal-in-plastic type of phosphor dielectric exhibits electroluminescence only under excitation by alternating electric fields, whereas in the two patents referred to above, the phosphors exhibit electroluminescence when excited by either alternating or unidirectional electric fields. The carrier-injection electroluminescence described in the aforementioned article is a type of electroluminescence excited by unidirectional electric fields.

Prior known electro-optical networks employing both electroluminescent phosphors and photoconductors disposed and interconnected for mutual cooperation have been used as amplifiers or oscillators, etc. Networks of this type are shown in U.S. patent application Serial No. 585,027, now Patent No. 2,904,696, by R. E. Halsted and J. F. Elliott, and U.S. patent application Serial No. 585,052, by C. F. Spitzer, both applications being assigned to the assignee of the instant application.

The term "photoconductor" as used herein is intended to apply to any material the impedance or conductivity of which varies as a function of the radiation emitted by a particular associated electroluminescent phosphor. A photoconductor is said to be in "radiation-coupled relationship" with an electroluminescent phosphor when they are so related that the impedance or conductivity of the photoconductor varies as a function of the radiation emission of the electroluminescent phosphor. Further, the network in which the photoconductor and the electroluminescent phosphor are included will be said to be an "electro-optical network" when there is an interaction in the network between electrical energy and radiant or light energy.

An electroluminescent cell and a photoconductor connected in electrical series relation and positioned in radiation-coupled relationship may be termed an "electro-optical pair," for purposes of this specification. Such an electro-optical pair, when connected across a predeter-

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mined value of voltage is adapted to be bistable; that is, the pair will draw one of two possible values of current, one high and one low. Correspondingly, the intensity of radiation emitted from the electroluminescent cell will be high or low, depending on whether the value of current is high or low. When the electro-optical pair is in its "dark" state (emission from the electroluminescent cell is low), application of an external radiation signal to the photoconductor will switch the pair to its other state. If two such independently stable electro-optical pairs are so mutually interrelated that proper signal feedback is transmitted from one pair to the other, a novel apparatus is obtained that has two stable states and is adapted to be shifted from either one of its stable states to the other by application of a radiation trigger signal to the respective photoconductor coupled to the "dark" electroluminescent cell. Such a bistable apparatus is extremely useful, especially in digital computers for register and counter elements. When used as a register element, the two stable states would be designated respectively as the binary digits 1 and 0. Input radiation triggering means is provided to independently switch the device to either of its stable states. When use as a counter element, the device is switched from the stable state in which it is operating to its other stable state upon application of a common input trigger signal; that is, the device would return to a particular stable state after each two input trigger signals.

A bistable device employing these electroluminescent phosphors has the additional desirable feature of providing a visible indication of the state of the device. Thus, one electroluminescent phosphor glows only when the network is in one of its two stable states and the other electroluminescent phosphor glows only when the network is in the other stable state.

It is therefore a principal object of this invention to provide a bistable device comprising two mutually interrelated electro-optical pairs.

Another object of this invention is to provide a novel bistable electro-optical network.

Another object of this invention is to provide an electrical network including electroluminescent phosphors and photoconductors as elements thereof and adapted to operate in either one of two stable states.

Another object of this invention is to produce an output signal from an electro-optical network in response to every two input signals.

Another object of this invention is to provide an electro-optical network adapted to operate in either one of two stable states in response to a respective one of two input signals.

Another object of this invention is to provide an electrical network including electroluminescent phosphors and photoconductors as elements thereof and adapted to operate in either one of two stable states, wherein the particular phosphors luminescing are indicative of the stable state in which the network is operating.

The foregoing objects are achieved by providing networks having first and second electro-optical pairs connected in parallel. A source of electrical energy is coupled across the parallel-connected electro-optical pairs. A point of the first electro-optical pair between the electroluminescent cell and the photoconductor thereof is connected to a point of the second electro-optical pair between the electroluminescent cell and the photoconductor thereof. This connection between the first and second electro-optical pairs is one means whereby feedback is provided so that the network can operate in only one of two stable states; that is, wherein the "on" electro-optical pair draws relatively large current and its electroluminescent phosphor emits a relatively intense radiant energy signal, and the "off" electro-optical pair draws relatively little current and its electroluminescent

phosphor emits relatively little, if any, radiant energy. Upon application of a radiant energy trigger signal to the photoconductor of the "off" electro-optical pair the network shifts to its other stable state. In this other stable state the formerly "off" electro-optical pair is "on" and vice versa.

The invention will be described with reference to the accompanying drawings, wherein:

FIGURE 1 is a circuit diagram of the bistable network of this invention, including one form of triggering means;

FIGURE 2 is a diagram of a modified embodiment of the circuit of FIGURE 1;

FIGURE 3 is a diagram of the circuit of FIGURE 1 modified to act as a register element;

FIGURE 4 is a circuit diagram of the bistable network of this invention, including a second form of triggering means;

FIGURE 5 is a perspective view, partly in section, of an electro-optical pair useful in the circuits of FIG. 1;

FIGURE 6 is a schematic representation of an electro-optical pair;

FIGURE 7 is a curve illustrating the operating conditions of the electro-optical pair of FIG. 6;

FIGURE 8 is a curve demonstrating electrical triggering of an electro-optical pair; and

FIGURE 9 is a curve demonstrating radiation triggering of an electro-optical pair.

In the bistable network of FIG. 1 an electro-optical pair of 11 is connected in parallel with an electro-optical pair 12. Pair 11 comprises a series-connected electroluminescent cell 13 and photoconductor 14 positioned in radiation-coupled relationship indicated by the arrow and broken line between them. The arrows and broken lines elsewhere in FIGS. 1 to 4 indicate the same radiation-coupled relationship and this convention will be employed throughout this application. Electro-optical pair 12 comprises a series-connected electroluminescent cell 15 and photoconductor 16 positioned in radiation-coupled relationship. A lead 17 interconnects points 18 and 19 located between the electroluminescent cell and photoconductor of pairs 11 and 12, to provide the feedback, described hereinafter, for causing this network to operate in only one of two stable states.

Electro-optical pair

Examples of electro-optical pairs useful in the circuit of FIG. 1 are shown and described in the aforementioned U.S. patent application Serial Number 585,052 by C. F. Spitzer. A device 31 including such an electro-optical pair is shown in FIG. 5. Device 31 is adapted to receive either or both electrical and light input signals and to produce either or both electrical and light output signals. In device 31 an electrode 32 consists of a rigid opaque metallic member serving as both an electrode and a supporting member and which is preferably polished for maximum light reflection. Deposited on one side of electrode 32 are an electroluminescent layer 33, a light-transmitting electrode 34, a photoconductive layer 35, and a light-transmitting electrode 36. Deposited on the other side of electrode 32 is an electroluminescent layer 43, a light-transmitting electrode 44, a photoconductive layer 46 and a light-transmitting electrode 47. Lead wires are soldered or otherwise electrically connected to each electrode.

Electroluminescent layer 33 and adjacent electrodes 32 and 34 comprise an electroluminescent cell EL-1, and electroluminescent layer 43 and adjacent electrodes 32 and 44 comprise another electroluminescent cell EL-2. The above two electroluminescent cells are connected in series by the common electrode 32, so as to make the cells EL-1 and EL-2 effectively one electroluminescent cell which is in radiation-coupled relation with two photoconductors for reasons that will appear later. Similarly, photoconductive layer 35 and its electrodes 34 and 36 comprise one photoconductor PC-1 and the photocon-

ductive layer 46 and its electrodes 44 and 47 comprise a second photoconductor PC-2. A casing 48 which consists of a light-opaque, electrically-insulating material is used to support the cells, photoconductors and a lens 49 adjacent electrode 36.

It should be understood that the word "light," as used in this application, includes any radiation emitted by an electroluminescent phosphor to which a photoconductor is responsive and may, for example, include ultraviolet or infrared radiation.

Light-transmitting, electrical conducting electrodes 34 and 36 may be layers of titanium dioxide or tin oxide, commonly referred to as conducting glass. Alternatively, a very thin light-transmitting layer of evaporated metal, such as aluminum or silver, may be used. If the light-transmitting, electrical conducting electrodes are titanium dioxide they may be prepared and rendered conductive in accordance with the teachings of U.S. Patent No. 2,717,844 to L. R. Koller.

Electroluminescent layers 33 and 43 may be phosphors such as zinc sulfide activated by three-tenths percent by weight of copper and written as ZnS:Cu, prepared as a continuous crystalline layer, as disclosed in the above-mentioned Patent 2,709,765 to L. R. Koller, or single crystalline phosphors of the type disclosed in the above-mentioned Patent 2,721,950 to Piper and Johnson. These types of electroluminescent layers are responsive to both direct or alternating electric fields. The average brightness B of the light output of an electroluminescent phosphor as a function of the voltage V_c applied to it may be closely approximated by the expression,

$$(1) \quad B = kV_c^n$$

where n is a constant characteristic of the particular electroluminescent phosphor used and k is a constant of proportionality. Values of n , in Equation 1, range approximately from 1 to 7 for known phosphors.

Photoconductive layers 35 and 46 are thin light-permeable layers of photoconductive material. This material may, for example, comprise cadmium sulfide or lead sulfide, which may be sprayed, sputtered, or evaporated on one of the light-transmitting electrodes 34 or 36 and 44 or 47. More generally, photoconductive layers 35 and 46 may, for example, consist of any of the sulfides, selenides, or tellurides of cadmium, lead, or zinc, or may be any other known photoconductor.

The physical arrangement of the device 31 is such that light emitted by electroluminescent cell EL-1 falls on photoconductor PC-1. This cell and photoconductor are connected in electrical series relation between terminals 40 and 42, and therefore constitute an electro-optical pair such as pair 11 or 12 (FIG. 1). The current drawn by this pair depends on the voltage applied to the terminals 40 and 42 and the amount of external radiation applied to photoconductor PC-1 through lens 49.

It will be noted with reference to FIG. 1 that electroluminescent cell 13, for example, is indicated as being in radiation-coupled relationship with two different photoconductors 14 and 25. Therefore, the device 31 of FIG. 5 includes two series connected electroluminescent cells composed of electroluminescent layers 33 and 43 with their common opaque electrode 32 and their respective light transmitting electrodes 34 and 44. Each of electroluminescent cells EL-1 and EL-2, is radiation-coupled to its respective photoconductor indicated generally by PC-1 and PC-2. The relationship between the diagrammatic illustration of FIG. 1, for example, and the physical embodiment of FIG. 5 may be understood, by noting that there is one device 31 for each of the electro-optical pairs 11 and 12 (FIG. 1) and their radiation-coupled photoconductors 25 and 28, respectively. Light may be transmitted from electroluminescent cell 27 to photoconductor 14 (FIG. 1) through lens 49 (FIG. 5) if it is desirable to physically separate the cell and photoconductor, or alternatively, the lens may be eliminated by locat-

ing electroluminescent cell 27 (FIG. 1) adjacent photoconductor PC-1 (FIG. 5) with the electrode 36 serving as a common electrode for the two. The device 31 for the electro-optical pair 12 may be similarly arranged for receiving light from electroluminescent cell 24.

Voltage feedback

Referring once more to FIG. 1, a source 21 of electrical energy is connected across the parallel-connected electro-optical pairs 11 and 12. Although in FIG. 1, source 21 is shown as a constant voltage source, this apparatus is not limited thereto, but may employ an alternating voltage source. It is preferred that electro-optical pairs 11 and 12 be substantially alike. The combination of electro-optical pairs 11 and 12, connected, as shown, across a voltage source is adapted to operate in either one of two stable states as follows.

Assume that electro-optical pair 11 is "on" and electro-optical pair 12 is "off." When pair 11 is "on," it draws relatively large current and electroluminescent cell 13 emits a relatively intense light signal, as compared with the light emitted by cell 15 of electro-optical pair 12. Each of photoconductors 14 and 16 have an impedance which decreases as the intensity of light falling thereon increases. Each of cells 13 and 15 emits a light signal, the intensity of which increases as the voltage applied to the cell increases. Thus, electroluminescent cell 13 illuminates photoconductor 14 causing its resistance to be relatively low compared with that of photoconductor 16, which has little if any light falling upon it. Since photoconductor 14 has a relatively low resistance a low voltage is coupled through lead 17 to electroluminescent cell 15 to maintain it substantially dark. Photoconductor 16 is thus maintained unilluminated with relatively high resistance, preventing electroluminescent cell 15 from lighting. This condition is designated the first of the two stable states of the network. In the designated second stable state of this network electro-optical pair 12 is "on" and electro-optical pair 11 is maintained "off" by feedback through lead 17 in a manner similar to that described with reference to the above-mentioned first stable state.

The network of FIG. 1 when operating in one of its two stable states is adapted to be switched to its other stable state upon application of a light signal or an electrical signal to the "off" electro-optical pair. Consider again the above-assumed first stable state operation in which electro-optical pair 12 is "off." Upon application of a light signal to photoconductor 16 from a source external to electro-optical pair 12 the resistance of photoconductor 16 decreases. As a result of this resistance decrease the voltage which is applied to electroluminescent cell 15 increases. This change in electrical condition of electro-optical pair 12 is coupled through lead 17 and tends to reduce the voltage across electroluminescent cell 13, which thereupon decreases its light output and correspondingly increases the resistance of photoconductor 14. If the external source of radiation applied to photoconductor 16 is maintained for a sufficient duration the current drawn by electro-optical pair 12 continues to increase toward its stable "on" value and electro-optical pair 11 switches to the "off" condition. A detailed analysis of the operation and switching of this bistable network is provided later.

Electrical circuit branches 22 and 23 connected in parallel across electro-optical pairs 11 and 12 provide one means for triggering the bistable network from one state to the other. Branch 22 comprises an electroluminescent cell 24, a photoconductor 25, and a photoconductor 26 connected in series. Electroluminescent cell 24 is positioned in radiation-coupled relationship with photoconductor 16. Photoconductor 25 is positioned in radiation-coupled relationship with electroluminescent cell 13. Branch 23 comprises an electroluminescent cell 27, a photoconductor 28, and a photoconductor 29 connected

in series. Electroluminescent cell 27 is positioned in radiation-coupled relationship with photoconductor 14. Photoconductor 28 is positioned in radiation-coupled relationship with electroluminescent cell 15. Photoconductors 26 and 29 are adapted to receive light radiation signals from a common input trigger source 30, which may be, for example, another electroluminescent cell.

Assume, once again, that electro-optical pair 11 is "on." In this condition, photoconductor 25 is illuminated by electroluminescent cell 13, but photoconductor 28 remains unilluminated since electroluminescent cell 15 is dark. In the absence of a radiation input trigger signal, photoconductors 26 and 29 have high values of resistance, and under this condition electroluminescent cells 24 and 27 are dark. Upon application of a radiation input trigger signal to photoconductor 26 its resistance is decreased and a large proportion of the voltage of source 21 is applied to electroluminescent cell 24. Electroluminescent cell 24 thereupon lights, illuminates photoconductor 16, and initiates the change of operational state of the bistable network to its above defined second stable state. It is desirable that the change of impedance of photoconductor 25 require a time relatively long compared to the time necessary for the bistable circuit to switch from one stable state to the other. This response time requirement of photoconductor 25 exists because electroluminescent cell 24 should remain lighted until the change of state has been completed, despite the fact that electroluminescent cell 13 is growing dimmer. Likewise, photoconductor 28 must have a relatively slow rate of change of impedance similar to that of photoconductor 25.

Application of the same or simultaneous radiation input trigger signal to photoconductor 29 when the bistable network is in its first stable state will, however, not affect electroluminescent cell 27 because of the high resistance of unilluminated photoconductor 28. Because of the slow rate of change of resistance of photoconductor 28 its impedance will not become sufficiently low for electroluminescent cell 27 to light during the switching interval.

When the bistable network is in its second stable state the application of a radiation input trigger signal to photoconductor 29 will switch the bistable network to its first stable state in a manner similar to that described above.

From the foregoing description it will be noted that in the embodiment shown in FIG. 1, the radiation input trigger signals are applied simultaneously from a common source 30 to photoconductors 26 and 29, and the circuit will change its state of operation each time the trigger signals are applied. Thus, a particular state of operation of the network is repeated for every two input trigger signals, and the network acts as a counter element or an element for dividing by two a series of input trigger signals.

A useful output from the network may be derived as either an electrical or an optical signal from several points. For example, the voltage across, and the light output of, electroluminescent cell 13 are relatively large for every two input trigger signals, and either this voltage or light may be applied as an input signal to a similar succeeding bistable network or to any utilization device.

FIGURE 2 is a modified embodiment of the circuit diagram shown in FIG. 1 and includes photoconductor 52 which is common to the electrical circuit branches 22' and 23' employed for changing the state of the bistable network.

As before, one of photoconductors 25 and 28 is illuminated in accordance with the state of operation of the bistable network. Upon application of a radiation input trigger signal to photoconductor 52 from a trigger source 53, the electrical circuit branch whose photoconductor was illuminated will draw a relatively heavy current through photoconductor 52, and the electroluminescent cell of this

heavily conducting branch will light and initiate the change of state in the manner previously described.

FIGURE 3 illustrates a circuit as in FIG. 1 modified to function only as a register element, wherein two independent input triggering means are each provided to switch the network to a respective one of its two stable states. FIGURE 3 includes the bistable network comprising electro-optical pairs 11 and 12 connected in parallel across direct current source 21 and interconnected by lead 17. Electrical circuit branches 54 and 55 are connected in parallel across electro-optical pairs 11 and 12. Branch 54 comprises an electroluminescent cell 56 and a photoconductor 57 connected in series. Electroluminescent cell 56 is positioned in radiation-coupled relationship with photoconductor 14 of electro-optical pair 11. Branch 55 comprises an electroluminescent cell 58 and a photoconductor 59 connected in series. Electroluminescent cell 58 is positioned in radiation-coupled relationship with photoconductor 16 of electro-optical pair 12. Photoconductor 57 is adapted to receive a first radiation input trigger signal from a trigger source 60. Photoconductor 59 is adapted to receive a second radiation input trigger signal from trigger source 61. Assume that the bistable network is operating in its first stable state in which electro-optical pair 11 is "on" and electro-optical pair 12 is "off." Application of a radiation input trigger signal to photoconductor 59 decreases the resistance thereof and increases the voltage applied to electroluminescent cell 58, thereby increasing its light output. The light of electroluminescent cell 58 falls on photoconductor 16 and initiates the change of operational state of the bistable network to its second stable state in which pair 12 is "on" and pair 11 is "off." Similarly, if the bistable network is operating in the second stable state, application of a radiation input trigger signal to photoconductor 57 causes the network to change to its first stable state. However, if the bistable network is operating in its second stable state and a radiation input trigger signal is applied to photoconductor 59, the light delivered by electroluminescent cell 58 to photoconductor 16 of the "on" electro-optical pair will merely supplement the light supplied by electroluminescent cell 56, and no change of state will occur. Thus, upon application of a radiation input trigger signal to photoconductor 57 the bistable network switches into or remains in its first stable state. Upon application of a radiation input trigger signal to photoconductor 59 the bistable network switches into or remains in its second stable state. Hence, the network of FIG. 3 is useful as a register element, wherein one of the stable states represents 1 and the other stable state represents 0. The radiation input trigger signal which causes the network to operate in the 1 state is indicative of a 1 input and the radiation input trigger signal which causes the network to operate in the 0 state is indicative of a 0 input.

Constant current feedback

A different technique for triggering the bistable network of this invention is shown in FIG. 4. Electro-optical pairs 62 and 63 are connected in parallel across a source of electrical energy, such as constant current source 64. Electro-optical pair 62 comprises a photoconductor 65 and an electroluminescent cell 66 connected in series. Electro-optical pair 63 comprises a photoconductor 67 and an electroluminescent cell 68 connected in series. A connection point 69 is provided between photoconductor 65 and electroluminescent cell 66 and a connection point 70 between photoconductor 67 and electroluminescent cell 68. A pair of series-connected photoconductors 71 and 72 is connected between points 69 and 70. Photoconductors 71 and 72 are positioned in radiation-coupled relationship with respective electroluminescent cells 68 and 66. The network is switched from one stable state to another upon application of a radiation input trigger signal from a trigger source 74 to a photoconductor 73 connected between the photoconductor ends of electro-optical pairs

62 and 63 and the common connection point of the series-connected photoconductors 71 and 72.

In the operation of the circuit of FIG. 4, current I from source 64 substantially divides between electro-optical pairs 62 and 63. The network is in its designated first stable state when electro-optical pair 62 is "on" and in its designated second stable state when electro-optical pair 63 is "on."

Assume now that the circuit is in its first stable state. Electroluminescent cell 66 is lighted and illuminates photoconductors 65 and 72. Electroluminescent cell 68 is dark and consequently photoconductors 67 and 71 are not illuminated and have a high resistance. The greater portion of current I therefore flows through electro-optical pair 62. Upon application of a radiation input trigger signal from trigger source 74 to photoconductor 73, a relatively low resistance is provided for current flow through photoconductor 73 and 72 to electroluminescent cell 68. The impedance of photoconductors 72 and 73 in parallel with the decreasing impedance of photoconductor 67 provide an impedance which is low as compared with that of photoconductor 65. The light output of electroluminescent cell 68 thereupon tends to increase and the resistance of radiation-coupled photoconductor 67 tends to decrease so that a greater portion of current I is drawn through electro-optical pair 63. The increase of current through electro-optical pair 63 is accompanied by a decrease in current through electro-optical pair 62, a consequent decrease in the light output of electroluminescent cell 66, and a consequent increase in the resistance of photoconductor 65. The current in electro-optical pair 63 continues to increase and that in electro-optical pair 62 continues to decrease while the radiation input trigger signal is applied to photoconductor 73, until electro-optical pair 63 has reached its stable "on" condition and electro-optical pair 62 has reached its stable "off" condition. At this time the circuit is in its second stable state. Upon application of the next radiation input trigger signal to photoconductor 73, passage of current through photoconductor 71, which has been illuminated by electroluminescent cell 68, serves to change the state of the network once again. Thus, the network of FIG. 4 is changed from one stable state to the other by application of an electrical signal to the "off" electro-optical pair.

Photoconductors 71 and 72 must have response times relatively slow compared to the time necessary for the network to switch from one stable state to the other in order that their resistances remain either high or low sufficiently long for the switching operation to reach completion.

A resistor 75 is included in series relationship with electro-optical pair 63 and serves to effectuate resetting or initial setting of the bistable circuit upon the respective removal and reapplication or initial application of the source of current. With the source of current 64 removed, both electro-optical pairs 62 and 63 are "off." When current source 64 is applied to the network, current increases more rapidly in electro-optical pair 62 than in electro-optical pair 63. Thus the network will assume its first stable state. In a similar manner a resistor connected in series with one of the electro-optical pairs of FIGS. 1-3 will insure that these networks assume a predetermined initial stable state or return to that stable state upon removal and reapplication of the voltage source 21.

In the above description of the operation of the circuit of FIG. 4 it may be seen that electro-optical pairs 62 and 63 connected in parallel to constant current source 64 constitute a bistable network. Feedback is provided by the high internal impedance of constant current source 64. It is within the scope of this invention to provide other means for electrically triggering this bistable network than that shown in FIG. 4. Furthermore, this triggering means may be applied so that the network

operates as either a register element or as a counter element.

Analysis of operation

A theory of the operation of the bistable apparatus of this invention, as presently understood, and a method of determining certain circuit parameters will now be described.

The circuit of FIGURE 6 is a schematic representation of a photoconductor 81 and an electroluminescent cell 82 connected in series across a source 83. For purposes of the following development, source 83 will be assumed to be a source of direct voltage. However, the invention is not so limited, and the source may be either alternating or direct and either constant voltage, constant current or a combination of both. The solutions following are all for the steady state condition. Transients developed during switching are presumed to have disappeared.

Photoconductor 81 is shown comprising two parallel resistors; R_D , the photoconductor resistance when unilluminated, and R_P , the photoconductor resistance when illuminated. When the photoconductor is unilluminated, $R_D \ll R_P$. When the photoconductor is substantially illuminated, $R_D \ll R_P$. Electroluminescent cell 82 is shown comprising the parallel capacitor C and resistance R_E . Photoconductor 81 and electroluminescent cell 82 are positioned in radiation-coupled relationship and thereby constitute an electro-optical pair.

It will now be shown that the electro-optical pair, connected as in FIG. 6, is adapted to operate in either one of two stable states. The voltage, E, across the electro-optical pair when substantial illumination falls on photoconductor 81 is

$$(2) \quad E = I(R_P + R_E)$$

However, R_P depends on the light delivered by electroluminescent cell 82

$$(3) \quad R_P = \frac{K_1}{B}$$

where K_1 is a constant and B is the brightness of the electroluminescent cell. B depends on the voltage V_c applied to the cell and was given in Equation 1

$$(1') \quad \frac{B}{R_P} = \frac{kV_c^n}{R_E}$$

Substituting Equation 1 in (3)

$$(4) \quad R_P = \frac{K_1}{kV_c^n}$$

The solutions to follow may be more easily interpreted if an arbitrary voltage V_0 is defined as the voltage across the cell when the photoconductor and cell resistances are equal:

$$(5) \quad V_0 = V_c$$

when

$$R_P = R_E$$

Substituting (5) in Equation 4

$$(6) \quad \frac{K_1}{k} = R_E V_0^n$$

and Equation 4 becomes

$$(7) \quad R_P = R_E \left(\frac{V_0}{V_c} \right)^n$$

Substituting Equation 7 in (2)

$$(8) \quad E = I R_E \left[1 + \left(\frac{V_0}{V_c} \right)^n \right]$$

or

$$(9) \quad I = \frac{E}{R_E \left[1 + \left(\frac{V_0}{V_c} \right)^n \right]}$$

Two distinct conditions of operation may be noted in

Equation 9. The first condition occurs when I is large and the photoconductor is brightly illuminated due a large V_c ; then $V_c \gg V_0$ and

$$(10) \quad I \approx \frac{E}{R_E}$$

This portion of the curve of I vs. E representing Equation 9 approximates a straight line with positive slope, and is shown in FIG. 7. In this curve portion most of the voltage E appears across the electroluminescent cell.

The second condition of operation of Equation 9 occurs when I is small and the photoconductor is dimly illuminated; then $V_c \ll V_0$ and

$$(11) \quad I = \frac{E}{R_E} \left(\frac{V_c}{V_0} \right)^n$$

Since $V_c = I R_E$, Equation 11 may be rewritten as

$$(12) \quad I^{n+1} = \frac{V_0^n}{E R_E^{n+1}}$$

This portion of the curve of I vs. E has a negative slope, as shown in FIG. 7, with E increasing as I decreases. However, the voltage across the electro-optical pair does not increase without limit as I decreases. The dark resistance, R_D , imposes a limit on this rise of voltage, as shown by the lower straight line of FIG. 7. The equation of this line is

$$(13) \quad I = \frac{V}{R_D}$$

and the peak voltage E_M observed across the pair with diminishing current is given approximately by the intersection of the two curves of Equations 12 and 13.

The minimum voltage, E_v , attained when the circuit is operating in accordance with Equation 8 is obtained by differentiating this equation with respect to I and setting equal to 0. There is obtained

$$(14) \quad I R_E = V_c = (n-1)^{1/n} V_0$$

Substituting Equation 14 in (8)

$$(15) \quad E_v = V_0 n (n-1)^{\frac{1}{n}-1}$$

For typical values of n:

n	E_v
2	$2.00 V_0$
3	$1.89 V_0$
4	$1.75 V_0$
5	$1.65 V_0$

It is seen that for a given circuit, a larger value of n yields a lower E_v . Furthermore, E_v is always greater than V_0 , so that the source voltage 83 should be greater than V_0 .

If a source voltage to E, which is greater than E_v , but less than E_M , is applied to the electro-optical pair of FIG. 7, the circuit will operate in either one of the two stable states shown as the intersections A and B in the figure. The intersection of the vertical broken line representing E_1 with the negatively sloping portion of the characteristic is unstable, and is merely incidentally traversed in the transfer of the network from one state to another. This negative sloping portion of the I-E characteristic is a necessary condition for bistability, and only exists if n in Equation 1 is greater than 1. This is shown incidentally in Equation 14, wherein no solution is obtained for $n \leq 1$.

The transfer of the operation of the electro-optical pair from one stable state to another by electrical triggering is illustrated in FIGURE 8. Assume that when the pair is operating at one stable point A, with corresponding current, a signal voltage is applied to the circuit so that the total voltage becomes greater than E_1 . The current rises along the lower straight-line portion, limited

primarily by R_D . When E becomes greater than E_M , the current jumps to the upper straight-line portion and continues to increase as the signal voltage is further increased. When the signal voltage is removed the current falls to the stable point B, and the circuit is operating in its other stable state. If the voltage E is now reduced below E_1 by a negative signal voltage, the current falls along the upper straight-line portion, limited primarily by R_E . When E becomes less than E_V , the current drops to the lower straight-line portion and continues to decrease as the signal voltage is further reduced. When the signal voltage is removed the current rises to the stable point A, and the circuit is operating in its original stable state.

FIGURE 9 illustrates the transfer of the operation of the electro-optical pair from one stable state to another by radiation triggering. Curve S shows the operation of the circuit with no radiation applied to photoconductor 81 other than that supplied by cell 82. Assume that the pair is operating at stable point A, which is the state in which the photoconductor is unilluminated by the electroluminescent cell of the electro-optical pair. Let an external source apply radiation to photoconductor 81, in the manner that cell 27 directs radiation on photoconductor 14 of FIG. 1. The effect of such an increase in illumination on photoconductor 81 with no increase in electroluminescent cell voltage is similar to an increase in the exponent n of Equation 1. As n increases, E_V falls, in accordance with Equation 15. Thus, curve S tends to shift to the left in FIG. 8 as the external radiation increases. Correspondingly, the current drawn increases along the lower portion of the curve. When the external radiation becomes sufficient for E_M to fall below E_1 , the current jumps to point C of the upper straight-line portion of the operating curve; which at this time is shown as the broken-line curve S'. Upon removal of the external source of radiation, the operating curve again becomes curve S, but the current falls only to point B, and the circuit is operating in its other stable state.

The foregoing analysis has demonstrated that each electro-optical pair is a bistable device and by suitable triggering is adapted to be transferred from one of its stable states to the other. The preceding description showed that two such electro-optical pairs may be suitably interconnected so that a bistable apparatus is obtained, which is readily transferrable from either of its two stable states to the other by electrical or radiation triggering. A simple extension of the above analysis to the preceding circuits will demonstrate that their operation may be considered to be a combination of radiation and optical triggering. Thus, in FIG. 1, assume that the network is in its first stable state; that is, pair 11 is on and pair 12 is off. Pair 11 is operating at point B and pair 12 at point A of FIG. 8. Upon application of a radiation trigger signal from cell 24 to photoconductor 16 of pair 12, a triggering action, as shown in FIG. 9, is initiated. Curve S shifts so that E_M' drops below E_1 and the current jumps to point C in pair 12. Simultaneously the voltage across the photoconductor 16 drops to a low value. This low voltage is coupled to electroluminescent cell 13. The effect of this low voltage coupled to cell 13 is similar to the application of a negative signal voltage to pair 11. Operation for pair 11 drops from point B to the lower curve portion in a manner shown in FIG. 8. Upon removal of the trigger signal of cell 24 from photoconductor 16, the current in pair 12 falls to point B and

that in pair 11 rises to point A. Hence, the apparatus is transferrable from one stable state to another by external radiation triggering.

While the principles of the invention have now been made clear in illustrative embodiments, there will be immediately obvious to those skilled in the art many modifications in structure, arrangement, proportions, the elements, materials, and components, used in the practice of the invention, and otherwise, which are particularly adapted for specific environments and operating requirements, without departing from those principles. The appended claims are therefore intended to cover and embrace any such modifications, within the limits only of the true spirit and scope of the invention.

What is claimed is:

1. A bistable network comprising at least three electrically distinct connection points, a first electroluminescent cell and a first photoconductor connected in parallel between the first and second of said points, a second electroluminescent cell and a second photoconductor connected in parallel between the second and third of said points, the first electroluminescent cell and the second photoconductor being further positioned in radiation-coupled relationship, the second electroluminescent cell and the first photoconductor being further positioned in radiation-coupled relationship, third and fourth electroluminescent cells, the third electroluminescent cell and the second photoconductor being further positioned in radiation-coupled relationship, the fourth electroluminescent cell and the first photoconductor being further positioned in radiation-coupled relationship, a source of steady electrical energy, and means for connecting said source to said first and third points.

2. A bistable network as in claim 1 further including first triggering means coupled to said third electroluminescent cell and adapted to apply an input trigger signal thereto, and second triggering means coupled to said fourth electroluminescent cell and adapted to apply an input trigger signal thereto.

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