MBI6650 Application Note

Overview

MBI6650 is a high efficiency, constant current, step-down DC/DC converter, designed to drive high power LED in constant current. Hysteretic PFM control scheme enhances the efficiency at light load condition. Output current can be programmed by an external resistor, and DIM pin provides another method to adjust the output current by connecting a PWM signal. MBI6650 also features Under Voltage Lock Out (UVLO), Over Temperature Protection, Open Circuit Protection and Short Circuit Protection to protect IC from being damaged.

MBI6650 needs only 4 external components to achieve power conversion. Built-in MOSFET allows the use in space sensitive application. The package of MBI6650 is TO252-5, it offers a thermal pad to enhance the heat dissipation and a large amount of output current can be handled safely.

Hysteretic PFM Control Scheme

The key feature of MBI6650 is hysteretic pulse-frequency-modulation (PFM) control scheme with high side current limit. When power on, V_{SEN} is lower than V_H, the internal MOSFET of MBI6650 turns on and V_{SEN} increases with I_L. As the V_{SEN} is equal to V_L, the internal MOSFET turns off, and V_{SEN} decreases with I_L until next period comes. The hysteretic voltage is 1.3 times of V_{SEN}. The inductor current will always works on Continuous Current Mode (CCM) due to the character of hysteretic PFM control. This is helpful to reduce LED ripple current. Figure 1 shows the waveform of hysteretic PFM control scheme.

The switching frequency of this control scheme is varied with output loading, the heavier loading results the lower switching frequency. At same loading condition, the larger inductance results the lower switching frequency. The lowest switching frequency is limited to 40 kHz to avoid audio noise.

The high side current limit allows uses choosing a smaller size and lower power consumption resistor than that in low side current limit unit. It's helpful to space saving and cost down.

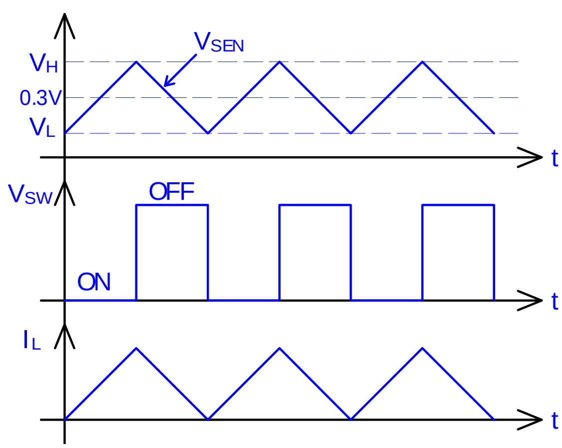

Figure 1. Waveform of hysteretic PFM control scheme

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Under Voltage Lock Out (UVLO)

The typical voltage of UVLO of MBI6650 is 7.4V, if input voltage is lower than 7.4V, the internal MOSFET of MBI6650 is off, and there is no current through in. Also MBI6650 features a hysteretic of UVLO, as the input voltage is lower than 6.8V again, the internal MOSFET of MBI6650 turns off.

Peak Current Limit

The peak current is limited to 1.3 times of preset current. As the peak current is limited, the internal MOSFET turns off and shuts the LED current, until the LED current is lower than 1.3 times of preset one. This peak current limit can protect LED from being damaged by large LED current.

Dimming

LED current can be adjusted by connecting a PWM signal to DIM pin of MBI6650. As a low level signal (lower than 1.5V) appears at DIM pin, the internal MOSFET turns off and shuts the LED current; vice versa. The PWM frequency is ranging from 1kH to 40kHz and the larger duty cycle results the higher LED current.

Open Circuit Protection

MBI6650 owns an open circuit protection. As LED is opened, the internal MOSFET stops switching and shuts the LED current.

Short Circuit Protection

MBI6650 offers a short circuit protection. As LED is short, the output voltage drops to zero, but the internal MOSFET keeps switching and the output current keeps in present value. In multi-LED in cascaded application, if one or more LEDs are short, the output voltage across LEDs will be decreased but the LED current can still keeps in present value.

Over Temperature Protection

MBI6650 offers an over temperature protection, and the protect temperature is 140℃. As junction temperature exceeds 140℃, the internal MOSFET turns off and shuts the LED current. Thus, the junction temperature starts to decrease. As the junction temperature is lower than 95℃, the internal MOSFET turns on again and starts switching.

Design Consideration

Switching Frequency

The selection of switching frequency is based on the trade-offs between efficiency (better at low frequency), components size/cost (smaller at high frequency), and the amplitude of output ripple voltage and current (smaller at high frequency). On many applications, the switching frequency is limited by EMI sensitivity. The switching frequency is ranging from 40kHz to 1.2MHz.

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LED Ripple Current

A LED constant current driver, such as MBI6650, was designed to control the current through the cascaded LED, but the voltage across it. Higher LED ripple current allows the use of smaller inductance, smaller output capacitance or even no output capacitor. The advantages of higher LED ripple current are reduction in PCB size and cost due to no output capacitor is used. Lower LED ripple current requires higher switching frequency, larger inductance, and output capacitor. The advantages of lower LED ripple current are LED life time extended and LED heating reduced. The recommended ripple current is 5% to 20% of normal LED current.

Component Selection

Output Current Setting

The output current can be programmed by an external resistor, the relationship between I_{OUT} and Rsen is

$$Rsen = (V_{SEN} / I_{OUT}) \qquad (1)$$

where Rsen is current sense resistor, which is connected between VIN and SEN pin of MBI6650, 1% tolerance is recommended for better output current accuracy. V_{SEN} is the voltage across Rsen, the normal value is 0.3V. The sustaining power dissipation on Rsen, P_{Rsen}, is

$$P_{Rsen} = (V_{SEN}^2 / Rsen) \qquad (2)$$

Inductor Selection

The inductance is determined by two factors, switching frequency and inductor ripple current. The calculation of inductance, L1, can be described as

$$L1 > (\mathbf{V}_{IN} - V_{OUT} - V_{SEN} - (R_{ds(on)} \times I_{OUT})) \times \frac{D}{f_{SW} \times \Delta I_L} \qquad (3)$$

Where

$\mathbf{R}_{ds(on)}$ is the on-resistor of internal MOSFET of MBI6650. The typical is 0.8Ω at $12V_{IN}$.

D is the duty cycle of MBI6650, $D = V_{OUT} / V_{IN}$.

$\mathbf{f}_{SW}$ is the switching frequency of MBI6650.

$\triangle \mathbf{I}_L$ is the ripple current of inductor, $\triangle I_L = (1.3 \times I_{OUT}) – (0.7 \times I_{OUT}) = 0.6 \times I_{OUT}$.

When select an inductor, the inductance not the only factor affects the performance of module, the saturation current also needs to be taken. In general, choose an inductor with 1.5 times of LED current to be the saturation current is recommended.

Schottky Diode Selection

MBI6650 needs a flywheel diode, D1, to carrying the inductor current during the MOSFET off time. The recommended choice of the flywheel diode is schottky diode with low forward voltage for better efficiency. Two factors determine the selection of schottky diode. One is the maximum reverse voltage, the rated of it should be input voltage at least, but 1.5 times of input voltage is a secure choice. Other is the maximum forward current, it works during the MOSFET off time, and the rated of it should be output current at least, but same as the selection on reverse voltage, the recommended forward current is 1.5 times of output current.

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Minimum Input Voltage

The minimum input voltage is sum of the voltage drops on Rsen, R_S, DCR of L1, $R_{ds(on)}$ of internal MOSFET and the total forward voltage of LEDs. R_S, the dynamic resistance of LED, is the inverse of the slope in linear forward voltage model for LED. This electrical characteristic can be provided by the manufacturer of LED. The equivalent circuit is shown as figure 2. To calculate these voltage drops, the peak LED current must be defined first. As previous mentioned, the peak current is 1.3 times of preset current, and then the voltage drops on each component can be calculated as bellow

$$V_{Rsen} = 0.3V \times 1.3 = 0.39V \tag{4}$$

$$V_{Rs} = R_S \times I_{OUT} \times 1.3 \times n, \text{ where n is the amount of LED.} \tag{5}$$

$$V_{MOSFET} = R_{ds(on)}) \times I_{OUT} \times 1.3 \tag{6}$$

$$V_{L1} = DCR \times I_{OUT} \times 1.3 \tag{7}$$

Thus, the minimum input voltage ($V_{IN,\,MIN}$) can be defined as

$$V_{IN,\,MIN} = V_{Rsen} + V_{Rs} + V_{MOSFET} + V_{L1} + V_{F,\,LED} \tag{8}$$

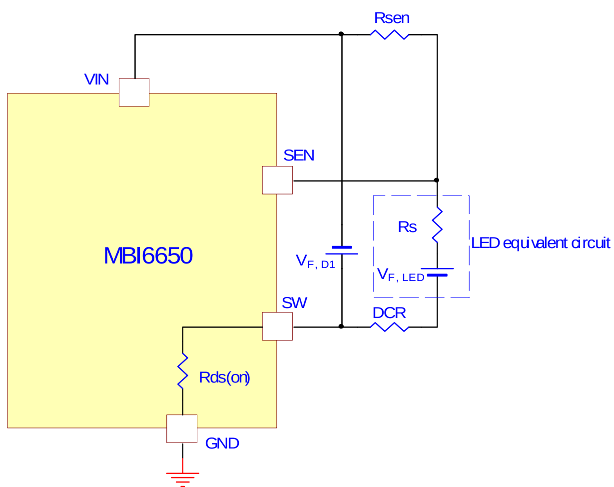

Figure 2 The equivalent circuit of MBI6650

Input Capacitor Selection

The input capacitor, C_{IN}, can supply pulses of current for MBI6650 during the MOSFET on time and be charged by input voltage during the MOSFET off time. As the input voltage is lower than the tolerable input voltage, the internal MOSFET of MBI6650 becomes always on, and the LED current is limited to 1.3 times of normal current. Therefore the key factor in input capacitor selection is the minimum input voltage, which can be tolerated. The minimum input capacitor ($C_{IN,\,MIN}$) can be calculated by the following equation

$$C_{IN,\,MIN} = 1.3 \times I_{OUT} \times \frac{D \times T_S}{V_{IN} - V_{IN,\,MIN}} \tag{9}$$

where

$V_{IN,\,MIN}$ is the tolerable input voltage, $V_{IN,\,MIN} = V_{IN} - V_{OUT,\,MAX}$.

The rated voltage of input capacitor should be 1.5 times of input voltage at least. A tantalum pr ceramic capacitor can be used for input capacitor. The advantages of tantalum capacitor are high capacitance and low ESR. The advantages of ceramic capacitor are good high frequency characteristic, small size and low cost. Users can choice an appropriate one for applications.

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Output Capacitor Selection (Selection)

A capacitor parallels with cascaded LED can reduce the LED ripple current and allow the use of smaller inductance. Or the switching frequency can be lower at same inductance to improve efficiency. Figure 3 shows the equivalent circuit of ripple circuit. A resistor, R_{LED}, represents the equivalent impedance of LED under the desired LED current, and ESR is the equivalent series resistance of output capacitor. $\triangle I_{OUT}$ means the LED ripple current and $\triangle I_C$ is the ripple current through to C_{OUT}. The calculation of C_{OUT} can be presented as following

$$\Delta I_{OUT} = \Delta I_L \frac{1}{1+\frac{R_{LED}}{Zc}} \qquad (10)$$

$$Zc = ESR + \frac{1}{2\pi \times f_{SW} \times C_{OUT}} \qquad (11)$$

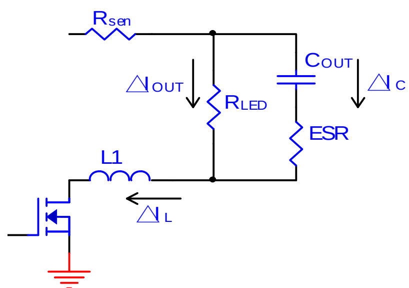

Figure 3 Equivalent circuit of ripple current

Efficiency

To estimate the efficiency, the power consumption in each current carrying element can be calculated and summed. The efficiency (η) can be described as

$$\eta = \frac{P_{OUT}}{P_{OUT} + P_{LOSS}} \qquad (12)$$

where

P_{OUT} is the power consumption of LED. The calculation is

$$P_{OUT} = V_{OUT} \times I_{OUT} \qquad (13)$$

The power loss (P_{LOSS}) in stet-down DC/DC converter includes

$$P_{LOSS} = P_C + P_{SW} + P_G + P_L + P_{D1} + P_{Rsen} \qquad (14)$$

where

$\mathbf{P_C}$ is conduction loss during the internal MOSFET turns on, $P_C = I_{OUT}^2 \times R_{ds\,(on)} \times D$.

$\mathbf{P_{SW}}$ is the switching loss of the MOSFET during switching, $P_{SW} = V_{IN} \times I_{OUT} \times (t_r + t_f) \times f_{SW}$. t_r and t_f are the rising and falling times of the switch signal.

$\mathbf{P_G}$ includes gate charging (Q_G) loss and the power consumption of MBI6650, $P_G = (I_{DD} + f_{SW} \times Q_G) \times V_{IN}$. I_{DD} is the supply current of MBI6650, normally is 1mA.

$\mathbf{P_L}$ is inductor loss caused by the DC resistance (DCR) of inductor, $P_L = I_{OUT}^2 \times DCR$.

$\mathbf{P_{D1}}$ is the power loss of schottky diode, $P_{D1} = V_{F,\,D1} \times I_{OUT} \times (1\text{-}D)$, $V_{F,\,D1}$ is the forward voltage of schottky diode.

$\mathbf{P_{Rsen}}$ is the power loss on Rsen, $P_{Rsen} = V_{SEN} \times I_{OUT}$.

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Raised Junction Temperature

The power losses will cause temperature rising on the body of MBI6650. As the junction temperature (T_J) gets 140℃, MBI6650 will into thermal protection model and shut the LED current off. Thus, it's important for designer to recognize the relationship between power losses and raised temperature. The relationship can be described as

$$T_J = T_A + P_{LOSS,\ IC} \times R_{th,\ JA} \tag{15}$$

where

TA is the ambient temperature.

$P_{LOSS,\ IC}$ is the power loss in MBI6650, $P_{LOSS,\ IC} = P_C + P_{SW} + P_G$.

$R_{th,\ JA}$ is thermal resistor of MBI6650 from junction to ambient, 32.9℃/W by simulation.

Design Example 1

For lighting 2 pieces of high power white LEDs, the forward voltage of LED is 3.72V/pcs. The desired LED current is 350mA, input voltage is 12V±5%. For better efficiency, the switching frequency is set to 200kHz. The required LED ripple current must lower than 10% of normal current. Please calculate the required components. (The used LED is from LUXEON, LXK2-PW14-U00, with 0.6Ω dynamic resistance)

I_{OUT}, Rsen and D

The Rsen can be calculated by (1), Rsen = 0.3V / 0.35A = 0.86Ω. Here select a 0.82Ω resistor to be Rsen. The sustaining power dissipation is $P_{Rsen} = 0.3V^2 / 0.82\Omega = 0.11W$. Thus, a 1%, 0.82Ω resistor with 0.25W power dissipation is recommended.

Because of the Rsen is 0.82Ω, the LED current would be IOUT = 0.3V / 0.82Ω = 366mA.

And the duty cycle is D = (3.72V x 2) / 12V = 0.62.

Inductor Selection

From (3), the inductor, L1, can be chosen

L1 > [12V – (3.72 x 2) – 0.3V – (0.8Ω x 0.366A)] x [0.62 / (200kHz x 0.6 x 0.366A)] = 56uH

Thus, the recommended inductor is 68uH with 0.6A saturation current and 0.175Ω DCR.

Schottky Diode Selection

In this application, the recommended selection in schottky diode is SSCD102 with 20V reverse voltage, 1A forward current and the maximum forward voltage is 0.5V.

Minimum Input Voltage

The minimum input voltage is the sum of voltage drops on each current carrying element and the forward voltage of LEDs during MOSFET turns on. The voltage drops on each component are

$V_{Rsen} = 0.3V \times 1.3 = 0.39V$

$V_{Rs} = 0.6\Omega \times 0.366A \times 1.3 \times 2 = 0.57V$

$V_{MOSFET} = 0.8\Omega \times 0.366A \times 1.3 = 0.38V$

$V_{L1} = 0.175\Omega \times 0.366A \times 1.3 = 0.083V$

Thus the minimum input voltage is $V_{IN,\ MIN} = 0.39V + 0.57V + 0.38V + 0.083V + 7.44 = 8.863V$

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Input Capacitor Selection

The minimum input capacitor can be calculated as

$$C_{IN,MIN} = 1.3 \times 0.366\text{A} \times \frac{0.62 \times 5\mu\text{s}}{12\text{V} - 8.863\text{V}} = 470.19\text{nF}$$

For handle this system safely, a 1uF ceramic capacitor with 16V sustaining voltage is recommended.

Output Capacitor Selection

For LED ripple current reduction, an output capacitor parallels with LED array is needed. The calculation is

$$0.1\text{x}0.366\text{A} = 0.6\text{x}0.366\text{A}\frac{1}{1+\frac{(7.44/0.366)}{Zc}}$$ à Z_C = 4.066, substitute Z_C to (11)

$$4.066 = \frac{1}{2\pi \times 200\text{kHz} \times C_{OUT}}$$ à C_{OUT} = 195.73nF

This calculation assumes that the ESR of C_{OUT} is negligible. Thus, the recommended output capacitor is 220nF ceramic capacitor with 10V rated voltage.

Efficiency

The power consumption on each component can be calculated as

$P_{OUT} = V_{OUT} \times I_{OUT}$ = 2 x 3.72V x 0.366A = 2.72W

$P_C = I_{OUT}^2 \times R_{ds(on)} \times D = (0.366\text{A})^2 \times 0.8\Omega \times 0.62$ = 66.44mW

$P_{SW} = V_{IN} \times I_{OUT} \times (t_r + t_f) \times f_{SW}$ = 12V x 0.366A x (46ns + 4.6ns) x 200kHz = 44.45mW

$P_G = (I_{DD} + f_{SW} \times Q_G) \times V_{IN} = (1\text{mA} + 200\text{kHz} \times 76 \times 10^{-12}) \times 12\text{V}$ = 12.18mW

$P_L = I_{OUT}^2 \times DCR = (0.366\text{A})^2 \times 0.175\Omega$ = 23.44mW

$P_{D1} = V_{F,D1} \times I_{OUT} \times (1-D)$ = 0.5V x 0.366A x (1-0.62) = 69.54mW

$P_{Rsen} = V_{SEN} \times I_{OUT}$ = 0.3V x 0.366A = 109.8mW

$P_{LOSS} = P_C + P_{SW} + P_G + P_L + P_{D1} + P_{Rsen}$ = 325.85mW

Thus, the efficiency in this application is

$$\eta = \frac{P_{OUT}}{P_{OUT} + P_{LOSS}} = \frac{2.72\text{W}}{2.72\text{W} + 325.85\text{mW}} \times 100\% = 89.30\%$$

Raised Junction Temperature

The raised junction temperature can be estimated by

$T_J = T_A + P_{LOSS,IC} \times R_{th,JA}$ = 25℃ + (66.4mW + 44.45mW + 12.18mW) x 32.9℃/W = 29.05℃.

Followings show the application circuit and BOM for reference.

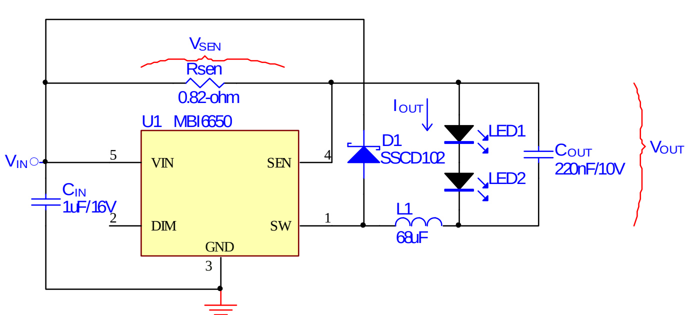

Figure 4 The application circuit of example 1

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Table 1 The BOM of example 1

Designator	Part Type	Description	Vendor	Contact Window
C1	1uF/16V	0603, EMK107BJ105KK-T, ceramic capacitor	TAIYO YUDEN	+886-2-2797-2155
C2	220nF/16V	0603, EMK107F224ZA-T, ceramic capacitor	TAIYO YUDEN	+886-2-2797-2155
D1	SSCD102	20V/1A Surface Mount Schottky Barrier Rectifier	ZOEWIE	+886-2-2219-5533-211
L1	68uH	SLF7045T-680MR60-PF	TDK	+886-3-592-7225
R1	0.82Ω	1206, RL1206FR-070R82, SMD Resistor	YAGEO	+886-3-534-5546
U1	MBI6650	Constant Current DC/DC Converter	MBI	+886-3-579-0068

Design Example 2

For lighting 3 pieces of high power white LEDs, the forward voltage of LED is 3.72V/pcs. The desired LED current is 1A, input voltage is 24V±5%. For space sensitive, the switching frequency is set to 500kHz. The required LED ripple current must lower than 10% of normal current. Please calculate the required components. (The used LED is from LUXEON, LXK2-PW14-U00, with 0.6Ω dynamic resistance)

By the formulas and calculations previous, the parameters and selected components are as bellow

1. The duty cycle is $D = (V_{F,\,LED} \times 3) / V_{IN} = (3.72V \times 3) / 24V = 0.465$
2. The current sense resistor is $Rsen = V_{SEN} / I_{OUT} = 0.3V / 1A = 0.3\Omega$. And the sustaining power dissipation is $P_{Rsen} = 0.3V^2 / 0.3\Omega = 0.3W$. Thus, the recommended is 1%, 0.3Ω with 0.3W power dissipation.
3. The inductor is

   $$L1 > (V_{IN} - V_{OUT} - V_{SEN} - (R_{ds(on)} x I_{OUT})) x \frac{D}{f_{SW} x \Delta I_L} = (24V - 11.16V - 0.3V - (0.8\Omega \times 1A)) x \frac{0.465}{500kHz x 0.6 \times 1A} = 18.2uH$$

   A 22uH inductor with 2.1A saturation current and 59.1mΩ DCR is recommended.
4. In this application, a schottky diode with 40V reverse voltage, 2A forward current, and the maximum forward voltage is 0.5V.
5. The minimum input voltage is

   $$V_{IN,\,MIN} = V_{Rsen} + V_{Rs} + V_{MOSFET} + V_{L1} + V_{F,\,LED}$$
   $$= (0.3V x1.3) + (0.6x1Ax1.3x3) + (0.8\Omega x1Ax1.3) + (59.1m\Omega x1Ax1.3) + (3.72Vx3) = 15.01V$$
6. The minimum input capacitor is $C_{IN,\,MIN} = 1.3 \times I_{OUT} \times \frac{D \times T_S}{V_{IN} - V_{IN,\,MIN}} = 1.3 \times 1A \times \frac{0.465 \times 2us}{24V - 15.01V} = 134.48nF$

   For stabilize system, a 1uF ceramic capacitor with 35V rated voltage is recommended.
7. The calculation of output capacitor is

   $$\Delta I_{OUT} = \Delta I_L \frac{1}{1 + \frac{R_{LED}}{Zc}} \quad à \quad 0.1x1A = 0.6x1A \frac{1}{1 + \frac{(11.16V/1A)}{Zc}} \quad à \quad Z_C = 2.232$$

   $$Zc = ESR + \frac{1}{2\pi \times f_{SW} \times C_{OUT}} \quad à \quad 2.232 = \frac{1}{2\pi \times 500kHz \times C_{OUT}} \quad à \quad C_{OUT} = 142.61nF$$

   Thus, the recommended selection of output capacitor is 0.22uF ceramic capacitor with 16V rated voltage.
8. The power consumptions on each component are

   $P_{OUT} = V_{OUT} \times I_{OUT} = 3 \times 3.72V \times 1A = 11.16W$

   $P_C = I_{OUT}^2 \times R_{ds(on)} \times D = (1A)^2 \times 0.8\Omega \times 0.465 = 372mW$

   $P_{SW} = V_{IN} \times I_{OUT} \times (t_r + t_f) \times f_{SW} = 24V \times 1A \times (46ns + 4.6ns) \times 500kHz = 607.2mW$

   $P_G = (I_{DD} + f_{SW} \times Q_G) \times V_{IN} = (1mA + 500kHz \times 76pF) \times 24V = 24.912mW$

   $P_L = I_{OUT}^2 \times DCR = (1A)^2 \times 59.1m\Omega = 59.1mW$

   $P_{D1} = V_{F,\,D1} \times I_{OUT} \times (1-D) = 0.5V \times 1A \times (1-0.465) = 267.5mW$

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$P_{Rsen} = V_{SEN} \times I_{OUT} = 0.3V \times 1A = 0.3W$

$P_{LOSS} = P_C + P_{SW} + P_G + P_L + P_{D1} + P_{Rsen} = 1.631W$

Thus, the efficiency in this application is $\eta = \frac{P_{OUT}}{P_{OUT} + P_{LOSS}} = \frac{11.16W}{11.16W + 1.631W} \times 100\% = 87.25\%$

9. The raised junction temperature can be estimated by

$T_J = T_A + P_{LOSS,\ IC} \times R_{th,\ JA} = 25℃ + (372mW + 607.2mW + 24.912mW) \times 32.9℃/W = 58.04℃.$

Followings show the application circuit and BOM for reference.

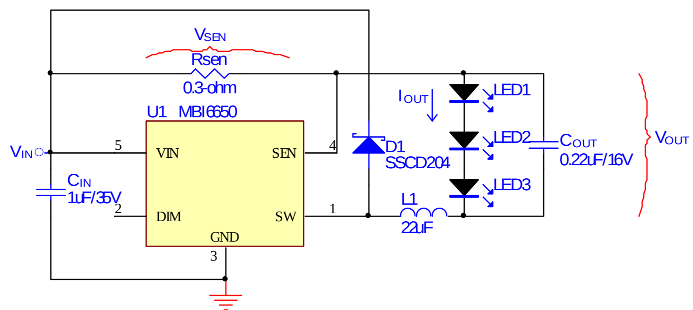

Figure 5 The application circuit of example 2

Table 2 The BOM of example 2

Designator	Part Type	Description	Vendor	Contact Window
C1	1uF/35V	0603, GMK107BJ105KA-T, ceramic capacitor	TAIYO YUDEN	+886-2-2797-2155
C2	220nF/16V	0603, EMK107BJ224KA-T, ceramic capacitor	TAIYO YUDEN	+886-2-2797-2155
D1	SSCD204	40V/2A Surface Mount Schottky Barrier Rectifier	ZOEWIE	+886-2-2219-5533-211
L1	22uH	SLF10145TL-220M1R9-PF	TDK	+886-3-592-7225
R1	0.3Ω	2010, CR-0AFL4-0R300, SMD Resistor	TMTEC	+886-3-564-1818-68
U1	MBI6650	Constant Current DC/DC Converter	MBI	+886-3-579-0068

PCB Layout Consideration

For enhance efficiency and stabilize system, careful printed circuit layout is important. There are several notes need to be taken.

1. Keeps a complete ground area is helpful to eliminate the switching noise.
2. Keep the IC's GND pin and the ground leads of input and output filter capacitors less than 5mm.
3. To maximize output power, efficiency and minimize output ripple voltage, use a ground plane and solder the IC's GND pin directly to the ground plane.
4. For stabilize system, the heat sink of MBI6650 is recommended to connect to ground plane directly.
5. For enhance heat dissipation, the area of ground plane, which IC's heat sink is soldered on it, should be as larger as possible.
6. The input capacitor should be placed to IC's VIN pin as close as possible.
7. The area, which is comprised by IC's SW pin, schottky diode and inductor, should be wide and short.
8. The path, which flows large current, should be wide and short to eliminate the parasite element.
9. When SW is on/off, the direction of power loop should keep the same way to enhance the efficiency. The sketch is shown as figure 6.

Figure 7 is the recommended layout diagram of MBI6650.

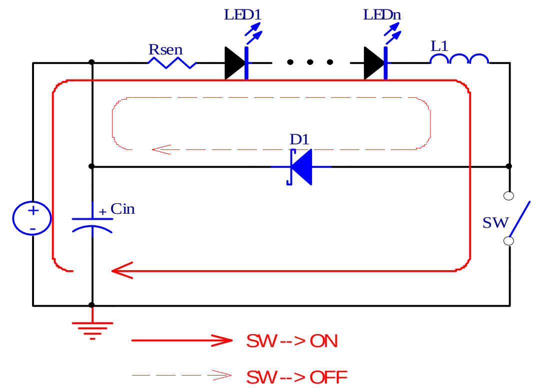

Figure 6 Power loop of MBI6650

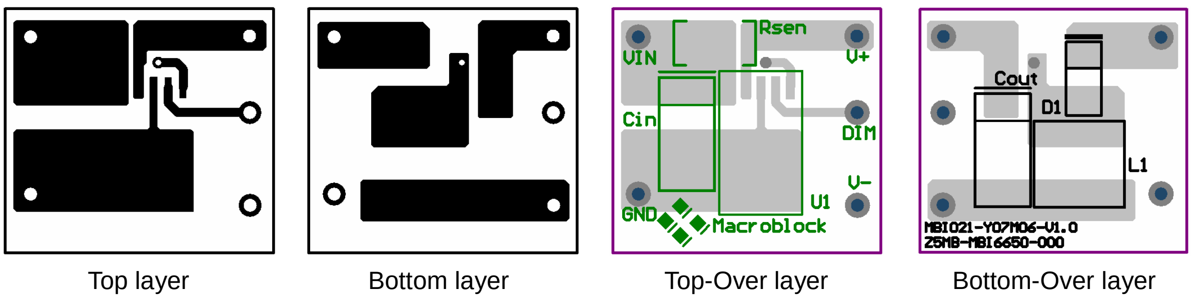

Figure 7. The layout diagram of MBI6650

END.

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