

PATENT SPECIFICATION

(11) 1355 150

1355 150

- (21) Application No. 53226/72 (22) Filed 17 Nov. 1972
(31) Convention Application No. 202475 (32) Filed 26 Nov. 1971 in
(33) United States of America (US)
(44) Complete Specification published 30 May 1974
(51) International Classification H05B 33/00
(52) Index at acceptance
H2H 2B2 2B8



(54) LIGHT EMITTING DIODE DRIVER CIRCUIT

(71) We, HEWLETT - PACKARD COMPANY, a Corporation organised and existing under the laws of the State of California, United States of America, of 1501 Page Mill Road, Palo Alto, California, United States of America, do hereby declare the invention, for which we pray that a Patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates generally to a circuit for driving a light-emitting diode at an increased operating efficiency.

To emit light, a light-emitting diode must be forward-biased, at which time the diode has a very low resistance. In order to prevent irreversible damage or premature aging of the diode, it is necessary to limit the current therethrough. Heretofore, one method of achieving this has been to connect a current-limiting resistance element in series with the diode. However, power dissipation in the resistance element causes a reduction in overall circuit efficiency because only a portion of the power input to the circuit is applied to the diode to produce light. The value of the current-limiting resistance, and thus the power dissipated therein, can be reduced somewhat by lowering the diode supply voltage. The effectiveness of this technique is limited because as the supply voltage approaches the "knee" of the voltage-current diode curve, small variations in supply voltage result in large variation in peak diode current. Also, the conventional approach will not work for supply voltages lower than the diode knee voltage as diode conduction and light emission essentially cease at this point.

In the past, most diode driver circuits have continuously driven the associated diode. It has been found that diodes presently commercially available demonstrate greater efficiency in converting electrical energy to light energy when the diode is forward-biased in a pulsed mode rather than in a continuous mode of operation.

It is a principal object of the present in-

vention to provide a simplified light-emitting diode driver circuit having improved efficiency in power conversion and capable of being constructed at low cost.

The present invention provides a circuit comprising a light-emitting diode; inductance means coupled with said light-emitting diode; a voltage source; means for coupling said voltage source to the circuit provided by said light-emitting diode and inductance means, the coupling means including switching means for applying current pulses to said light-emitting diode, said switching means being operable in a first conductive mode to store energy in said inductance means, and in a second nonconductive mode to produce current flow from said inductance means through said light-emitting diode.

The inductance means may be coupled in parallel with said light-emitting diode and is preferably a signal inductor element having one end terminal connected to said switching means and the other end terminal connected to said voltage source, and preferably said coupling means is arranged to reverse-bias said light-emitting diode in said first conductive mode of operation.

Preferably said inductance means includes a transformer having primary and secondary windings, the primary winding being coupled by the coupling means to said voltage source, and the secondary winding being coupled to said light-emitting diode, thereby to provide d.c. isolation of said voltage source from said light-emitting diode.

Preferably said switching means is a transistor having control electrode means for receiving input pulses, and a pair of main current-carrying electrodes coupled between said voltage source, and said inductance means and light-emitting diode.

Preferably said light-emitting diode and said voltage source each have a pair of opposite polarity terminals, and the coupling means is arranged to couple each terminal of said light-emitting diode to the opposite polarity terminal of the voltage source. Said light-emitting diode has an anode electrode

and a cathode electrode and said voltage source has positive and negative output terminals, and the coupling means is arranged to connect said anode electrode to said negative output terminal through said switching means and to connect said cathode electrode to said positive output terminal.

In one of the illustrated embodiments of the invention, a transistor has an inductive load coupled to its collector and is driven by repetitively occurring pulses from an external source. A light-emitting diode is coupled across the inductive load. The transistor is pulsed to switch it into a conductive mode, thereby to build up energy in the inductive load. At this time, the diode is reverse-biased and consequently inactive. At the termination of a driving pulse, the energy stored in the inductive load produces a current flow through the diode, thereby to cause it to operate in a light-emitting mode. The repetition rate and magnitude of current pulses through the diode are adjusted so that the light pulses emitted thereby appear to be continuous to the eye of an observer.

Peak current through the diode is precisely controlled without the use of a resistor in series therewith. Such peak current control permits limiting of the current so as to prevent damage to or premature aging of the diode.

The over-all circuit increases the operating efficiency of the diode with a minimum number of components because there are no lumped resistive elements in series with the diode and because the diode is operated in a pulsed mode rather than in a continuous mode. A feature of this circuit arrangement is that the diodes and their associated driver circuits may easily be arrayed to form a large display.

There now follows a detailed description which is to be read with reference to the accompanying drawings of two circuits according to the present invention; it is to be clearly understood that these circuits have been selected for description to illustrate the invention by way of example and not by way of limitation.

Figure 1 is a schematic circuit diagram of one circuit according to the present invention including a plurality of light-emitting diodes;

Figures 2a-c are waveforms illustrating the operation of the circuit of Figure 1;

Figure 3 is a characteristic curve illustrating the relative light intensity from a light-emitting diode as a function of the peak driving current applied thereto;

Figure 4 is a schematic circuit diagram of another circuit according to the present invention.

Referring now to Figure 1, a pulse signal V_i from an external signal source is applied to an input terminal 12 and thence through a

resistor 14 to the base electrode of an NPN transistor 16. This resistor 14 serves to limit the base current of the transistor 16. The collector of the transistor 16 is connected through an inductive load 18 to a power source 10 providing a voltage V_b . A light-emitting diode 20 is coupled across the inductor 18 as shown. The negative return line from the power source 10 is connected to the emitter of the transistor 16.

In the absence of pulses at the terminal 12, the transistor 16 is cut off and no current flows in the circuit. At this time, the diode 20 is nonconducting and does not emit light.

The pulses applied to the terminal 12 are shown in Figure 2a. Each pulse is positive-going, and when applied to the base electrode of the transistor 16, the transistor is switched into a conducting mode of operation. This in turn causes the current in the inductor 18 to build up linearly with time to a peak value I_{pk} given by the expression

$$\frac{V_b t_p}{L},$$

where V_b is the voltage of the power source 10, t_p is the pulse duration, and L is the value of the inductor 18. During this current build-up time, the voltage at one end of the inductor 18, i.e., at the end point 19, is greater than the voltage at the other end point 21. The diode 20 is poled with its anode connected to the end point 21 and its cathode connected to the end point 19 so that the diode is maintained in a reverse-biased condition and conducts only a small leakage current. The direction of the input current I_i through inductor 18 and transistor 16 is shown in Figure 1.

At the end of the positive pulse applied to the terminal 12, the transistor 16 is switched into its nonconducting mode. Thereafter, the energy stored in the inductor 18 produces an output current flow through the diode 20, thereby to forward-bias the diode and drive it into a light-emitting mode of operation. The direction of this output current I_o applied through the diode 20 by the inductor 18 is shown in Figure 1.

Figure 2b illustrates the current through the inductor 18 is a time related function of the pulses applied to the terminal 12 and shown in Figure 2a. The input current I_i occurs during the time interval t_p corresponding to the duration of an input pulse. The inductor output current I_o occurs during the time interval t_i which begins at the end of the input pulse. The instantaneous current through the inductor 18 remains the same when the input pulse terminates and the transistor 16 switches from its conducting to its nonconducting state. Therefore, the initial value of the output current I_o through the diode 20 is the same as the

value of the input current I_i which was reached at the end of the input pulse.

The output current I_o through the diode 20 is shown in Figure 2c. Current I_o continues to flow at an approximately linearly decreasing value until it reaches zero. Thereafter, light emission ceases and the light-emitting diode driver circuit remains in a quiescent state with not current flowing therein until the arrival of the next positive pulse at the terminal 12.

The peak current through the diode 20 occurs at the time when the transistor 16 switches from its conducting to its nonconducting state. The peak current value is established by the parameters which determine the energy stored in the inductor 18. For a given supply voltage V_b and a given value of inductance for the inductor 18 the width t_p of the pulses comprising the signal V_s applied to the terminal 12 can be varied to optimize the peak current through the diode 20 for the amount of light produced thereby. By comparing Figures 2a and 2b, it can be seen that the greater the pulse width t_p the higher will be the peak current I_{pk} . A feature of the present invention is that the magnitude of peak current may be precisely controlled by adjusting the width of the input pulses. The use of a current-limiting resistor in series with the diode is unnecessary. The voltage source 10 may be coupled across the diode, as shown. In addition, the voltage V_b of the source 10 may be less than that at the "knee" of the characteristic voltage-current curve for the diode. More specifically, for a typical gallium arsenide phosphide light-emitting diode, the voltage at the "knee" of this curve is about 1.6 volts, i.e., the diode conducts heavily when the anode-cathode voltage is greater than 1.6 volts, whereas for lower anode-cathode voltages, the diode conducts only a small leakage current. Due to the effects of the inductor 18, the diode 20 will be driven into conduction even though the voltage V_b of the source 10 is less than 1.6 volts. A consequent advantage of this feature is that a conventional battery having a terminal voltage of the order of 1.4 volts may be used as the power source 10.

Figure 3 illustrates the relationship between the relative intensity of the light output from the diode 20 as a function of the peak current I_{pk} input thereto. The curve shown is for the case where the average current I_{av} through the diode 20 is constant. The average current I_{av} is held constant as the peak current I_{pk} increases by reducing the duty cycle of the pulses comprising the input signal V_s . The curve shown in Figure 3 is for a typical gallium arsenide phosphide light-emitting diode such as the No. 5082-7212 diode manufactured by the applicant company. Pulsed mode operation of the diode substantially increases the intensity of the light output from the diode compared to d.c. operation of the diode at the same average current. More specifically, d.c.

operation of the diode is shown at the point P_1 , where the peak current I_{pk} is the same as the average current I_{av} , both being equal to 0.5 milliamp. At the point P_1 the light output from the diode is 0.7 on the relative intensity scale. All other points on the curve of Figure 3 illustrate operation of the diode in the pulsed mode. At the operating point P_2 , for example, the current pulses through the diode have a peak current value of 60 milliamps. in order to hold the average current the same as in the d.c. operating case, the duty cycle of the current pulses is small, of the order of 0.9%. Such a duty cycle may be achieved, for example, when the current pulses are 2.5 microseconds long and occur at 280 microsecond intervals. It can be seen that the relative light intensity at the pulsed mode operating point P_2 is 4.4, which is about six times greater than the light intensity at the d.c. mode operating point P_1 .

The frequency of the pulses comprising the input signal V_s may be varied to establish the minimum number of pulses per second which are required to produce a visible display that appears steady without flickering.

The transistor 16 may be replaced by any suitable switching device capable of performing a like switching function. If a transistor is used, its β should be high and its $V_{CE(Sat)}$ be low to minimize resistive losses. The diode 20 should have a reverse breakdown voltage rating that is greater than the voltage V_b of the power source 10.

The circuit described above can be easily arrayed by coupling a plurality of such circuits in parallel. Figure 1 illustrates how additional diodes and their associated driver circuits may be coupled to the common power source 10. For example, as shown, a second diode 30 and its associated transistor 26 and inductor 28 are coupled in a circuit configuration which is the same as that described above with respect to the diode 20, transistor 16 and inductor 18. The peak current through each diode is dependent on the pulse width t_p of the pulses comprising the driving signal V_s . Since the same type of driving signal is applied to all diode circuits, the peak current through each will be the same. Consequently, the intensity of the light output from each will be the same for identical diodes and the display produced by the plurality of diodes in the array will be of uniform intensity.

Figure 4 illustrates another circuit according to the present invention. This circuit is the same as that in Figure 1 except that the inductance 18 is replaced with a transformer having a primary winding 44 and a secondary winding 45. This circuit may be used in applications requiring d.c. isolation of the diodes from the power source 10. In Figure 4, the diode 20 is coupled across the secondary winding 45. Current from the power source 10 through the transistor 16 causes energy to

build up in the primary winding 44. This energy is transferred through the secondary winding 45 to the diode 20. The diode is poled so that when the transistor 16 switches to its nonconducting state in response to the end of the input pulse at the terminal 12, the output current I_o flows therethrough. The current through the diode 20 is the same shape as that shown in Figure 2c described above; however, the magnitude thereof will depend on the transformer winding ratio. For example, when a step-up transformer is used, small currents switched by the transistor 16 will cause a large current flow through the diode. As shown in Figure 4, a plurality of diode circuits may be connected in parallel to the power source 10. The array thus formed is similar to that described with respect to Figure 1.

20 WHAT WE CLAIM IS:—

1. A circuit comprising: a light-emitting diode; inductance means coupled with said light-emitting diode; a voltage source; means for coupling said voltage source to the circuit provided by said light-emitting diode and inductance means, the coupling means including switching means for applying current pulses to said light-emitting diode, said switching means being operable in a first conductive mode to store energy in said inductance means, and in a second nonconductive mode to produce current flow from said inductance means through said light-emitting diode.

2. A circuit according to claim 1 wherein said inductance means is coupled in parallel with said light-emitting diode and is a single inductor element having one end terminal connected to said switching means and the other end terminal connected to said voltage source, and wherein said coupling means is arranged to reverse-bias said light-emitting diode in said first conductive mode of operation.

3. A circuit according to claim 1 wherein said inductance means includes a transformer having primary and secondary windings, the primary winding being coupled by the coupling means to said voltage source, and the secondary winding being coupled to said light-emitting diode, thereby to provide d.c. isolation of said voltage source from said light-emitting diode.

4. A circuit according to any one of claims 1 to 3 wherein said switching means is a transistor having control electrode means for receiving input pulses, and a pair of main current-carrying electrodes coupled between said voltage source, and said inductance means and light-emitting diode.

5. A circuit according to claim 1 wherein said light-emitting diode and said voltage source each have a pair of opposite polarity terminals, and wherein the coupling means is arranged to couple each terminal of said light-emitting diode to the opposite polarity terminal of the voltage source.

6. A circuit according to claim 5 wherein said light-emitting diode has an anode electrode and a cathode electrode and said voltage source has positive and negative output terminals, and wherein the coupling means is arranged to connect said anode electrode to said negative output terminal through said switching means and to connect said cathode electrode to said positive output terminal.

7. A circuit according to claim 1 substantially as hereinbefore described with reference to the accompanying drawings.

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