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Lee et al.

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(54) **DIMMING CONTROL CIRCUIT FOR LIGHT-EMITTING DIODES**

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G05F 1/00 (2006.01)

(52) **U.S. Cl.** **315/291**; 315/308; 315/360; 315/224; 315/169.3; 315/DIG. 4

(58) **Field of Classification Search** 315/291, 315/307, 308, 312, 294, 360, 362, 193, 169.3, 315/DIG. 4; 363/89, 90, 126; 362/800
See application file for complete search history.

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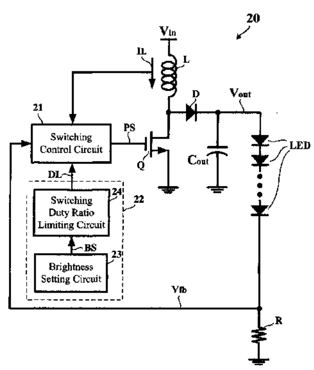
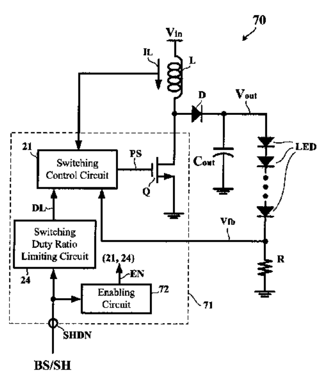
(57) **ABSTRACT**

A dimming control circuit generates a dimming control signal for determining brightness of at least one light-emitting diode. The dimming control signal has a plurality of bright-dark cycles, each of which consists of a bright phase and a dark phase. The bright phase starts with an adaptive rising portion. The adaptive rising portion restricts the brightness of the at least one light-emitting diode to increase gradually from zero.

10 Claims, 8 Drawing Sheets





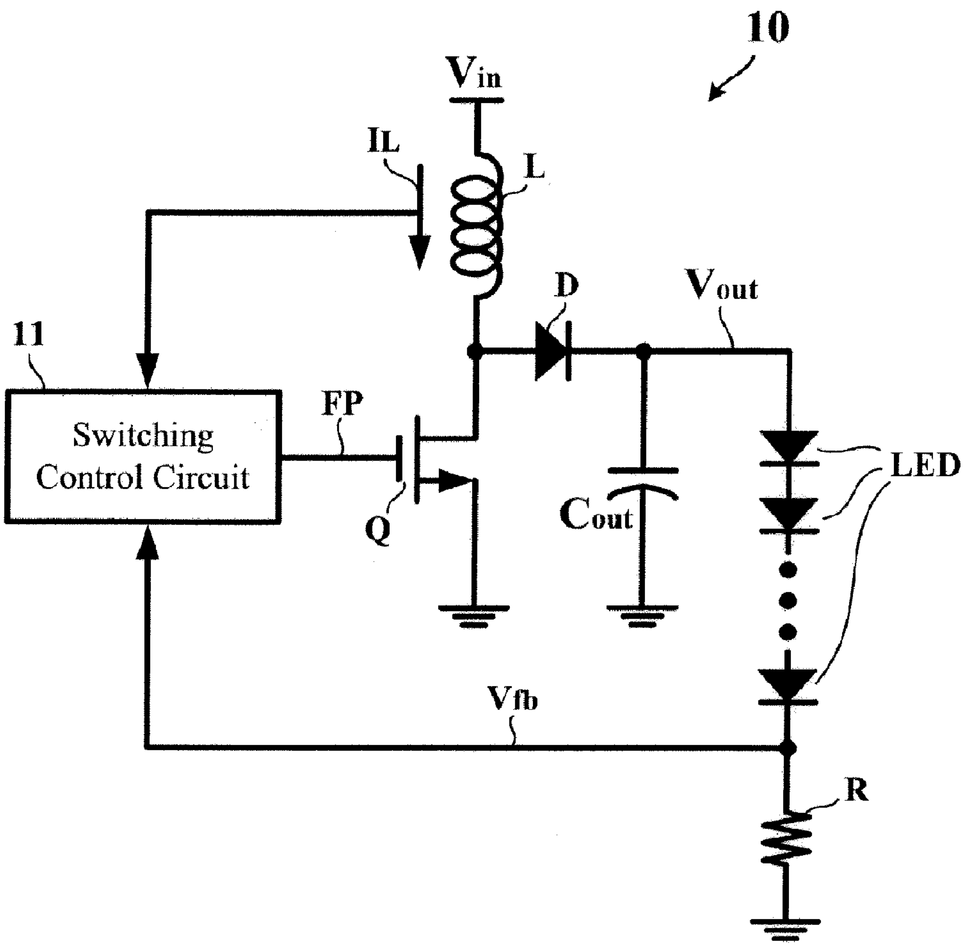


FIG. 1
(Prior Art)

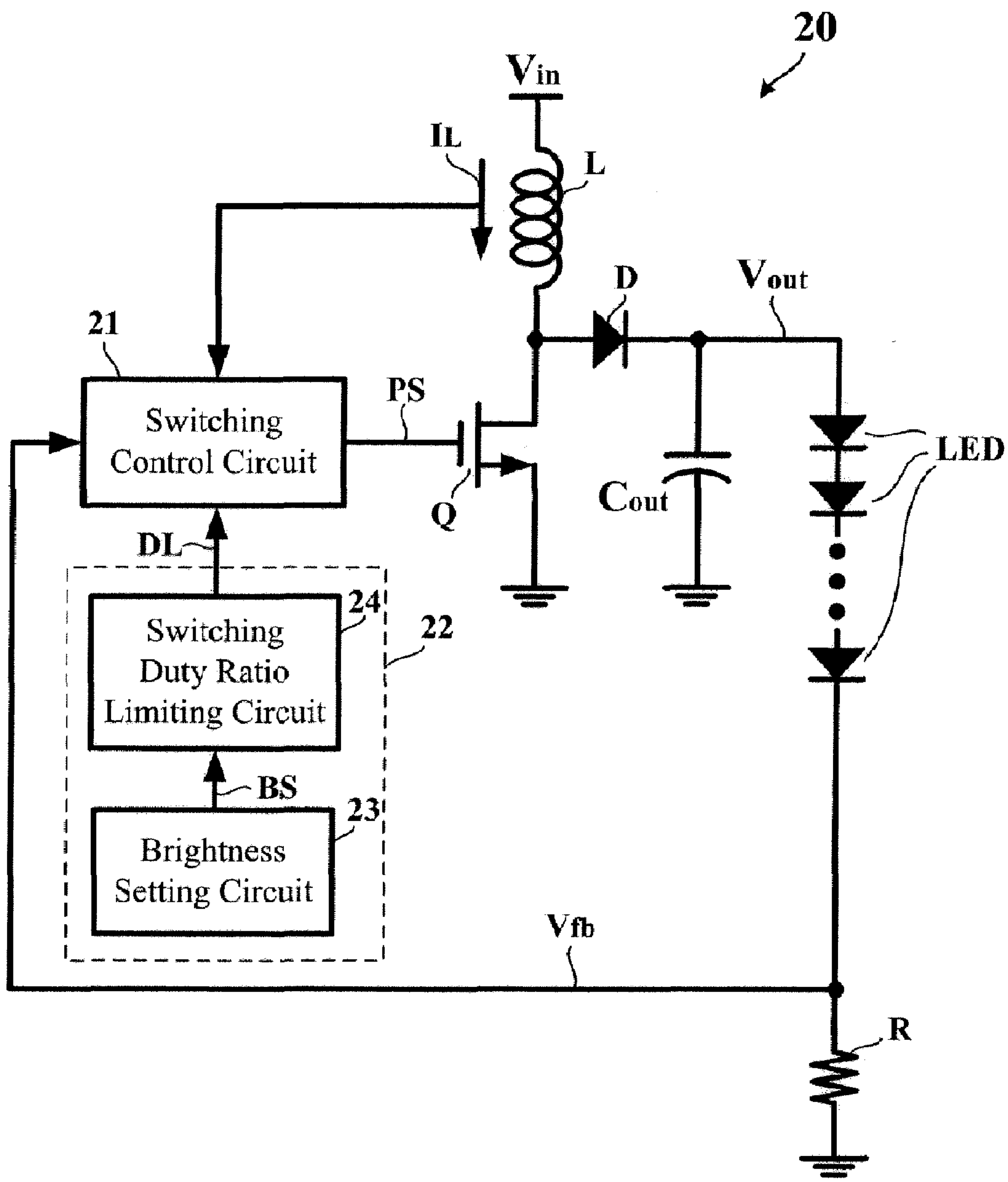

20
Vin
IL
L
D
Vout
21
PS
Switching Control Circuit
Q
Cout
LED
DL
24
Switching Duty Ratio Limiting Circuit
22
BS
23
Brightness Setting Circuit
Vfb
R

FIG. 2

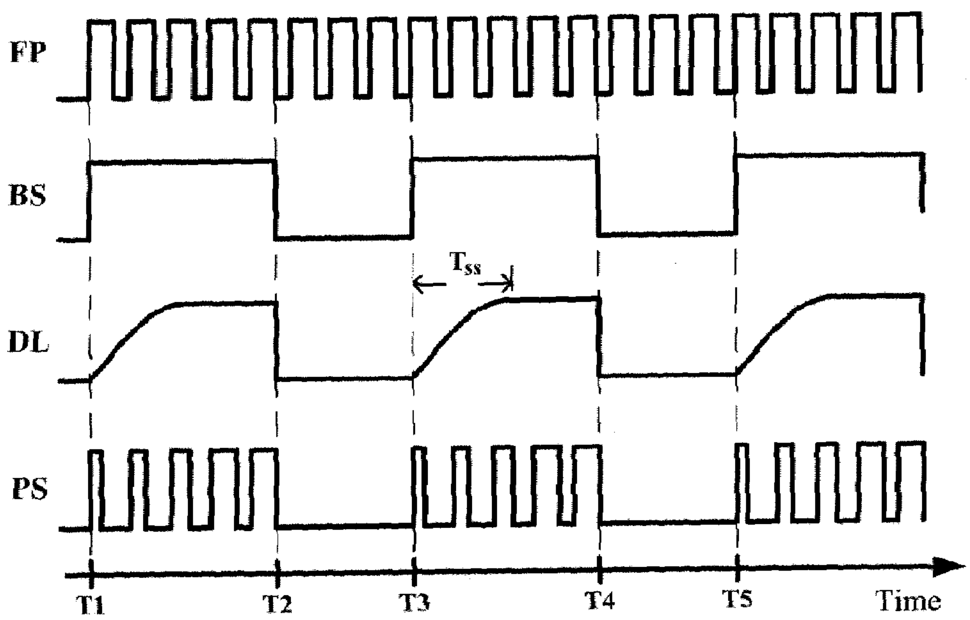


FIG. 3(A)

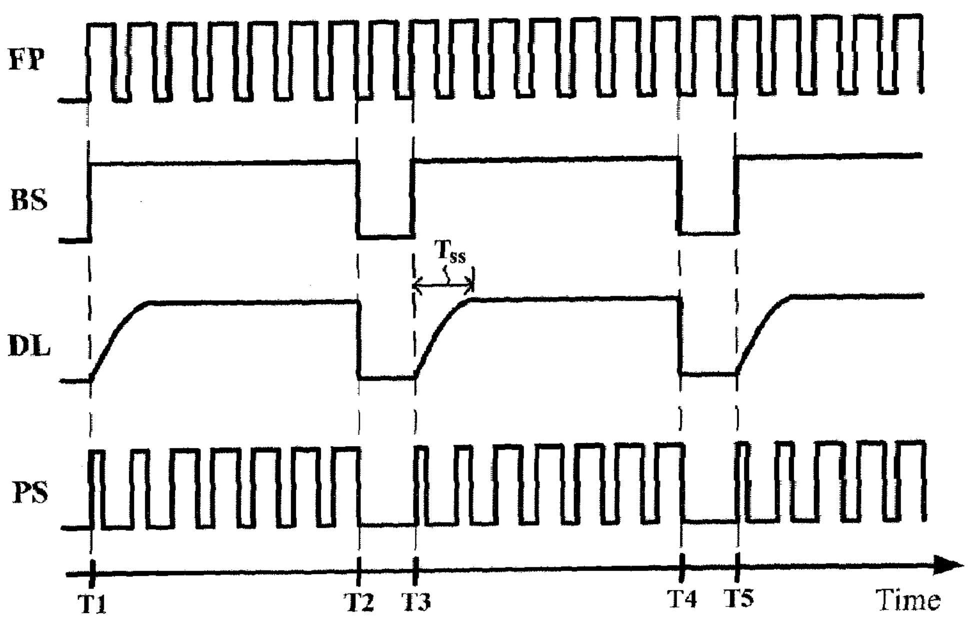


FIG. 3(B)

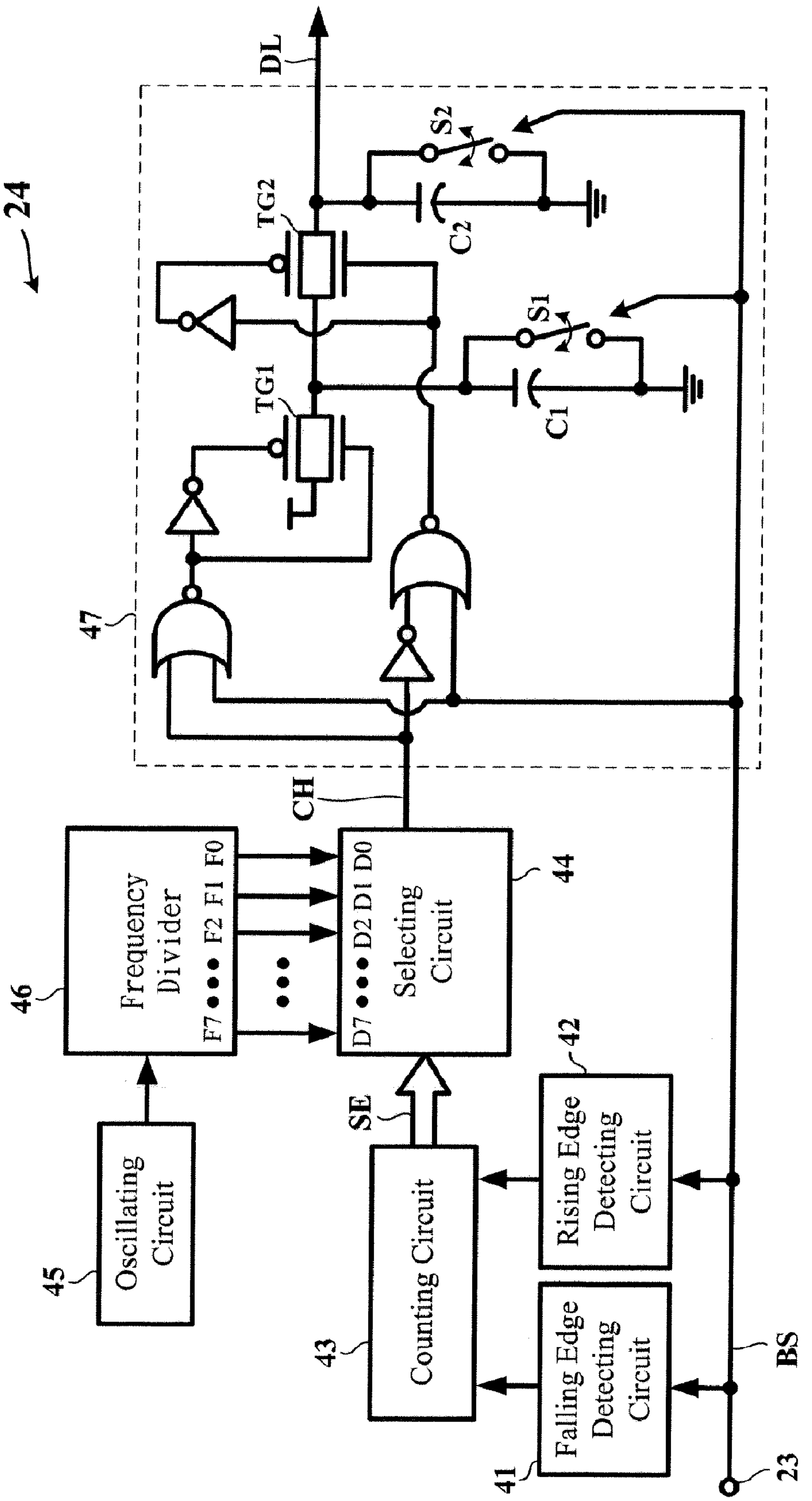

24
DL
TG2
S2
C2
TG1
S1
C1
47
CH
46
Frequency Divider
F7 ••• F2 F1 F0
D7 ••• D2 D1 D0
Selecting Circuit
44
45
Oscillating Circuit
SE
42
Rising Edge Detecting Circuit
43
Counting Circuit
41
Falling Edge Detecting Circuit
BS
23

FIG. 4

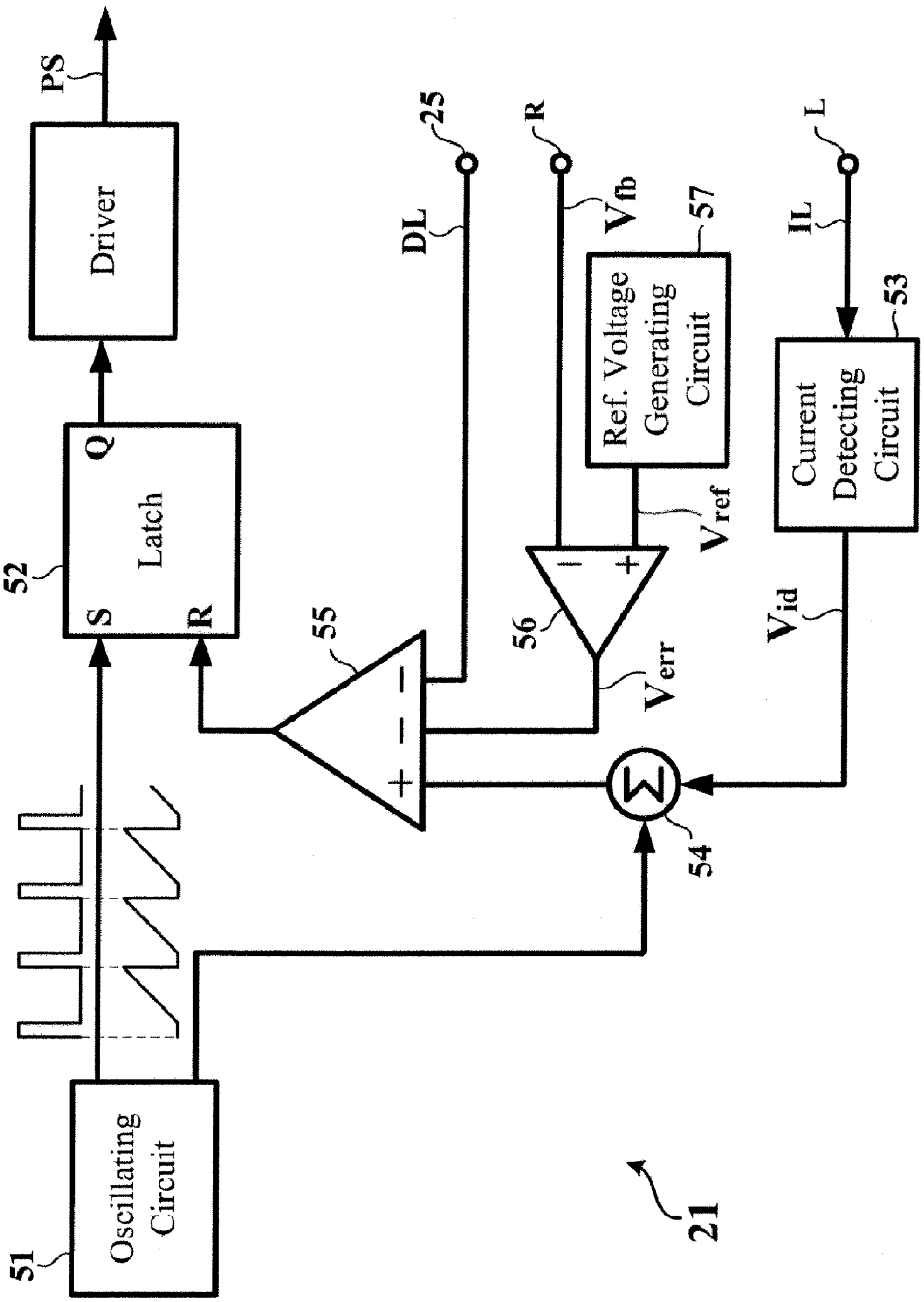

PS
Driver
Q
Latch
52
S
R
DL
25
R
V_{fb}
57
Ref. Voltage Generating Circuit
V_{ref}
L
IL
53
Current Detecting Circuit
55
56
V_{err}
V_{id}
54
Oscillating Circuit
51
21

FIG. 5

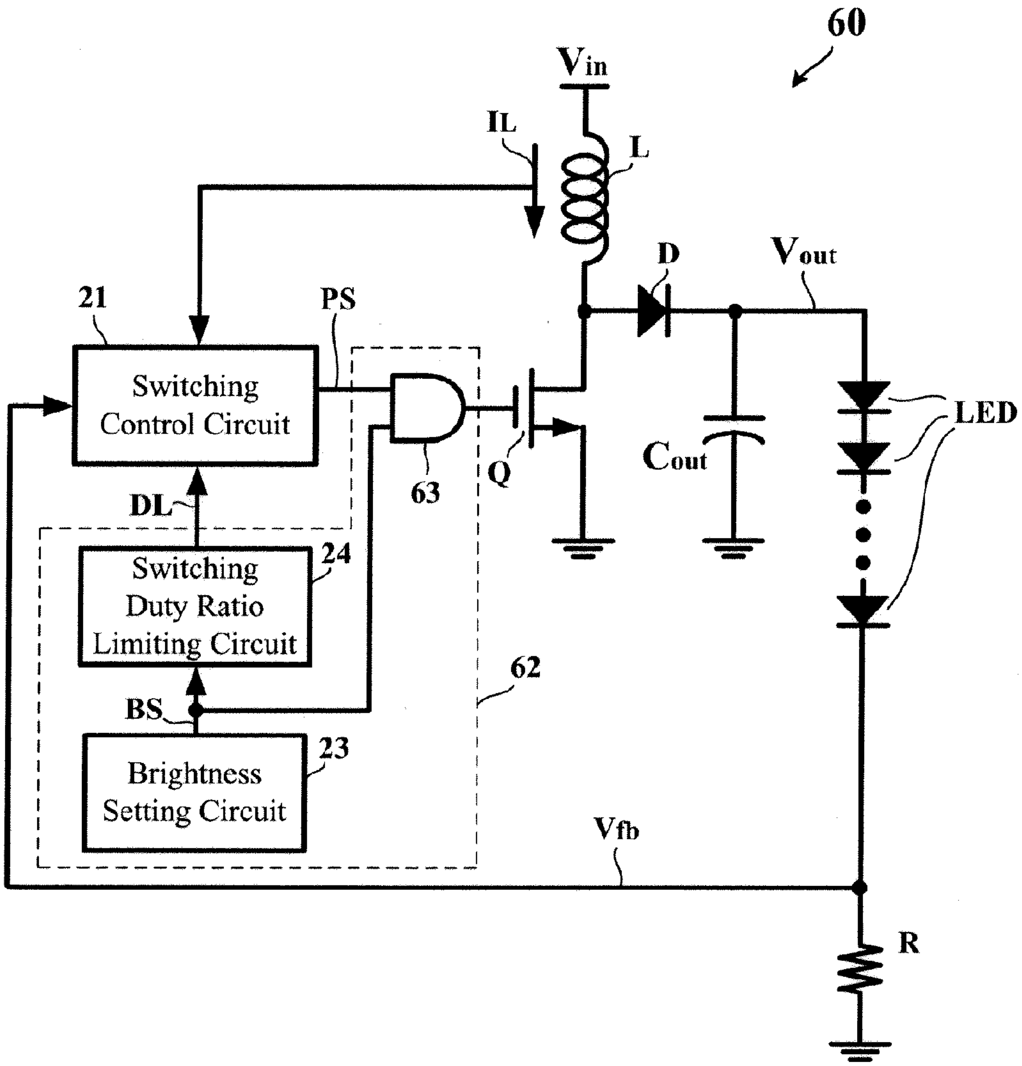

60
Vin
IL
L
D
Vout
21
PS
Switching Control Circuit
LED
Q
Cout
63
DL
Switching Duty Ratio Limiting Circuit
24
BS
62
23
Brightness Setting Circuit
Vfb
R

FIG. 6

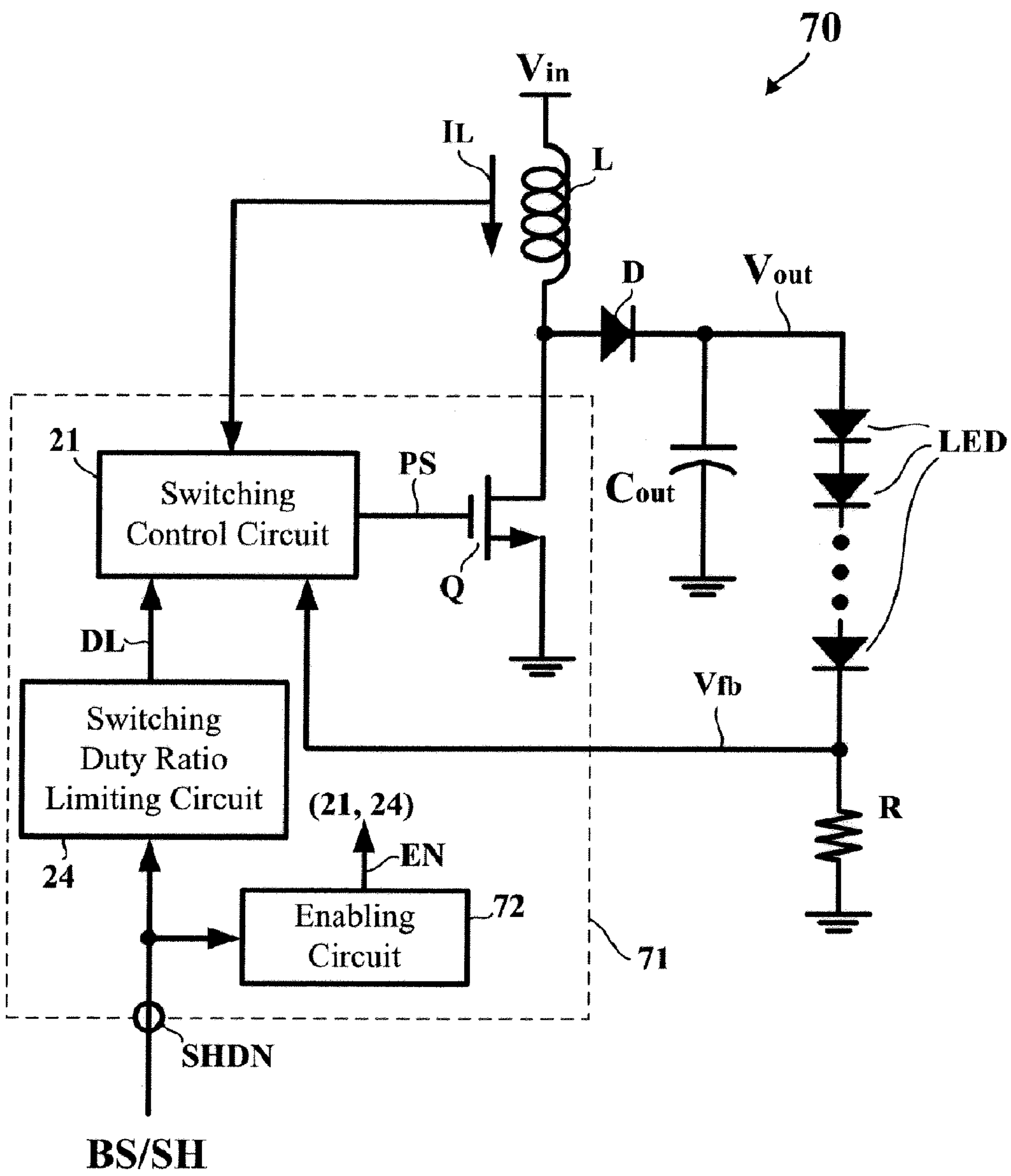

70
Vin
IL
L
D
Vout
21
Switching
Control Circuit
PS
Q
Cout
LED
DL
Switching
Duty Ratio
Limiting Circuit
Vfb
(21, 24)
EN
R
24
Enabling
Circuit
72
71
SHDN
BS/SH

FIG. 7

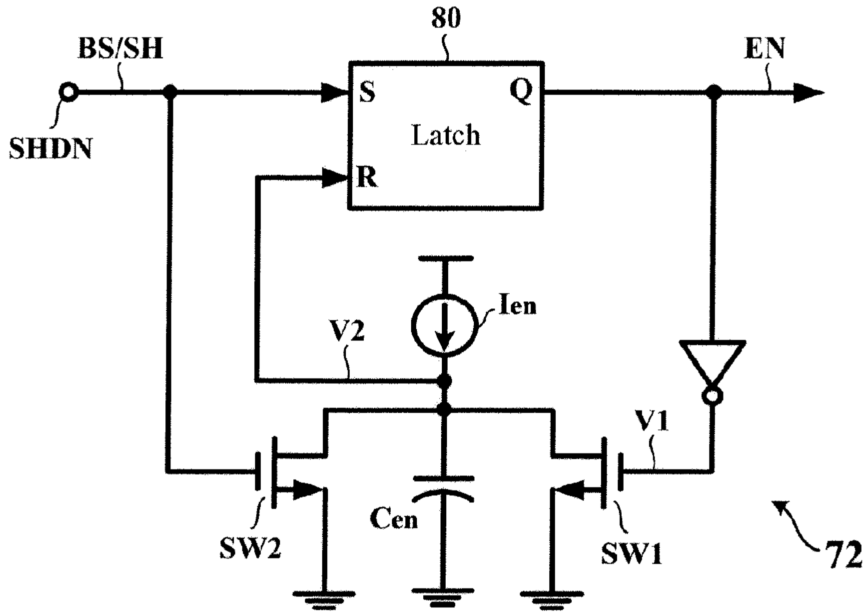

80
BS/SH
EN
S
Q
Latch
R
SHDN
Ien
V2
V1
Cen
SW2
SW1
72

FIG. 8

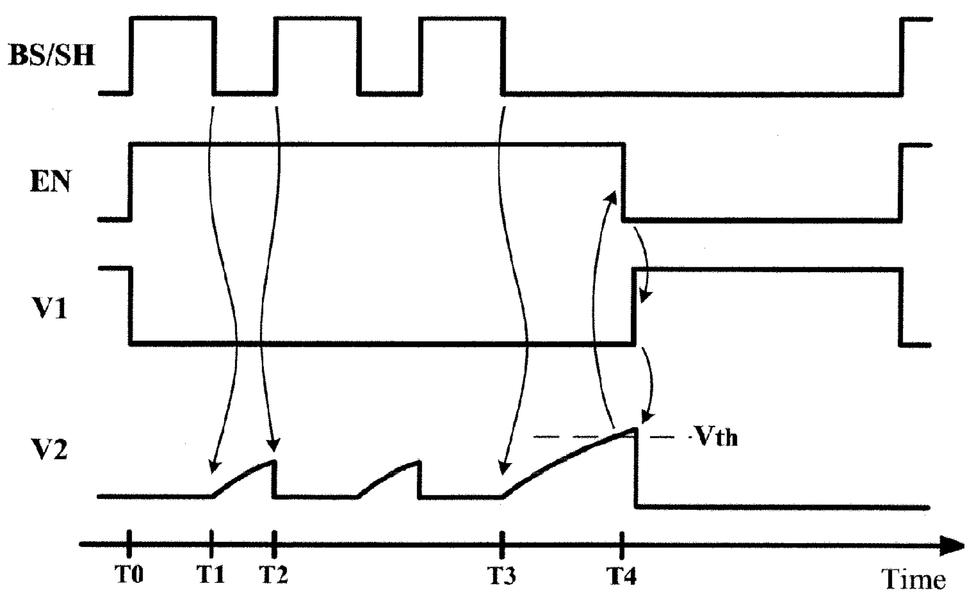

BS/SH
EN
V1
V2
Vth
T0
T1
T2
T3
T4
Time

FIG. 9

DIMMING CONTROL CIRCUIT FOR LIGHT-EMITTING DIODES

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a dimming control circuit and, more particularly, to a dimming control circuit applied to a drive circuit for driving light-emitting diodes.

2. Description of the Prior Art

FIG. **1** is a circuit diagram showing a conventional light-emitting diode drive circuit **10**. In the example of FIG. **1**, the light-emitting diode drive circuit **10** is implemented by a boost-type switching voltage regulator for converting an input voltage V_{in} into an output voltage V_{out} desired for driving one or more series-connected light-emitting diodes LED. In accordance with a current I_L flowing through an inductor L and a feedback voltage V_{fb} from a resistor R, a switching control circuit **11** generates a fixed-duty pulse drive signal FS for turning on/off a switching transistor Q. The duty ratio of the switching transistor Q determines the proportional relationship between the output voltage V_{out} and the input voltage V_{in}. The brightness of the light-emitting diodes LED varies depending on the diode current I_{LED} flowing through themselves. From FIG. **1** is derived an equation regarding to the diode current I_{LED}: $I_{LED}=V_{fb}/R=(V_{out}-N*V_d)/R$, where N is the number of the light-emitting diodes and V_d is a voltage drop of one single conductive light-emitting diode. Since the voltage drop V_d may be considered approximately constant, the diode current I_{LED} as well as the brightness of the light-emitting diodes LED is easily controlled by the adjustment to the output voltage V_{out}.

Another method of controlling the brightness of the light-emitting diodes LED appeals to the nature of human-eye perceptions. For bright-dark cycles alternating over about 60 Hz, the human eyes perceive an average brightness instead of flickering. In the bright phase the switching transistor Q is, as conventional, turned on/off by the fixed-duty pulse drive signal FS from the switching control circuit **11**, but in the dark phase the fixed-duty pulse drive signal FS is blocked in order to keep the switching transistor Q nonconductive. In other words, through controlling the ratio of the bright phase to the dark phase, the desired average brightness is achieved. However, such a dimming method by using bright-dark cycles causes a huge current noise peak at the beginning of each bright phase. Because the frequency of the bright-dark cycles may be set within the audio-frequency range, the serially-occurred current noise peaks actually produce noisy sounds to human ears.

SUMMARY OF THE INVENTION

In view of the above-mentioned problems, an object of the present invention is to provide a dimming control circuit for light-emitting diodes, capable of reducing current noise peaks at the beginning of each bright cycle.

According to a first aspect of the present invention, a dimming control circuit generates a dimming control signal to determine a brightness of at least one light-emitting diode. The dimming control signal has a plurality of bright-dark cycles, each of which consists of a bright phase and a dark phase. The bright phase starts with an adaptive rising portion for restricting the brightness of the at least one light-emitting diode to increase gradually.

According to a second aspect of the present invention, a light-emitting diode drive circuit includes a switching control circuit, a switching voltage regulator, and a dimming control circuit. The switching control circuit generates a pulse drive signal. The switching voltage regulator is controlled by the pulse drive signal for driving at least one light-emitting diode. The dimming control circuit generates a dimming control signal to restrict a switching duty ratio of the pulse drive signal through the switching control circuit. The dimming control signal has a plurality of bright-dark cycles, each of which consists of a bright phase and a dark phase. The bright phase starts with an adaptive rising portion for restricting the switching duty ratio of the pulse drive signal to increase gradually.

According to a third aspect of the present invention, a light-emitting diode drive chip includes a pin, a control circuit, and an enabling circuit. The pin receives a brightness/shutdown signal. The control circuit generates a dimming signal in response to the brightness/shutdown signal so as to control a brightness of at least one light-emitting diode. The dimming signal has a plurality of bright-dark cycles, each of which consists of a bright phase and a dark phase. The bright phase starts with an adaptive rising portion for restricting the brightness of the at least one light-emitting diode to increase gradually. The enabling circuit generates an enable signal in response to the brightness/shutdown signal such that the enable signal activates the control circuit in the bright phase and terminates the control circuit when the dark phase exceeds a predetermined threshold time.

These and other objectives of the present invention will no doubt become obvious to those of ordinary skill in the art after reading the following detailed description of the preferred embodiment that is illustrated in the various figures and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-mentioned and other objects, features, and advantages of the present invention will become apparent with reference to the following descriptions and accompanying drawings, wherein:

FIG. **1** is a circuit diagram showing a conventional light-emitting diode drive circuit;

FIG. **2** is a circuit diagram showing a light-emitting diode drive circuit according to a first embodiment of the present invention;

FIGS. **3**(A) and **3**(B) are timing charts showing operations of a light-emitting diode drive circuit according to a first embodiment of the present invention;

FIG. **4** is a circuit diagram showing a switching duty ratio limiting circuit according to a first embodiment of the present invention;

FIG. **5** is a circuit diagram showing a switching control circuit according to a first embodiment of the present invention;

FIG. **6** is a circuit diagram showing a light-emitting diode drive circuit according to a second embodiment of the present invention;

FIG. **7** is a circuit diagram showing a light-emitting diode drive circuit according to a third embodiment of the present invention;

FIG. **8** is a circuit diagram showing an enabling circuit according to the present invention; and

FIG. **9** is a timing chart showing an operation of an enabling circuit according to the present invention.

DETAILED DESCRIPTION

The preferred embodiments according to the present invention will be described in detail with reference to the drawings.

FIG. **2** is a circuit diagram showing a light-emitting diode drive circuit **20** according to a first embodiment of the present invention. The light-emitting diode drive circuit **20** is provided with a switching control circuit **21** and a dimming control circuit **22**, for driving a switching transistor Q and effectively controlling brightness of one or more series-connected light-emitting diodes LED. The dimming control circuit **22** applies a dimming control signal DL to the switching control circuit **21**. Therefore, in addition to, the switching control circuit **21** generates a pulse drive signal PS whose switching duty ratio is determined in response not only to the conventional inductor current I_L and feedback voltage V_{fb} but also to the dimming control signal DL. More specifically, the dimming control circuit **22** has a brightness setting circuit **23** and a switching duty ratio limiting circuit **24**. The brightness setting circuit **23** generates a brightness setting signal BS for determining an average brightness of the light-emitting diodes LED. In order to prevent the current noise peak at the beginning when the switching transistor Q is turned on from being so large as to cause noisy sounds, it is necessary for the brightness setting signal BS to be modulated through the switching duty ratio limiting circuit **24** into the dimming control signal DL, which is actually applied to the switching control circuit **21**. In response to the dimming control signal DL, the switching control circuit **21** generates the pulse drive signal PS to be applied to the switching transistor Q.

FIGS. **3**(A) and **3**(B) are timing charts showing operations of a light-emitting diode drive circuit **20** according to a first embodiment of the present invention. A brightness setting signal BS with a longer dark phase is illustrated in FIG. **3**(A), which is applied to produce a darker average brightness of the light-emitting diodes LED. Another brightness setting signal BS with a shorter dark phase is illustrated in FIG. **3**(B), which is applied to produce a brighter average brightness of the light-emitting diodes LED.

As shown in FIG. **3**(A), the brightness setting signal BS is a pulse signal, alternating between a high level state and a low level state. The high level state is applied to allow the switching control circuit **21** to output a pulse signal PS having a switching duty ratio larger than zero. In this case, the input voltage V_{in} can be consistently converted into the output voltage V_{out} for supplying energy to drive the light-emitting diodes LED. Therefore, such a high level state represents a bright phase of a bright-dark cycle. In contrast, the low level state is applied to suppress the switching duty ratio of the pulse drive signal PS to become zero. In this case, the input voltage V_{in} Stops supplying energy and then the brightness of the light-emitting diodes LED becomes dark. Therefore, such a low level state represents a dark phase of a bright-dark cycle. The bright-dark cycles provided by the brightness setting signal BS are applied to produce an average brightness of the light-emitting diodes LED when perceived by the human eyes. Through adjusting the ratio of the bright phase to the dark phase, the average brightness of the light-emitting diodes LED is effectively determined by the brightness setting signal BS.

In order to reduce the current noise peaks, the bright phase of the brightness setting signal BS should have to be modified through the switching duty ratio limiting circuit **24** so as to make the dimming control signal DL get started with an adaptive rising portion in the bright phase each cycle. The time taken by the adaptive rising portion, referred to as a soft-start time T_{ss} later, is determined in accordance with the time taken by a dark phase of a previous bright-dark cycle. This is the reason why the rising portion is called adaptive in this specification. When the dark phase of the previous bright-dark cycle is longer in time, the soft-start time T_{ss} of the bright phase immediately after the longer dark phase is made longer. This is because the longer dark phase results in a greater degree of reduction in the output voltage V_{out}, in some case even down to the ground potential, a longer soft-start time T_{ss} provides a longer transition of the switching duty ratio from zero to a maximum and therefore helps reduce the current noise peak at the beginning of the bright phase. In comparison of FIGS. **3**(A) and **3**(B), easily realized is that the dimming control signal DL in FIG. **3**(A) has a longer soft-start time T_{ss} since the dark phase of the previous bright-dark cycle is longer, for example, from the time T**2** to T**3**.

For appropriately illustrating the restriction provided by the dimming control signal DL to the switching duty ratio of the pulse drive signal PS, FIGS. **3**(A) and **3**(B) additionally shows a conventional pulse drive signal FS with a fixed duty ratio generated from the circuit **11** of FIG. **1**. Through the restriction provided by the dimming control signal DL, the pulse drive signal PS has a first portion, corresponding to the bright phase, having a duty ratio gradually increasing from zero to a maximum during the adaptive soft-start time T_{ss} and a second portion, corresponding to the dark phase, having a zero duty ratio suppressed to zero. It should be noted that the frequency of the pulse drive signal PS is in practice much higher than that of the dimming control signal DL. For example, the frequency of the pulse drive signal PS is about 1.2 MHz while the frequency of the dimming control signal DL is only about 1 KHz. For the sake of simplicity, only are some exemplary pulses shown in FIGS. **3**(A) and **3**(B), especially for the first portion corresponding to the bright phase of the dimming control signal DL.

FIG. **4** is a circuit diagram showing a switching duty ratio limiting circuit **24** according to a first embodiment of the present invention. A falling edge detecting circuit **41** is triggered by a falling edge of the brightness setting signal BS while a rising edge detecting circuit **42** is triggered by a rising edge of the brightness setting signal BS. Starting to count upon the occurrence of the falling edge and stopping counting upon the occurrence of the rising edge, a counting circuit **43** generates a digital selection signal SE for indicating the time taken by the dark phase of the brightness setting signal BS. In response to the digital selection signal SE, a selecting circuit **44** outputs a charge signal CH whose frequency is selected from eight different frequencies F**0** to F**8**. When the counting circuit **43** indicates a longer dark phase of the brightness signal BS, the selecting circuit **44** outputs a charge signal CH with a lower frequency. When the counting circuit **43** indicates a shorter dark phase of the brightness setting signal BS, the selecting circuit **44** outputs a charge signal CH with a higher frequency. After frequency-dividing an oscillating signal from an oscillating circuit **45**, a frequency divider **46** generates these eight-different-frequency charge signals CH. It should be noted that the selecting circuit **44** and the frequency divider **46** according to the present invention are not limited to generating eight different frequencies, but may be applied to generate more or less than eight different frequencies. The charge signal CH is applied to a charging circuit **47** to control transmission gates TG**1** and TG**2** for charging capacitors C**1** and C**2**. When the charge signal CH has a lower frequency, the capacitors C**1** and C**2** are charged at a slower rate. As a result, the adaptive rising portion of the dimming control signal DL is provided with a longer soft-start time T_{ss}, as shown in FIG. **3**(A). When the charge signal CH has a higher frequency, the capacitors C**1** and C**2** are charged at a faster rate. As a result, the adaptive rising portion of the dimming control signal DL is provided with a shorter soft-start time T_{ss}, as shown in FIG. **3**(B).

When the brightness setting signal BS from the brightness setting circuit **23** is at the low level state, two switching units S**1** and S**2** are both short-circuited. As a result, the dimming control signal DL output from the charging circuit **47** is kept at the ground potential. Once the brightness setting signal BS transitions to the high level, the switching units S**1** and S**2** are open-circuited such that the charging circuit **47** is allowed to perform the charging operation at the frequency determined by the charge signal CH from the selecting circuit **44**. Consequently, the dimming control signal DL gradually increases from the ground potential to the maximum during the soft-start time T_{ss} determined in accordance with the time taken by the dark phase of the previous bright-dark cycle.

FIG. **5** is a circuit diagram showing a switching control circuit **21** according to a first embodiment of the present invention. An oscillating circuit **51** applies a pulse signal to a set input terminal S of a latch **52** for triggering the pulse drive signal PS into the high level state so as to turn on the switching transistor Q of FIG. **2**. Once the switching transistor Q is turned on, the inductor current I_L flowing through the inductor L starts to increase. A current detecting circuit **53** generates a current detection signal V_{id} representative of the inductor current I_L. After the slope-compensation carried out through an adding circuit **54**, the current detection signal V_{id} is applied to a non-inverting input terminal of a comparing circuit **55**. Furthermore, the comparing circuit **55** has two inverting input terminals for receiving an error signal V_{err} and the dimming control signal DL, respectively. The error signal V_{err} is generated from an error amplifying circuit **56** for indicating a difference between the feedback voltage V_{fb} from the resistor R of FIG. **2** and a reference voltage V_{ref} from a reference voltage generating circuit **57**. Once the slope-compensated current detection signal V_{id} exceeds the smaller of the error signal V_{err} and the dimming control signal DL, the comparing circuit **55** triggers a reset input terminal R of the latch **52**. Therefore, the dimming control signal DL effectively limits the switching duty ratio of the pulse drive signal PS.

FIG. **6** is a circuit diagram showing a light-emitting diode drive circuit **60** according to a second embodiment of the present invention. The second embodiment is different from the first embodiment in that a dimming control circuit **62** according to the second embodiment further includes a logic unit **63**. As shown, the logic unit **63** makes possible the brightness setting signal BS to directly turn off the switching transistor Q. More specifically, once the brightness setting signal BS transitions to the low level, the switching transistor Q is immediately turned off without waiting for the response from the pulse drive signal PS. On the other hand, when the brightness setting signal BS is at the high level state, the logic unit **63** simply allows the pulse drive signal PS to pass through and to control the switching transistor Q as the first embodiment does.

FIG. **7** is a circuit diagram showing a light-emitting diode drive circuit **70** according to a third embodiment of the present invention. Referring to FIG. **7**, in today's integrated circuits manufacturing, the switching control circuit **21**, the switching duty ratio limiting circuit **24**, and the switching transistor Q are usually incorporated into a single chip **71** with several electrical pins provided around the circumference of the chip's package for connecting external circuits. In order to save the number of the pins, the light-emitting diode drive control chip **71** utilizes a shutdown pin SHDN to receive a two-fold brightness/shutdown signal BS/SH. More specifically, the brightness/shutdown signal BS/SH can, on one hand, set the brightness of the light-emitting diodes LED like a brightness setting signal and, on the other hand, disconnect the power from all components of the whole chip **71** like a shutdown signal. Through such a common pin SHDN, the brightness/shutdown signal BS/SH is applied to the switching duty ratio limiting circuit **24** and an enabling circuit **72**. The enabling circuit **72** generates an enable signal EN for activating or terminating the switching control circuit **21** and the switching duty ratio limiting circuit **24**.

FIG. **8** is a circuit diagram showing an enabling circuit **72** according to the present invention. FIG. **9** is a timing chart showing an operation of an enabling circuit **72** according to the present invention. When the brightness/shutdown signal BS/SH transitions to the high level, as shown at the time T**0** of FIG. **9**, a latch **80** is triggered to generate a high level in the enabling signal EN for activating the light-emitting diode drive control chip **71**. In addition, the transistor SW**1** is turned off and the transistor SW**2** is turned on such that a potential difference V**2** across a capacitor C_{en} falls to zero. When the brightness/shutdown signal BS/SH transitions to the low level, as shown at the time T**1** of FIG. **9**, the transistor SW**2** is turned off to allow a current source I_{en} to charge the capacitor C_{en}, resulting in a gradual increase of the potential difference V**2**. If the brightness/shutdown signal BS/SH transitions back to the high level in a short time, as shown at the time T**2** of FIG. **9**, the potential difference might not be large enough to trigger a reset input terminal R of the latch **80**. In this case, the enable signal EN stays at the high level state without any change and therefore the brightness/shutdown signal BS/SH is functioning as a brightness setting signal. If the brightness/shutdown signal BS/SH stays at the low level long enough for allowing the potential difference V**2** to exceed a threshold voltage V_{th} so as to trigger the reset input terminal R, as shown at the time T**4** of FIG. **9**, the enable signal EN transitions to the low level and shutdowns the light-emitting diode drive control chip **71**.

It should be noted that although the embodiments described above are related to the boost-type switching voltage regulator, the present invention is not limited to this and may be applied to other types of voltage regulators such as buck-type, synchronous switching type, and so on. Except for the current-mode pulse-width-modulation technique, the switching control circuit according to the present invention may use a voltage-mode pulse-width-modulation technique or a constant ON-time or OFF-time pulse-frequency-modulation technique, and so on.

While the invention has been described by way of examples and in terms of preferred embodiments, it is to be understood that the invention is not limited to the disclosed embodiments. To the contrary, it is intended to cover various modifications. Therefore, the scope of the appended claims should be accorded the broadest interpretation so as to encompass all such modifications.

What is claimed is:

1. A light-emitting diode drive circuit comprising:

a switching control circuit for generating a pulse drive signal;

a switching voltage regulator controlled by the pulse drive signal for driving at least one light-emitting diode; and a dimming control circuit for generating a dimming control signal to restrict a switching duty ratio of the pulse drive signal through the switching control circuit, wherein:

the dimming control signal has a plurality of bright-dark cycles, each of which consists of a bright phase and a dark phase, the bright phase starting with an adaptive rising portion for restricting the switching duty ratio of the pulse drive signal to increase gradually.

2. The circuit according to claim **1**, wherein:

the adaptive rising portion is determined in accordance with a dark phase of a previous bright-dark cycle.

3. The circuit according to claim **2**, wherein:

the adaptive rising portion is longer when the dark phase of the previous bright-dark cycle is longer.

4. The circuit according to claim **1**, further comprising:

a logic unit for preventing the pulse drive signal from being applied to the switching voltage regulator in the dark phase, and for allowing the pulse drive signal to be applied to the switching voltage regulator in the bright phase.

5. The circuit according to claim **1**, further comprising:

an enabling circuit for activating the switching control circuit and the dimming control circuit in the bright phase, and for terminating the switching control circuit and the dimming control circuit when the dark phase exceeds a predetermined threshold time.

6. A light-emitting diode drive chip, comprising:

a pin for receiving a brightness/shutdown signal;

a control circuit for generating a dimming signal in response to the brightness/shutdown signal so as to control a brightness of at least one light-emitting diode, the dimming signal having a plurality of bright-dark cycles, each of which consists of a bright phase and a dark phase, the bright phase starting with an adaptive rising portion for restricting the brightness of the at least one light-emitting diode to increase gradually; and

an enabling circuit for generating an enable signal in response to the brightness/shutdown signal such that the enable signal activates the control circuit in the bright phase and terminates the control circuit when the dark phase exceeds a predetermined threshold time.

7. The chip according to claim **6**, wherein:

the adaptive rising portion is determined in accordance with a dark phase of a previous bright-dark cycle.

8. A dimming control circuit generating a dimming control signal to determine a brightness of at least one light-emitting diode, the dimming control signal having a plurality of bright-dark cycles, each of which consists of a bright phase and a dark phase, the bright phase starting with an adaptive rising portion for restricting the brightness of the at least one light-emitting diode to increase gradually.

9. The circuit according to claim **8**, wherein:

the adaptive rising portion is determined in accordance with a dark phase of a previous bright-dark cycle.

10. The circuit according to claim **9**, wherein:

the adaptive rising portion is longer when the dark phase of the previous bright-dark cycle is longer.

* * * * *