

1.5A, 2 MHz Integrated Switch Buck Regulator

Features

- 2.7V to 5.5V Supply Voltage
- 2 MHz PWM Mode
- Output Current to 1.5A
- Up to 94% Efficiency
- 100% Maximum Duty Cycle
- Adjustable Output Voltage Option Down to 1V
- Ultra-Fast Transient Response
- Ultra-Small External Components
- Stable with a 1 μ H Inductor and a 4.7 μ F Output Capacitor
- Fully Integrated 1.5A MOSFET Switch
- Micropower Shutdown
- Power Good Pin
- Thermal Shutdown and Current Limit Protection
- Pb-Free 10-Lead MSOP Package
- -40°C to $+125^{\circ}\text{C}$ Junction Temperature Range

Applications

- FPGA/DSP/ASIC Applications
- General Point-of-Load
- Broadband Communications
- DVD/TV Recorders
- Point-of-Sale
- Printers/Scanners
- Set Top Boxes
- Computing Peripherals
- Video Cards

General Description

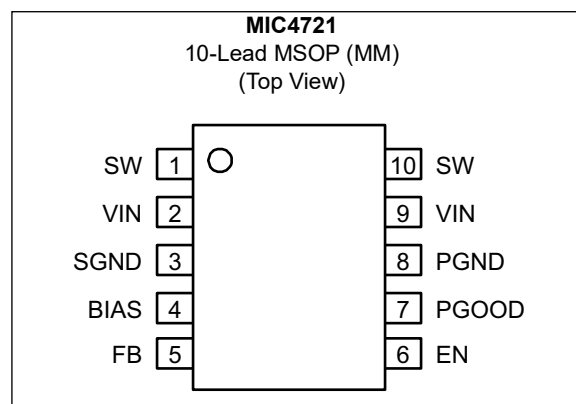
The MIC4721 is a high efficiency, PWM buck (step-down) regulator that provides up to 1.5A of output current. The MIC4721 operates at 2 MHz and has proprietary internal compensation that allows a closed loop bandwidth of over 200 kHz.

The low on-resistance internal P-channel MOSFET of the MIC4721 allows efficiencies up to 94%, reduces external components count, and eliminates the need for an expensive current sense resistor.

The MIC4721 operates from a 2.7V to 5.5V input and the output can be adjusted down to 1V. The device can operate with a maximum duty cycle of 100% for use in low-dropout conditions.

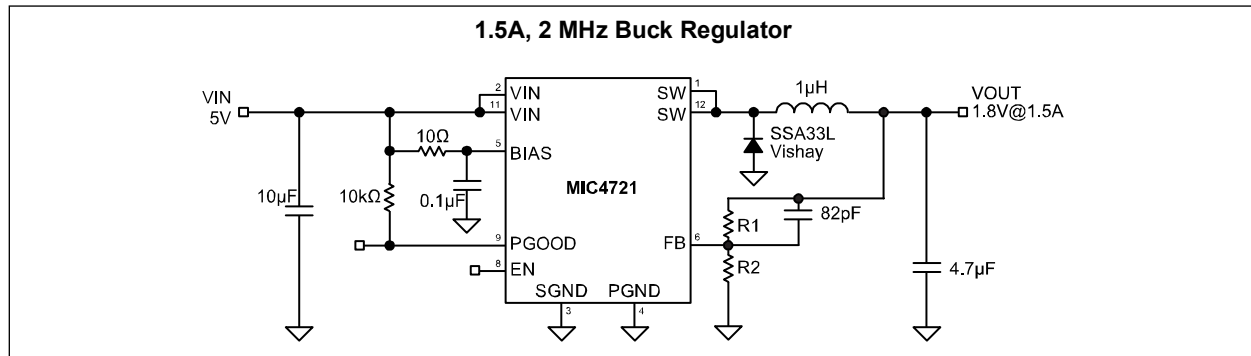
The MIC4721 is available in a 10-lead MSOP package with a junction operating range from -40°C to $+125^{\circ}\text{C}$.

Package Type

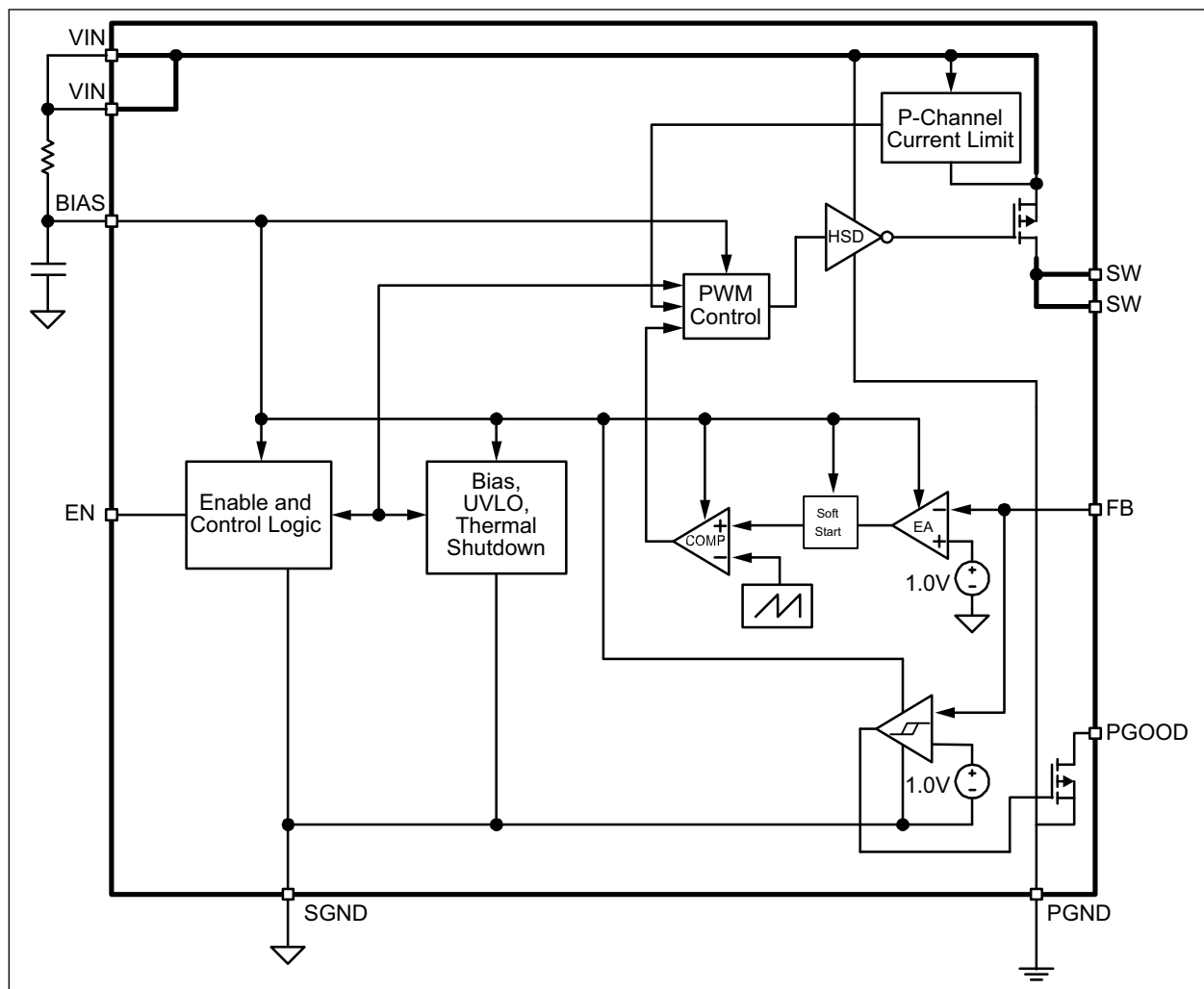


MIC4721

Typical Application Circuit



Functional Block Diagram



1.0 ELECTRICAL CHARACTERISTICS

Absolute Maximum Ratings †

Supply Voltage (V_{IN})	+6V
Output Switch Voltage (V_{SW})	+6V
Output Switch Current (I_{SW})	11A
Logic Input Voltage (V_{EN})	-0.3V to V_{IN}

Operating Ratings ‡

Supply Voltage (V_{IN})	+2.7V to +5.5V
Logic Input Voltage (V_{EN})	0V to V_{IN}

† **Notice:** Stresses above those listed under “Absolute Maximum Ratings” may cause permanent damage to the device. This is a stress rating only and functional operation of the device at those or any other conditions above those indicated in the operational sections of this specification is not intended. Exposure to maximum rating conditions for extended periods may affect device reliability.

‡ **Notice:** The device is not guaranteed to function outside its operating ratings.

ELECTRICAL CHARACTERISTICS

$V_{IN} = V_{EN} = 3.6V$; $L = 1 \mu H$; $C_{OUT} = 4.7 \mu F$; $T_A = +25^\circ C$, unless noted. **Bold** values valid for $-40^\circ C \leq T_J \leq +125^\circ C$. (Note 1)

Parameter	Min.	Typ.	Max.	Units	Conditions
Supply Voltage Range	2.7	—	5.5	V	—
Undervoltage Lockout Threshold	2.45	2.55	2.65	V	Turn-on
UVLO Hysteresis	—	100	—	mV	—
Quiescent Current	—	570	900	μA	$V_{FB} = 0.9 \times V_{NOM}$ (not switching)
Shutdown Current	—	2	10	μA	$V_{EN} = 0V$
Adjustable Feedback Voltage	0.98	—	1.02	V	$\pm 2\%$ (over temperature) $I_{LOAD} = 100 \text{ mA}$
Feedback Pin Input Current	—	1	—	nA	—
Current Limit in PWM Mode	3.5	5	—	A	$V_{FB} = 0.9 \times V_{NOM}$
Output Voltage Line Regulation	—	0.07	—	%	$V_{OUT} > 2V$; $V_{IN} = V_{OUT} + 500 \text{ mV}$ to $5.5V$; $I_{LOAD} = 100 \text{ mA}$
	—	0.07	—	%	$V_{OUT} < 2V$; $V_{IN} = 2.7V$ to $5.5V$; $I_{LOAD} = 100 \text{ mA}$
Output Voltage Load Regulation	—	0.2	—	%	$20 \text{ mA} < I_{LOAD} < 3A$
Maximum Duty Cycle	100	—	—	%	$V_{FB} \leq 0.4V$
PWM Switch ON-Resistance	—	95	200	$m\Omega$	$I_{SW} = 50 \text{ mA}$; $V_{FB} = 0.7 \times V_{FB(NOM)}$ (High-Side Switch)
	—	—	300	$m\Omega$	
Oscillator Frequency	1.8	2	2.2	MHz	—
Enable Threshold	0.5	0.85	1.3	V	—
Enable Hysteresis	—	50	—	mV	—
Enable Input Current	—	0.1	2.3	μA	—
Power Good Range	—	± 7	± 10	%	—
Power Good Resistance	—	145	250	Ω	$I_{PGOOD} = 500 \mu A$
Overtemperature Shutdown	—	160	—	$^\circ C$	—
Overtemperature Hysteresis	—	20	—	$^\circ C$	—

Note 1: Specification for packaged product only.

MIC4721

TEMPERATURE SPECIFICATIONS

Parameters	Sym.	Min.	Typ.	Max.	Units	Conditions
Temperature Ranges						
Junction Temperature Range	T_J	-40	—	+125	°C	—
Storage Temperature Range	T_S	-65	—	+150	°C	—
Package Thermal Resistances						
Thermal Resistance, MSOP 10-Ld	θ_{JA}	—	130	—	°C/W	—
	θ_{JC}	—	43	—	°C/W	—

2.0 TYPICAL PERFORMANCE CURVES

Note: The graphs and tables provided following this note are a statistical summary based on a limited number of samples and are provided for informational purposes only. The performance characteristics listed herein are not tested or guaranteed. In some graphs or tables, the data presented may be outside the specified operating range (e.g., outside specified power supply range) and therefore outside the warranted range.

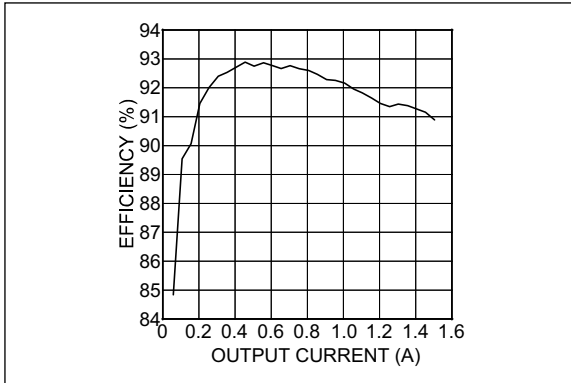


FIGURE 2-1: 3.3V V_{IN} to 2.5V V_{OUT}
Efficiency.

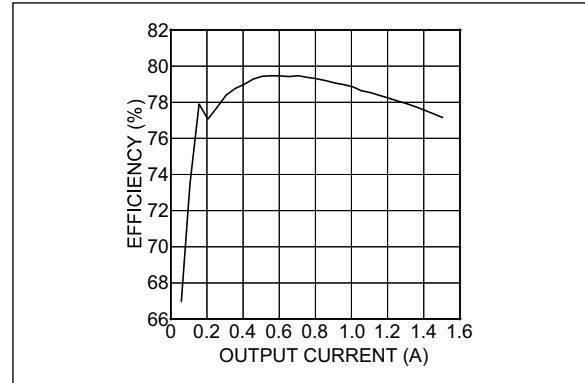


FIGURE 2-4: 3.3V V_{IN} to 1.2V V_{OUT}
Efficiency.

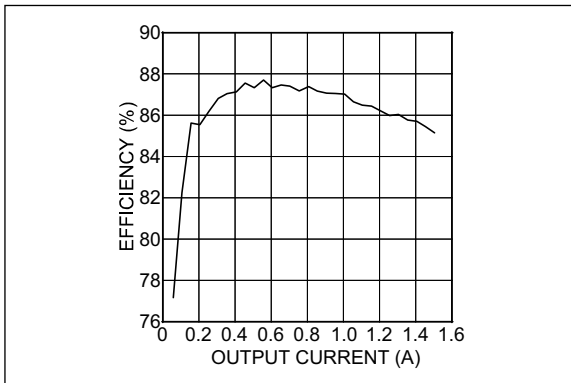


FIGURE 2-2: 3.3V V_{IN} to 1.8V V_{OUT}
Efficiency.

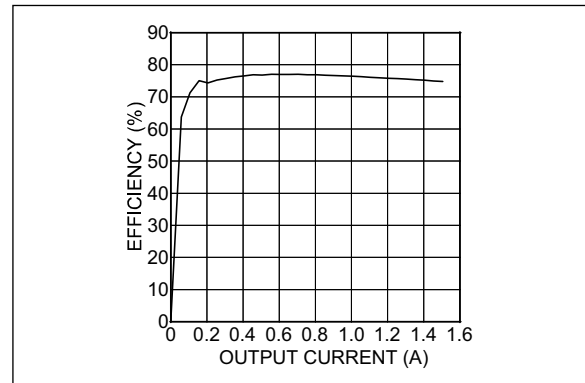


FIGURE 2-5: 3.3V V_{IN} to 1.0V V_{OUT}
Efficiency.

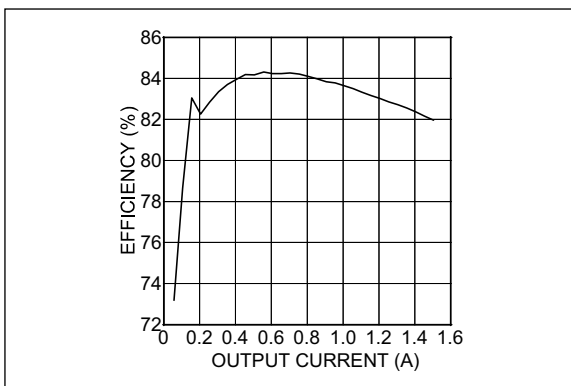


FIGURE 2-3: 3.3V V_{IN} to 1.5V V_{OUT}
Efficiency.

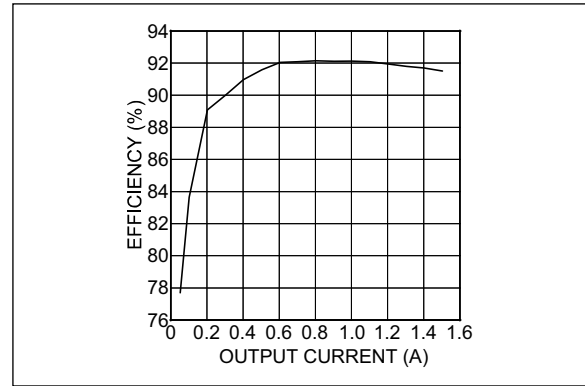


FIGURE 2-6: 5.0V V_{IN} to 3.3V V_{OUT}
Efficiency.

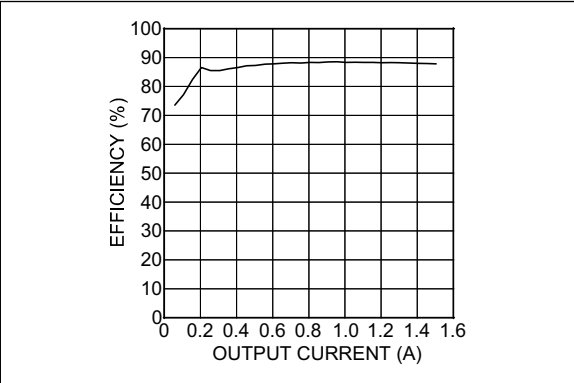


FIGURE 2-7: 5.0V V_{IN} to 2.5V V_{OUT} Efficiency.

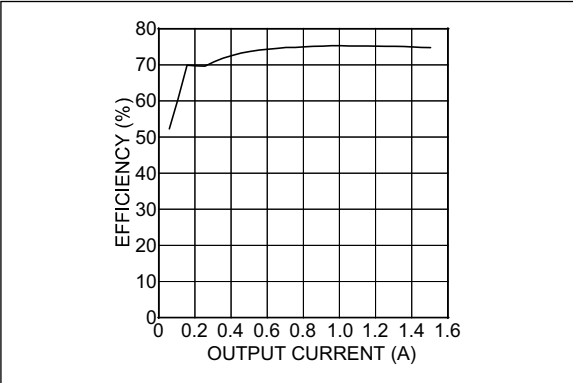


FIGURE 2-10: 5.0V V_{IN} to 1.2V V_{OUT} Efficiency.

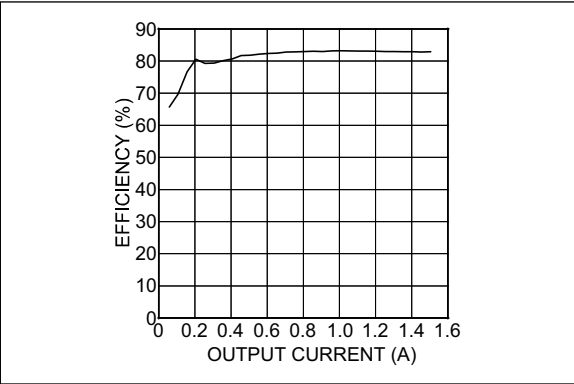


FIGURE 2-8: 5.0V V_{IN} to 1.8V V_{OUT} Efficiency.

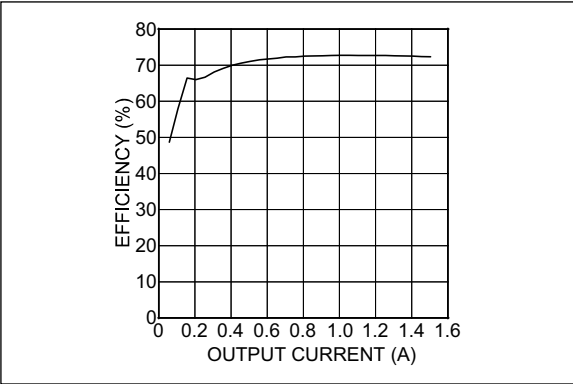


FIGURE 2-11: 5.0V V_{IN} to 1.0V V_{OUT} Efficiency.

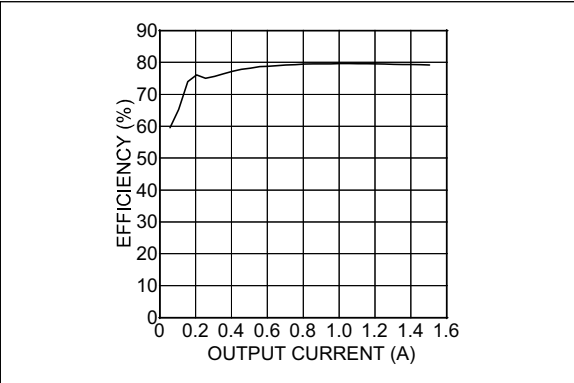


FIGURE 2-9: 5.0V V_{IN} to 1.5V V_{OUT} Efficiency.

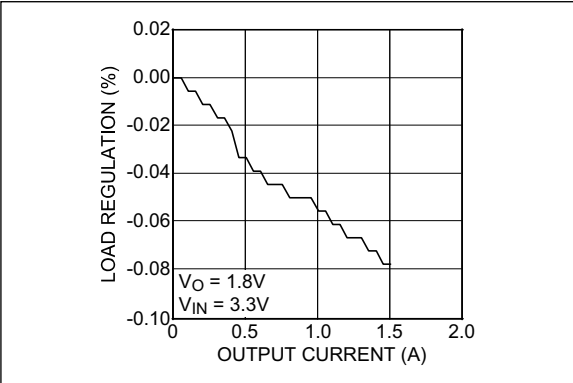


FIGURE 2-12: Load Regulation.

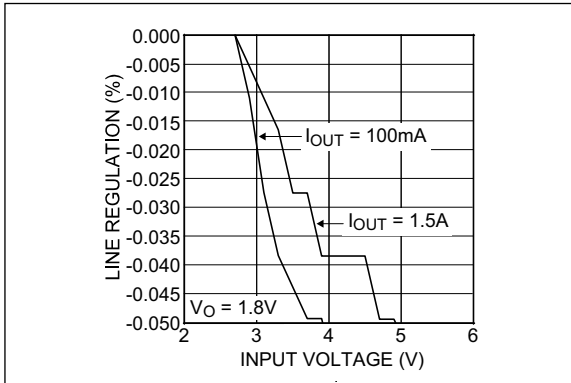


FIGURE 2-13: Line Regulation.

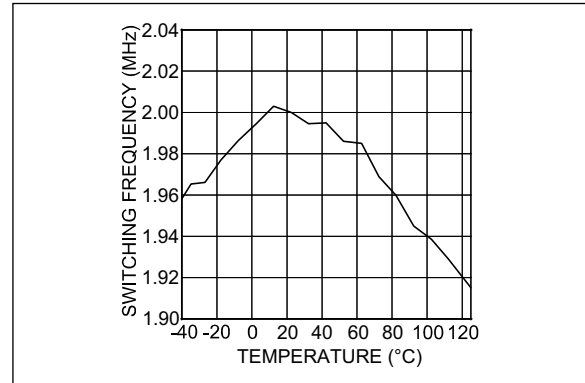


FIGURE 2-16: Switching Frequency vs. Temperature.

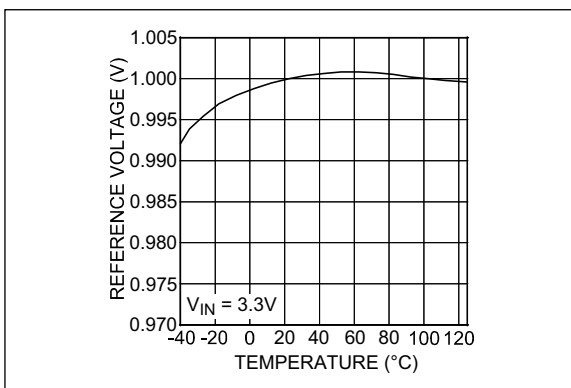


FIGURE 2-14: Reference Voltage vs. Temperature.

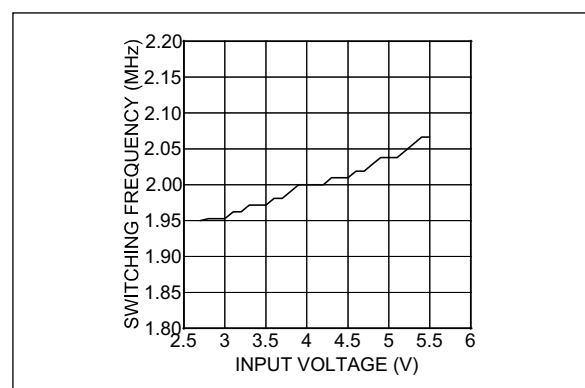


FIGURE 2-17: Switching Frequency vs. Input Voltage.

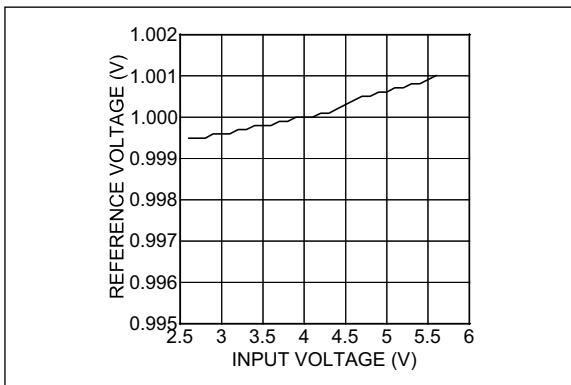


FIGURE 2-15: Reference Voltage vs. Input Voltage.

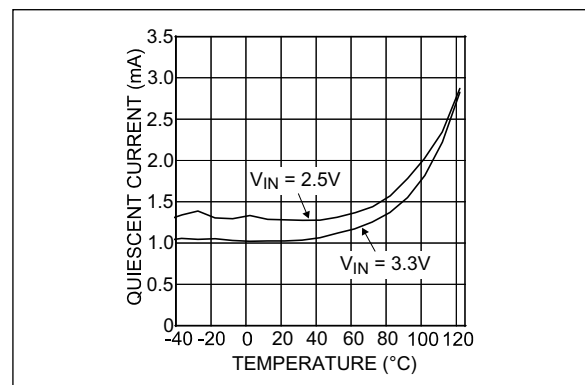


FIGURE 2-18: Quiescent Current vs. Temperature.

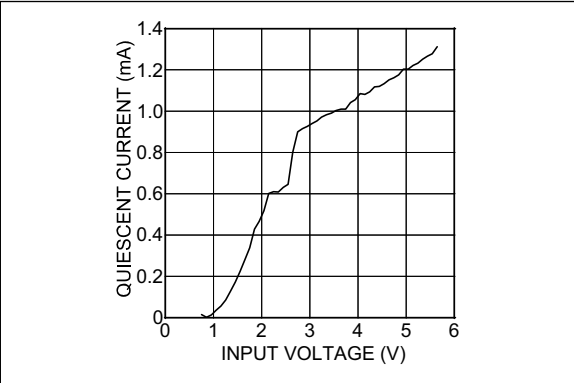


FIGURE 2-19: Quiescent Current vs. Input Voltage.

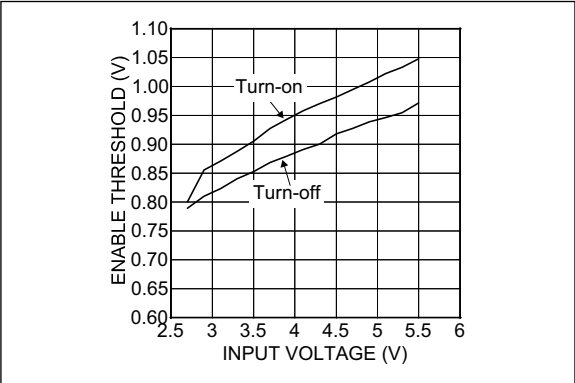


FIGURE 2-22: Enable Threshold vs. Input Voltage.

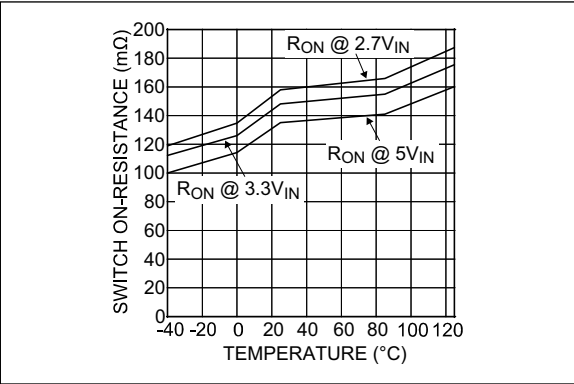


FIGURE 2-20: Switch On-Resistance vs. Temperature.

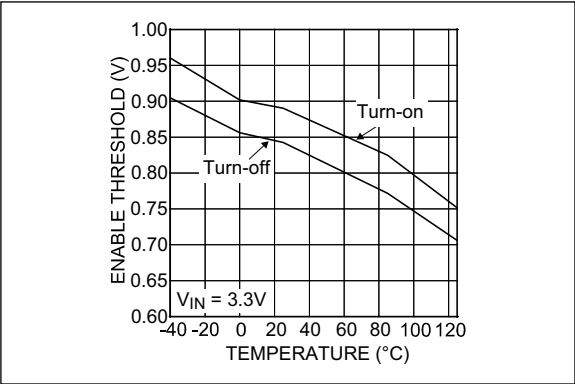


FIGURE 2-23: Enable Threshold vs. Temperature.

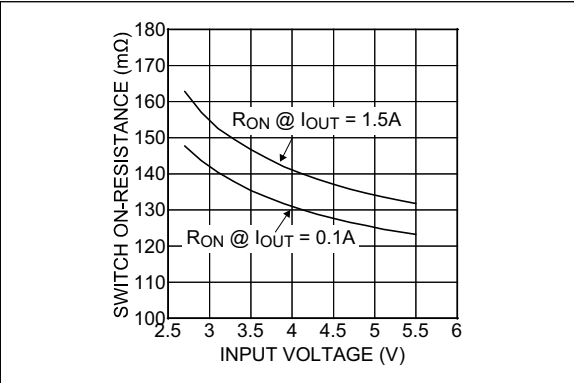


FIGURE 2-21: Switch On-Resistance vs. Input Voltage.

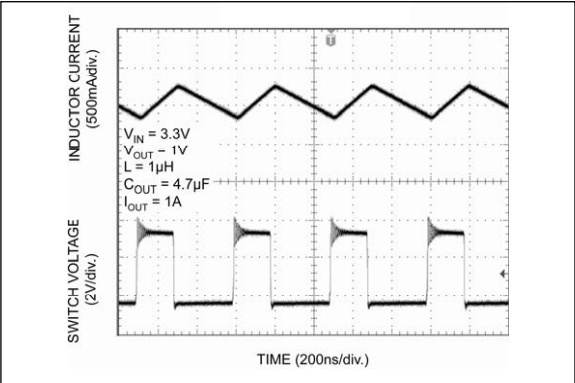


FIGURE 2-24: Continuous Current.

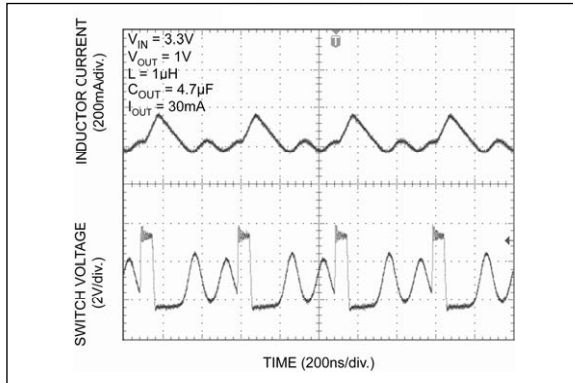


FIGURE 2-25: Discontinuous Current.

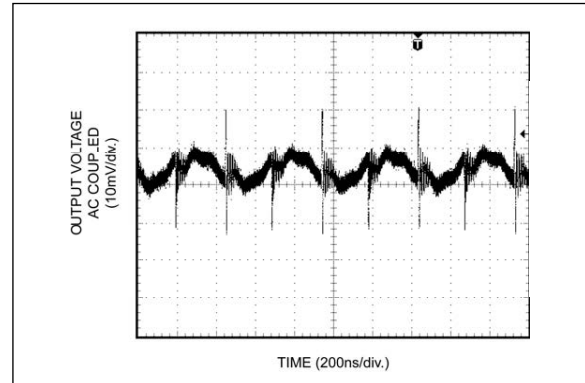


FIGURE 2-27: Output Ripple.

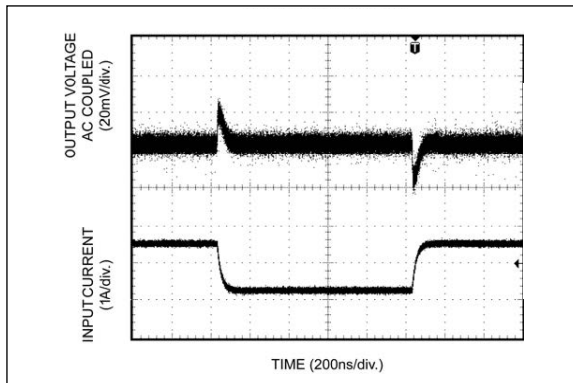


FIGURE 2-26: Transient Response.

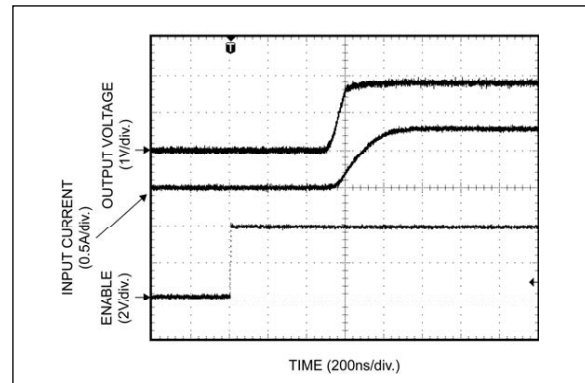


FIGURE 2-28: Turn-On.

3.0 PIN DESCRIPTIONS

The descriptions of the pins are listed in [Table 3-1](#).

TABLE 3-1: PIN FUNCTION TABLE

Pin Number	Pin Name	Description
1, 10	SW	Switch (Output): Internal power P-Channel MOSFET output switch.
2, 9	VIN	Supply Voltage (Input): Supply voltage for the source of the internal P-channel MOSFET and driver. Requires bypass capacitor to GND.
3	SGND	Signal (Analog) Ground. Provides return path for control circuitry and internal reference.
4	BIAS	Internal circuit bias supply. Must be bypassed with a 0.1 μ F ceramic capacitor to SGND.
5	FB	Feedback. Input to the error amplifier. Connect to the external resistor divider network to set the output voltage.
6	EN	Enable (Input). Logic level low will shut down the device, reducing the current draw to less than 5 μ A.
7	PGOOD	Power Good. Open-drain output that is pulled to ground when the output voltage is within $\pm 7.5\%$ of the set regulation voltage.
8	PGND	Power Ground. Provides the ground return path for the high-side drive current.

3.1 VIN

Two pins for VIN provide power to the source of the internal P-channel MOSFET along with the current limiting sensing. The VIN operating voltage range is from 2.7V to 5.5V. Due to the high switching speeds, a 10 μ F capacitor should be placed close to VIN and power ground (PGND) at each pin for bypassing. Please refer to the section on layout recommendations.

3.2 BIAS

The bias provides power to the internal reference and control sections of the MIC4721. A 10 Ω resistor from VIN to BIAS and a 0.1 μ F from BIAS to SGND are required.

3.3 EN

The enable pin provides a logic level control of the output. At a low level, the output is shut off and supply current at the VIN pin is greatly reduced (typically <2 μ A). A high level turns the output on. The enable pin must not be driven above the supply voltage.

3.4 FB

The feedback pin connects to the negative input of the internal error amplifier. The pin is connected to an external resistor divider, which sets the output voltage.

A feedforward capacitor across the upper resistor in the divider is recommended for most designs. To reduce current draw, a 10 k Ω feedback resistor is recommended from the output to the FB pin (R1). The large resistor value and the parasitic capacitance of the FB pin can cause a high frequency pole that can reduce the overall system phase margin. By placing a feedforward capacitor, these effects can be significantly reduced.

3.5 SW

The switch pin connects directly to the inductor and provides the switching current necessary to operate in PWM mode. Due to the high speed switching on this pin, the switch node should be routed away from sensitive nodes. This pin also connects to the cathode of the free-wheeling diode.

3.6 PGOOD

The power good pin pulls low to indicate the output voltage is within its regulation range. When power good is low, then the output voltage is within $\pm 10\%$ of the set regulation voltage. For output voltages greater or less than 10%, the PGOOD pin is high. This should be connected to the input supply through a pull-up resistor. A delay can be added by placing a capacitor from PGOOD to ground.

3.7 PGND

Power ground is the ground path for the MOSFET drive current. The current loop for the power ground should be as small as possible and separate from the Signal ground (SGND) loop. Refer to the section on layout recommendations for more details.

3.8 SGND

Signal ground is the ground path for the biasing and control circuitry. The current loop for the signal ground should be separate from the power ground (PGND) loop. Refer to the section on layout recommendations for more details.

4.0 APPLICATION INFORMATION

The MIC4721 is a 1.5A PWM non-synchronous buck regulator. A regulated DC output voltage is obtained by switching an input voltage supply and filtering the switched voltage through an inductor and capacitor. Figure 4-1 shows a simplified example of a non-synchronous buck converter and its input/output voltage.

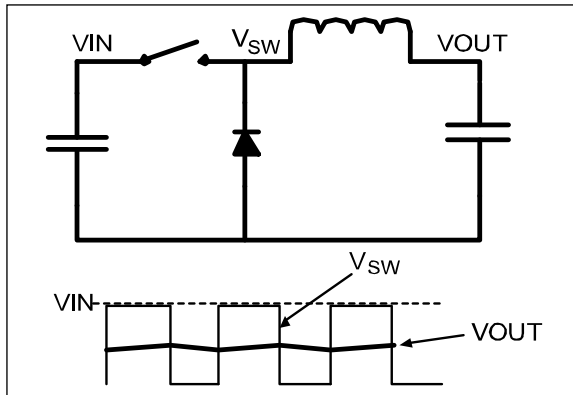


FIGURE 4-1: Simplified Buck Converter.

For a non-synchronous buck converter, there are two modes of operation: continuous and discontinuous. The mode refers to the state of current in the inductor. If current continuously flows through the inductor throughout the switching cycle, it is in continuous operation. If the inductor current drops to zero during the off time, it is in discontinuous operation. Critically continuous is the point where any decrease in output current will cause it to enter discontinuous operation. The critically continuous load current can be calculated as follows.

EQUATION 4-1:

$$I_{OUT(CRIT)} = \frac{V_{OUT} - \frac{V_{OUT}^2}{V_{IN}}}{2 \times L \times f_{SW}}$$

Where:

f_{SW} = The switching frequency (2 MHz for the MIC4721).

L = The output inductance (in Henry).

When I_{OUT} is less than $I_{OUT(CRIT)}$, the buck converter operates in discontinuous mode and the inductor current goes to zero before the end of each switching cycle. When I_{OUT} is greater than $I_{OUT(CRIT)}$, the converter operates in continuous mode and current always flows through the inductor. Continuous or discontinuous operation determines how peak inductor current is calculated.

4.1 Continuous Operation

Figure 4-2 illustrates the switch voltage and inductor current during continuous operation.

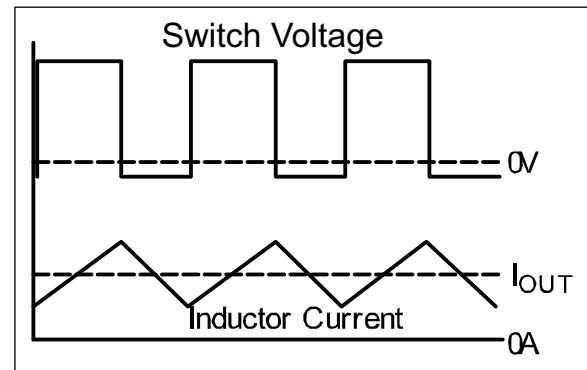


FIGURE 4-2: Continuous Operation.

The output voltage is regulated by pulse width modulating (PWM) the switch voltage to the average required output voltage. The switching can be divided into two cycles: On and Off.

As seen in Figure 4-3, the high-side switch is turned on (on-time) and the current flows from the input supply through the inductor and to the output.

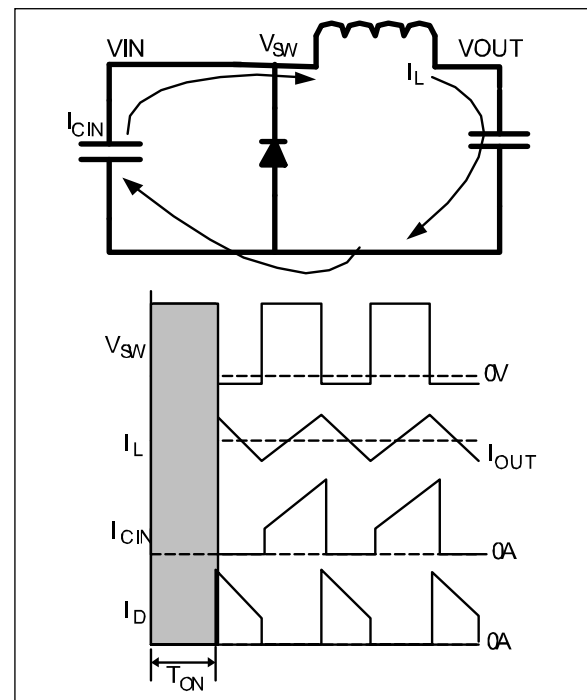


FIGURE 4-3: On-Time.

The inductor current is charged at the rate:

EQUATION 4-2:

$$\frac{(V_{IN} - V_{OUT})}{L}$$

To determine the total on-time, or the time at which the inductor charges, the duty cycle needs to be calculated. The duty cycle can be calculated as:

$$D = \frac{V_{OUT}}{V_{IN}}$$

and the On-Time is:

$$t_{ON} = \frac{D}{f_{SW}}$$

therefore, peak-to-peak inductor ripple is:

$$I_{PK-PK} = I_{OUT} + \frac{(V_{IN} - V_{OUT}) \times \frac{V_{OUT}}{V_{IN}}}{f_{SW} \times L}$$

Peak-to-peak ripple current is used in calculating output voltage ripple.

The peak current (or maximum inductor current) is equal to the output current plus ½ the peak-to-peak current.

EQUATION 4-3:

$$I_{PK} = I_{OUT} + \frac{(V_{IN} - V_{OUT}) \times \frac{V_{OUT}}{V_{IN}}}{2 \times f_{SW} \times L}$$

The peak inductor current is used when selecting a suitable output inductor.

Figure 4-4 demonstrates circuit activity during the off-time. When the high-side internal P-channel MOSFET turns off, the current must flow through the free-wheeling diode, because inductor current must remain continuous. In this case, the inductor discharge rate is:

EQUATION 4-4:

$$\frac{(V_{OUT} + V_D)}{L}$$

The total off-time can be calculated as:

$$t_{OFF} = \frac{1-D}{f_{SW}}$$

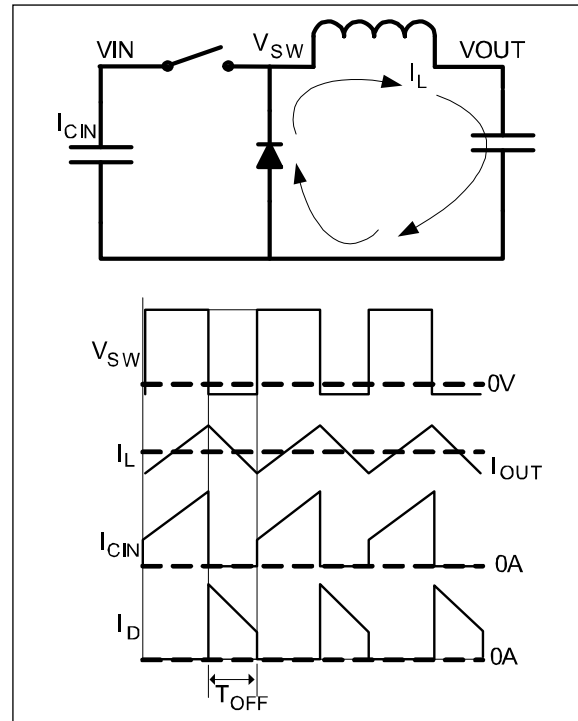


FIGURE 4-4: Off-Time.

4.2 Discontinuous Operation

Discontinuous operation is when the inductor current discharges to zero at sometime during the off cycle. Figure 4-5 demonstrates the switch voltage and inductor currents during discontinuous operation.

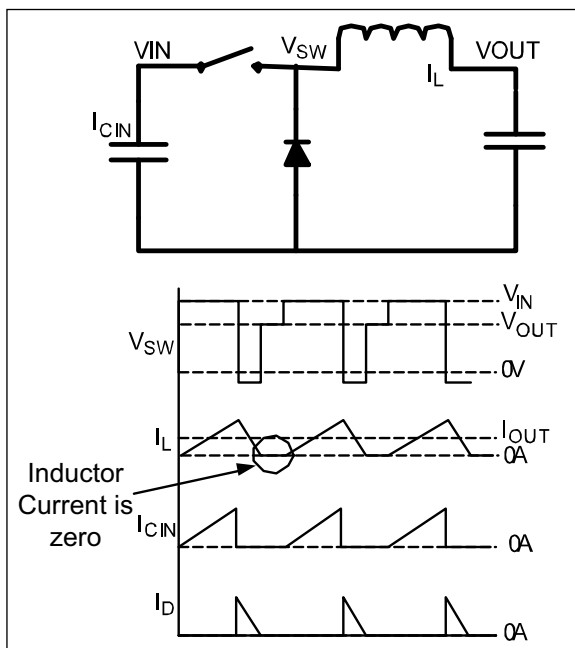


FIGURE 4-5: Discontinuous Operation.

When the inductor current (I_L) has completely discharged, the voltage on the switch node rings at the frequency determined by the parasitic capacitance and the inductor value. In Figure 4-5, it is drawn as a DC voltage, but to see actual operation (with ringing) refer to the functional characteristics.

Discontinuous mode of operation has the advantage over full PWM in that, at light loads, the MIC4721 will skip pulses as necessary, reducing gate drive losses and drastically improving light load efficiency.

4.3 Duty Cycle Considerations

The P-Channel MOSFET inside the MIC4721 allows the FET to remain in the on-state indefinitely (100% duty cycle). This feature is useful for maintaining output voltage regulation in battery-powered and other applications where the input voltage drops close to the output voltage.

When the MOSFET is operating at the 2 MHz switching frequency, the maximum operating duty cycle is typically 82%. In situations where a duty cycle greater than the maximum operating duty cycle is required, the MIC4721 will keep the FET turned on for additional cycles to maintain output voltage regulation. This effectively decreases the switching frequency, allowing a larger duty cycle. The output voltage ripple increases slightly when the MIC4721 is in pulse skipping mode.

4.4 Efficiency Considerations

Calculating the efficiency is as simple as measuring power out and dividing it by the power in.

EQUATION 4-5:

$$Efficiency = \frac{P_{OUT}}{P_{IN}} \times 100$$

Where:

$$P_{IN} = V_{IN} \times I_{IN}$$

$$P_{OUT} = V_{OUT} \times I_{OUT}$$

The efficiency of the MIC4721 is determined by several factors:

- $R_{DS(ON)}$ (internal P-channel resistance)
- Diode conduction losses
- Inductor conduction losses
- Switching losses

$R_{DS(ON)}$ losses are caused by the current flowing through the high side P-channel MOSFET. The amount of power loss can be approximated by:

EQUATION 4-6:

$$P_{SW} = R_{DS(ON)} \times I_{OUT}^2 \times D$$

Where:

D = Duty cycle.

Because the MIC4721 uses an internal P-channel MOSFET, $R_{DS(ON)}$ losses are inversely proportional to supply voltage. Higher supply voltage yields a higher gate to source voltage, reducing the $R_{DS(ON)}$, thus reducing the MOSFET conduction losses. A graph showing typical $R_{DS(ON)}$ versus input supply voltage can be found in the typical characteristics section of this data sheet.

Diode conduction losses occur due to the forward voltage drop (V_F) and the output current. Diode power losses can be approximated as follows:

EQUATION 4-7:

$$P_D = V_F \times I_{OUT} \times (1 - D)$$

For this reason, Schottky diodes with low forward voltage drop are preferred as rectifiers. The low forward voltage drop will help reduce diode conduction losses and improve efficiency. Duty cycle, or the ratio of output voltage to input voltage, determines whether the dominant factor in conduction losses will be the internal MOSFET or the Schottky diode. Higher duty cycles

place the power losses on the high-side switch and lower duty cycles place the majority of power loss on the Schottky diode.

Inductor conduction losses (P_L) can be calculated by multiplying the DC resistance (DCR) times the square of the output current:

EQUATION 4-8:

$$P_L = DCR \times I_{OUT}^2$$

Also, special attention should be given to the additional core losses associated with switching current in an inductor. Because most inductor manufacturers do not provide data about the type of material used, approximating core losses becomes very difficult, so the inductor temperature rise should be measured.

Switching losses occur twice each cycle, when the switch turns on and when the switch turns off. This is caused by a non-ideal world where switching transitions are not instantaneous and neither are current transitions. Figure 4-6 demonstrates how switching losses caused by the transitions dissipate power in the switch.

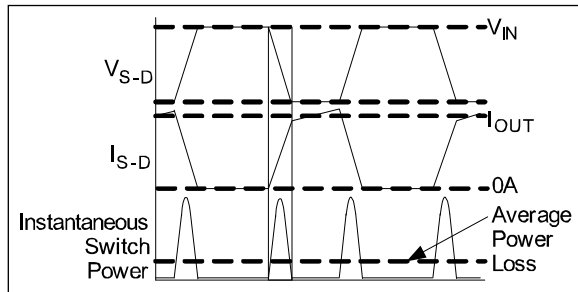


FIGURE 4-6: Switching Transition Losses.

Normally, when the switch is on, the voltage across the switch is low (virtually zero) and the current through the switch is high. This equates to low power dissipation. When the switch is off, voltage across the switch is high and the current is zero, again with power dissipation being low. During the transitions, the voltage across the switch (V_{S-D}) and the current through the switch (I_{S-D}) are at midpoint of their excursions and cause the transition to be at the highest instantaneous power point. During continuous mode, these losses are the highest. Also, with higher load currents, these losses are higher. For discontinuous operation, the transition losses only occur during the “off” transition because during the “on” transitions there is no current flow through the inductor.

4.5 Component Selection

4.5.1 INPUT CAPACITOR

A 10 μF ceramic is recommended on each VIN pin for bypassing. X5R or X7R dielectrics are recommended for the input capacitor. Y5V dielectrics lose most of their capacitance over temperature and voltage and are, therefore, not recommended. Also, tantalum and electrolytic capacitors alone are not recommended because of their reduced RMS current handling, reliability, and higher ESR. Smaller case size capacitors are recommended due to their lower ESL (equivalent series inductance). Please refer to layout recommendations for proper layout of the input capacitors.

4.5.2 OUTPUT CAPACITOR

The MIC4721 is designed for a 4.7 μF output capacitor. X5R or X7R dielectrics are recommended for the output capacitor. Y5V dielectrics lose most of their capacitance over temperature and voltage and are, therefore, they are not recommended. Smaller case size capacitors are recommended due to their lower ESL. The MIC4721 utilizes type III voltage mode internal compensation and utilizes an internal zero to compensate for the double pole roll-off of the LC filter. For this reason, larger output capacitors can create instabilities. In cases where a 4.7 μF output capacitor is not sufficient, the MIC2208 offers the ability to externally control the compensation, allowing for a wide range of output capacitor types and values.

4.6 Inductor Selection

The MIC4721 is designed for use with a 1 μH inductor. Proper selection should ensure the inductor can handle the maximum RMS and peak currents required by the load. Maximum current ratings of the inductor are generally given in two methods: permissible DC current and saturation current. Permissible DC current can be rated either for a 40°C temperature rise or a 10% to 20% loss in inductance. Ensure the inductor selected can handle the maximum operating current. When saturation current is specified, make sure that there is enough margin at the peak current because, at higher temperatures, the inductor will saturate at a lower current.

4.7 Diode Selection

Because the MIC4721 is non-synchronous, a free-wheeling diode is required for proper operation. A Schottky diode is recommended due to the low forward voltage drop and fast reverse recovery time. The diode should be rated to handle the average output current. Also, the reverse voltage rating of the diode should exceed the maximum input voltage. Please refer to the layout recommendations to minimize switching noise.

4.8 Feedback Resistors

The feedback resistors set the output voltage by dividing down the output and sending it to the feedback pin. The feedback voltage is 1.0V. Calculating the set output voltage is as follows:

EQUATION 4-9:

$$V_{OUT} = V_{FB} \times \left(\frac{R1}{R2} + 1 \right)$$

Where:

R1 = The resistor from VOUT to FB.

R2 = The resistor from FB to GND.

The recommended feedback resistor values for common output voltages are available in the [Bill of Materials](#). Although the resistance range of the FB resistors is very wide, R1 is recommended to be 10 kΩ. This minimizes the effect the parasitic capacitance of the FB node. Resistor R2 can be calculated by:

EQUATION 4-10:

$$R2 = \frac{R1 \times V_{FB}}{V_{OUT} - V_{FB}}$$

4.9 Feedforward Capacitor (C_{FF})

A capacitor across the resistor connected from the output to the Feedback pin (R1) is recommended for most designs. This capacitor can give a boost to phase margin and increase the bandwidth for transient response. Also, large values of feedforward capacitance can slow down the turn-on characteristics, reducing inrush current. For maximum phase boost, C_{FF} can be calculated as follows:

EQUATION 4-11:

$$C_{FF} = \frac{1}{2\pi \times 200kHz \times R1}$$

4.10 Bias Filter

A small 10Ω resistor is recommended from the input supply to the bias pin along with a small 0.1 μF ceramic capacitor from BIAS to Ground. This will bypass the high frequency noise generated by the violent switching of high currents from reaching the internal reference and control circuitry. Tantalum and electrolytic capacitors are not recommended because these types of capacitors aren't as effective at filtering high frequencies.

4.11 Loop Stability and Bode Analysis

Bode analysis is an excellent way to measure small signal stability and loop response in power supply designs. Bode analysis monitors gain and phase of a control loop. This is done by breaking the feedback loop and injecting a signal into the feedback node and comparing the injected signal to the output signal of the control loop. This will require a network analyzer to sweep the frequency and compare the injected signal to the output signal. The most common method of injection is the use of a transformer. [Figure 4-7](#) demonstrates how a transformer is used to inject a signal into the feedback network.

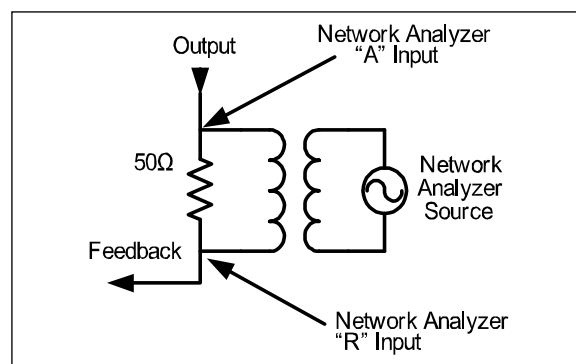


FIGURE 4-7: Transformer Injection.

A 50Ω resistor allows impedance matching from the network analyzer source. This method allows the DC loop to maintain regulation and allows the network analyzer to insert an AC signal on top of the DC voltage.

The network analyzer will then sweep the source while monitoring A and R for an A/R measurement. While this is the most common method for measuring the gain and phase of a power supply, it does have significant limitations. Firstly, to measure low frequency gain and phase, the transformer needs to be high in inductance. This makes frequencies <100 Hz require an extremely large and expensive transformer. Conversely, it must be able to inject high frequencies. Transformers with these wide frequency ranges generally need to be custom made and are extremely expensive. By using an op-amp, cost and frequency limitations caused by an injection transformer are completely eliminated. [Figure 4-8](#) demonstrates using an op-amp in a summing amplifier configuration for signal injection.

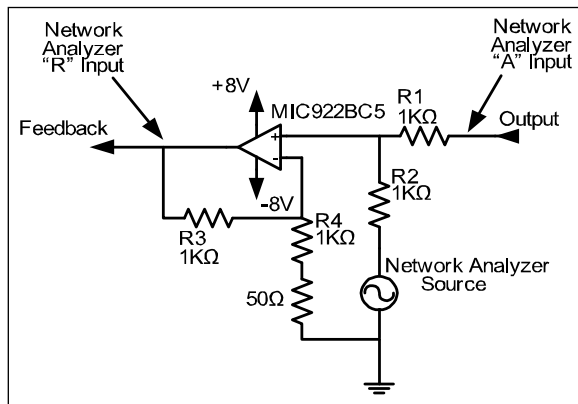


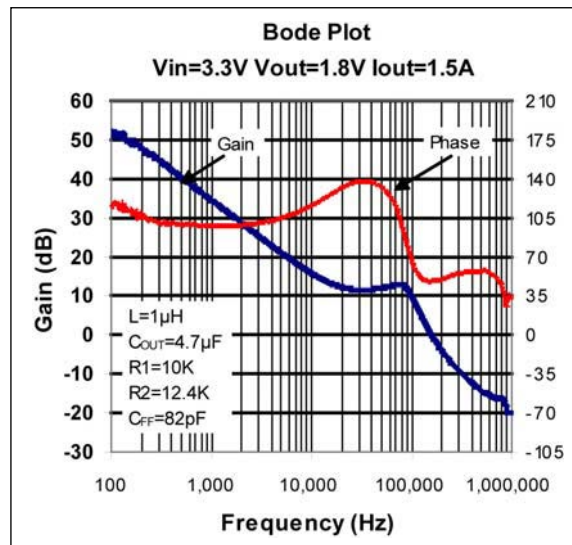
FIGURE 4-8: Op Amp Injection.

R1 and R2 reduce the DC voltage from the output to the non-inverting input by half. The network analyzer is generally a 50Ω source. R1 and R2 also divide the AC signal sourced by the network analyzer by half. These two signals are “summed” together at half of their original input. The output is then amplified by two by R3 and R4 (the 50Ω is to balance the network analyzer’s source impedance) and sent to the feedback signal. This essentially breaks the loop and injects the AC signal on top of the DC output voltage and sends it to the feedback. By monitoring the feedback “R” and output “A”, gain and phase are measured. This method has no minimum frequency. Ensure that the bandwidth of the op-amp being used is much greater than the expected bandwidth of the power supply’s control loop. An op-amp with >100 MHz bandwidth is more than sufficient for most power supplies (which includes both linear and switching) and are more common and significantly cheaper than the injection transformers previously mentioned. The one disadvantage to using the op-amp injection method is that the supply voltages need to be below the maximum operating voltage of the op-amp.

Also, the maximum output voltage for driving 50Ω inputs using the MIC922 is 3V. For measuring higher output voltages, a 1M input impedance is required for the A and R channels. Remember to always measure the output voltage with an oscilloscope to ensure the measurement is working properly. You should see a single sweeping sinusoidal waveform without distortion on the output. If there is distortion of the sinusoid, reduce the amplitude of the source signal. You could be overdriving the feedback causing a large signal response.

The following Bode analysis shows the small signal loop stability of the MIC4721. The MIC4721 utilizes a type III compensation. This is a dominant low frequency pole, followed by 2 zeroes and finally the double pole of the inductor capacitor filter, creating a final 20 dB/decade roll off. Bode analysis gives us a few important data points; speed of response (Gain Bandwidth or GBW) and loop stability. Loop speed or GBW determines the response time to a load transient.

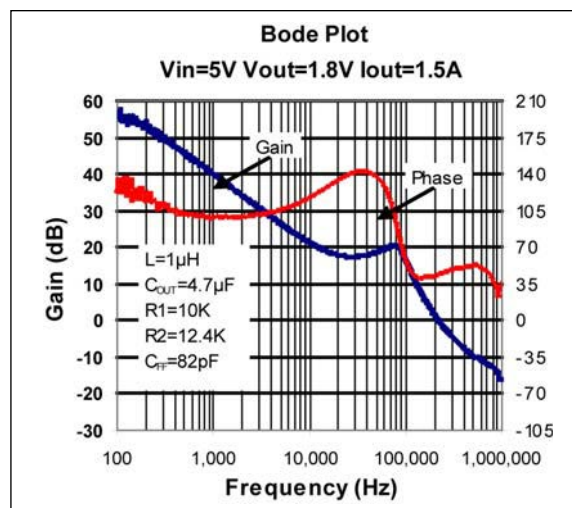
Faster response times yield smaller voltage deviations to load steps. Instability in a control loop occurs when there is gain and positive feedback. Phase margin is the measure of how stable the given system is. It is measured by determining how far the phase is from crossing zero when the gain is equal to 1 (0 dB).



Typically for 3.3V_{IN} and 1.8V_{OUT} at 1.5A:

- Phase Margin = 47 Degrees
- GBW = 156 kHz

Gain will also increase with input voltage. The following graph shows the increase in GBW for an increase in supply voltage.

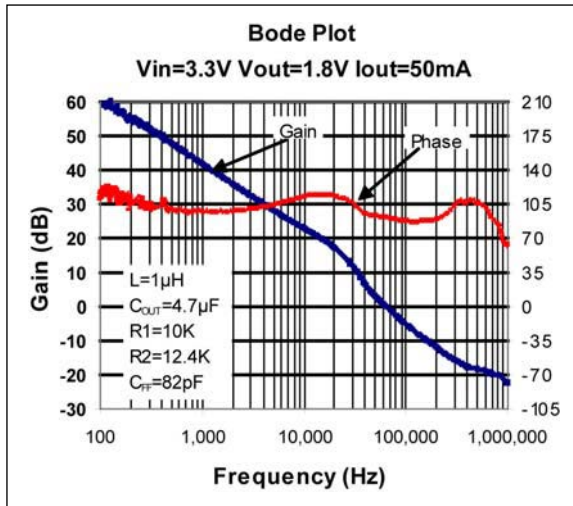


5V_{IN} and 1.8V_{OUT} at 1.5A load:

- Phase Margin = 43.1 Degrees
- GBW = 218 kHz

The non-synchronous MIC4721 regulator only has the ability to source current. This means that the regulator must rely on the load to sink current. This causes a non-linear response at light loads. The following plot

shows the effects of the pole created by the nonlinearity of the output drive during light load (discontinuous) conditions.

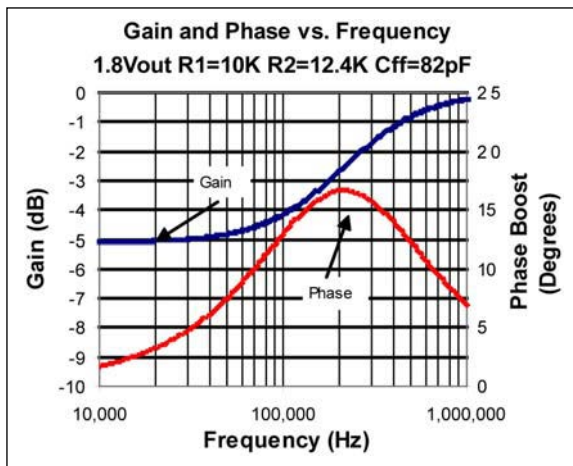


3.3V_{IN} and 1.8V_{OUT}, I_{OUT} = 50 mA:

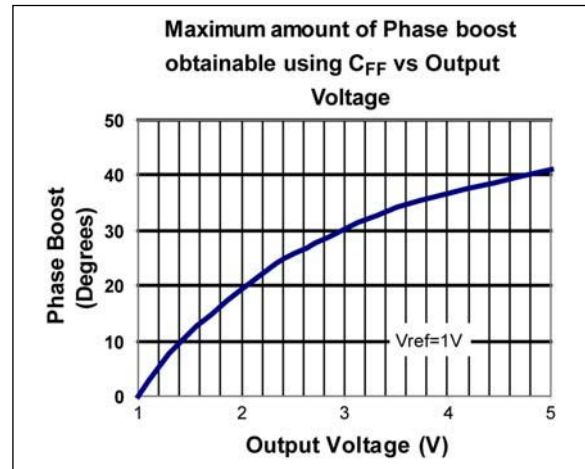
- Phase Margin = 90.5 Degrees
- GBW = 64.4 kHz

4.11.1 FEEDFORWARD CAPACITOR

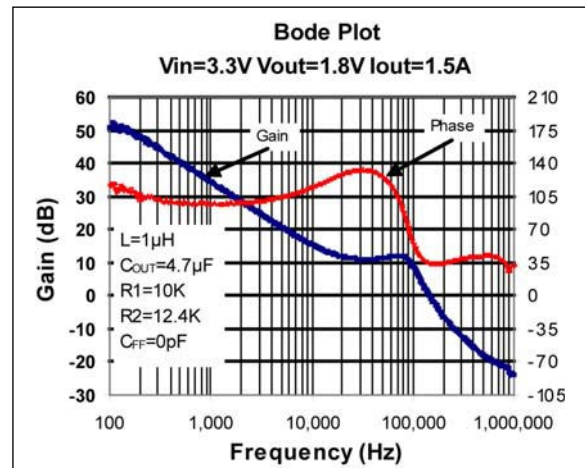
The feedback resistors are a gain reduction block in the overall system response of the regulator. By connecting a capacitor from the output to the feedback pin, high frequency signal can bypass the resistor divider, causing a gain increase up to unity gain.



The graph above shows the effects on the gain and phase of the system caused by feedback resistors and a feedforward capacitor. The maximum amount of phase boost achievable with a feedforward capacitor is shown in the next graph.



By looking at the graph, phase margin can be affected to a greater degree with higher output voltages. The next bode plot shows the phase margin of a 1.8V output at 1.5A without a feedforward capacitor.



In this case, the typical phase margin using the same resistor values as before without a feedforward capacitor results in 33.6 degrees of phase margin. The prior measurement with a feedforward capacitor yielded a phase margin of 47 degrees. The feedforward capacitor has given a phase boost of 13.4 degrees (47 degrees – 33.6 degrees = 13.4 degrees).

4.12 Output Impedance and Transient Response

Output impedance, simply stated, is the amount of output voltage deviation versus the load current deviation. The lower the output impedance, the better.

EQUATION 4-12:

$$Z_{OUT} = \frac{\Delta V_{OUT}}{\Delta I_{OUT}}$$

MIC4721

Output impedance for a buck regulator is the parallel impedance of the output capacitor and the MOSFET and inductor divided by the gain:

EQUATION 4-13:

$$Z_{TOTAL} = \frac{R_{DS(ON)} + DCR + X_L}{GAIN} \parallel X_{COUT}$$

To measure output impedance versus frequency, the load current must be swept across the frequencies measured while the output voltage is monitored. Figure 4-9 shows a test set-up to measure output impedance from 10 Hz to 1 MHz using the MIC5190 high speed controller.

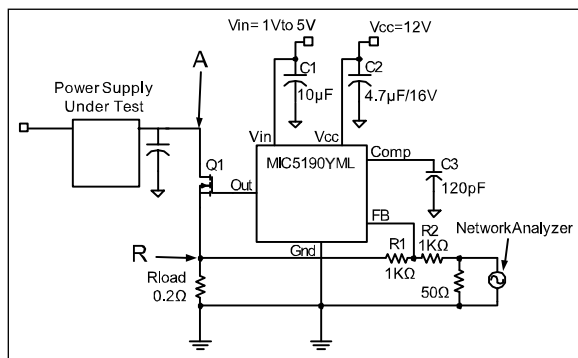


FIGURE 4-9: Output Impedance Measurement.

By setting up a network analyzer to sweep the feedback current while monitoring the output of the voltage regulator and the voltage across the load resistance, output impedance is easily obtainable. To keep the current from being too high, a DC offset needs to be applied to the network analyzer's source signal. This can be done with an external supply and 50Ω resistor. Make sure that the currents are verified with an oscilloscope first, to ensure the integrity of the signal measurement. It is always a good idea to monitor the A and R measurements with a scope while you are sweeping it. To convert the network analyzer data from dBm to something more useful (such as peak-to-peak voltage and current in our case):

EQUATION 4-14:

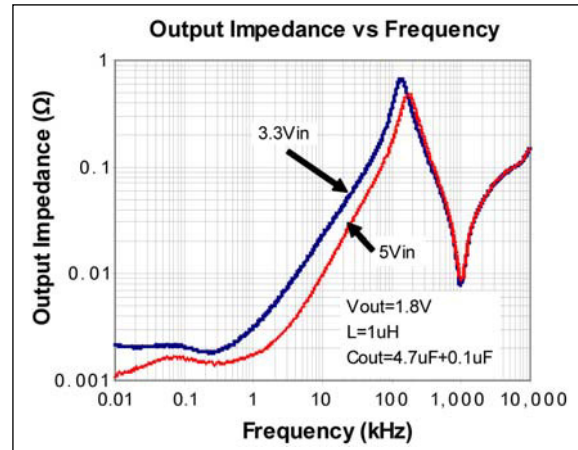
$$\Delta V = \frac{\sqrt{10 \frac{dbm}{10} \times 1mW \times 50\Omega \times 2}}{0.707}$$

Peak-to-peak current is calculated thusly:

EQUATION 4-15:

$$\Delta V = \frac{\sqrt{10 \frac{dBm}{10} \times 1mW \times 50\Omega \times 2}}{0.707 \times R_{LOAD}}$$

The following graph shows output impedance vs frequency at 2A load current sweeping the AC current from 10 Hz to 10 MHz, at 1A peak-to-peak amplitude.



From this graph, the effects of bandwidth and output capacitance can be easily seen. For frequencies <200 kHz, the output impedance is dominated by the gain and inductance. For frequencies >200 kHz, the output impedance is dominated by the capacitance. A good approximation for transient response can be calculated from determining the frequency of the load step in amps per second:

EQUATION 4-16:

$$f = \frac{A/sec}{2\pi}$$

Then, determine the output impedance by looking at the output impedance vs frequency graph. Next, calculate the voltage deviation times the load step:

EQUATION 4-17:

$$\Delta V_{OUT} = \Delta I_{OUT} \times Z_{OUT}$$

The output impedance graph shows the relationship between supply voltage and output impedance. This is caused by the lower $R_{DS(ON)}$ of the high-side MOSFET and the increase in gain with increased supply voltages. This explains why higher supply voltages have better transient response.

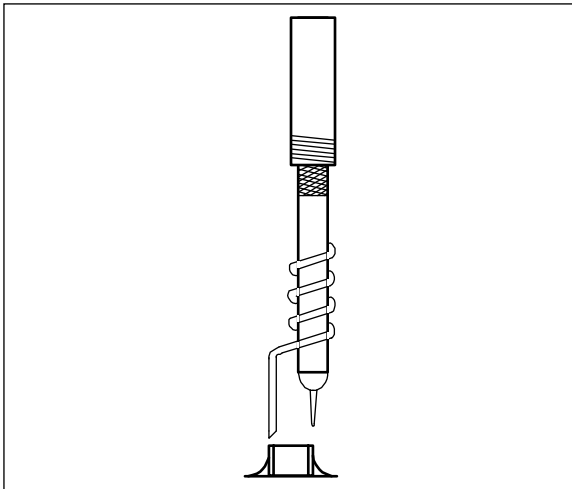
EQUATION 4-18:

$$\uparrow Z_{TOTAL} = \frac{\downarrow R_{DS(ON)} + DCR + X_L}{\uparrow GAIN} \parallel X_{COUT}$$

To properly measure voltage ripple on either input or output of a switching regulator, a proper ring in tip measurement is required. Standard oscilloscope probes come with a grounding clip, or a long wire with an alligator clip.

Unfortunately, for high frequency measurements, this ground clip can pick-up high frequency noise and erroneously inject it into the measured output ripple.

The standard evaluation board accommodates a home made version by providing probe points for both the input and output supplies and their respective grounds. This requires the removing of the oscilloscope probe sheath and ground clip from a standard oscilloscope probe and wrapping a non-shielded bus wire around the oscilloscope probe. If there does not happen to be any non-shielded bus wire immediately available, the leads from axial resistors will work. By maintaining the shortest possible ground lengths on the oscilloscope probe, true ripple measurements can be obtained.



5.0 RECOMMENDED LAYOUT MIC4721 1.5A EVALUATION BOARD

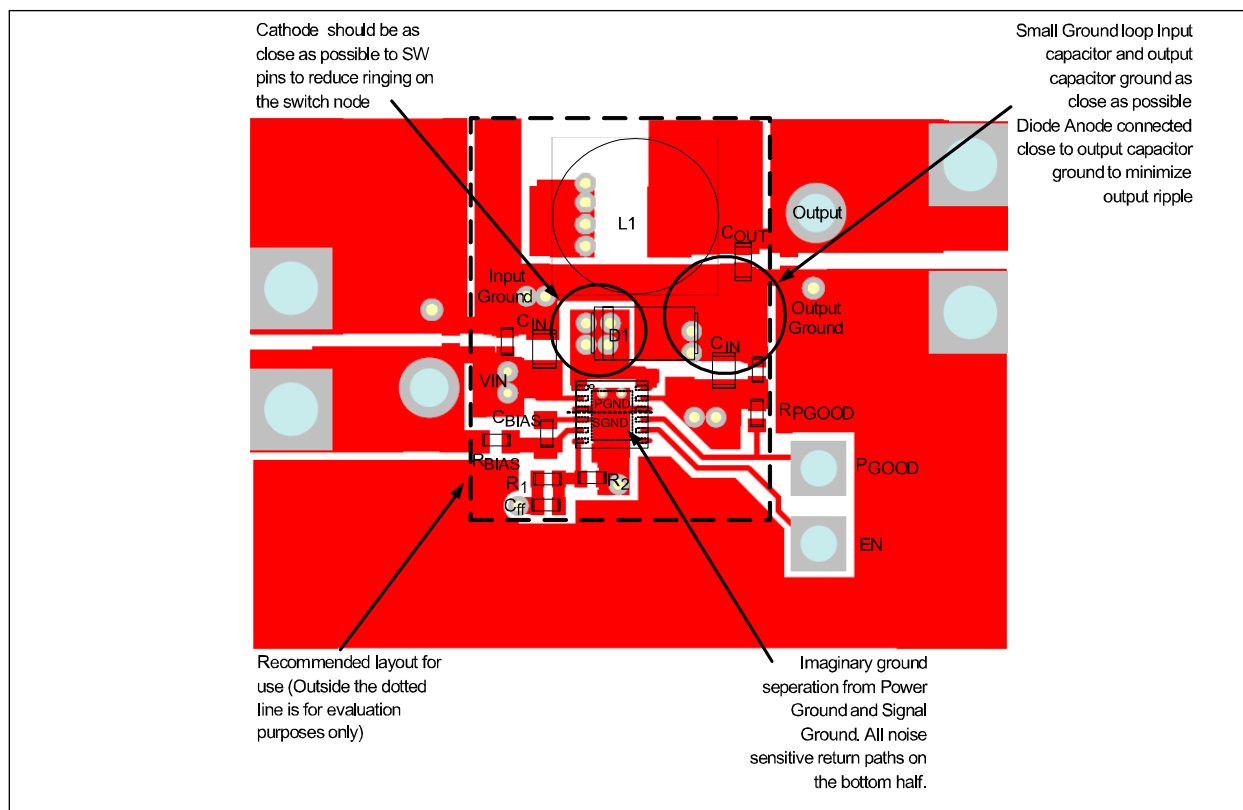


FIGURE 5-1: Top.

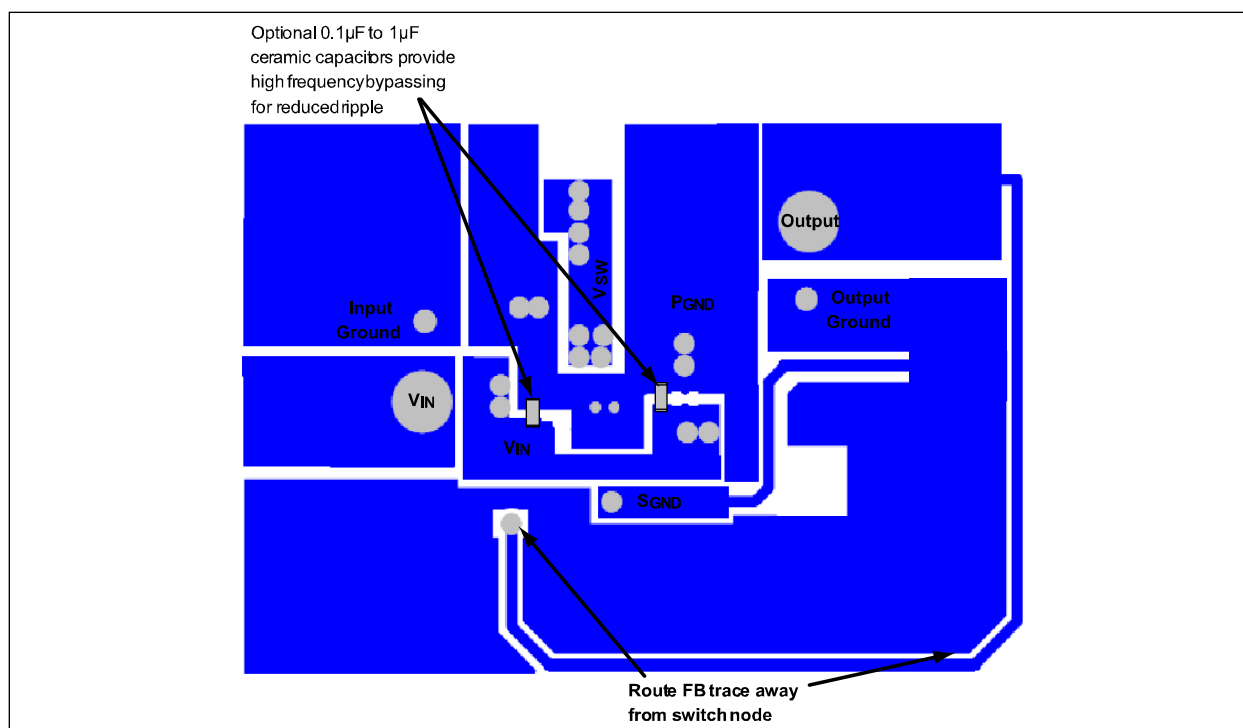


FIGURE 5-2: Bottom.

6.0 EVALUATION BOARD SCHEMATIC

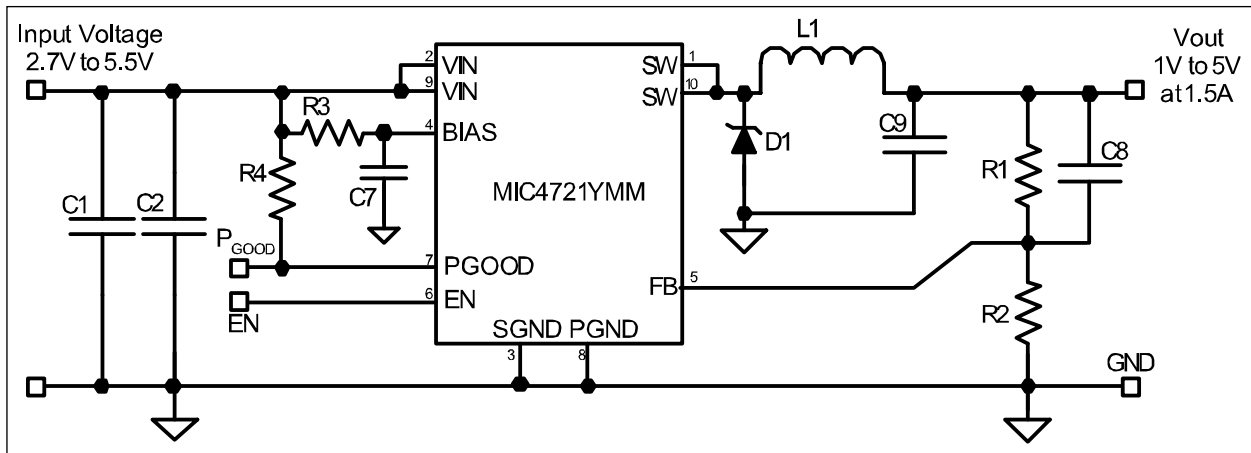


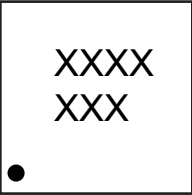
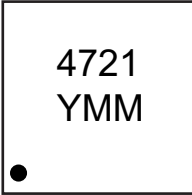
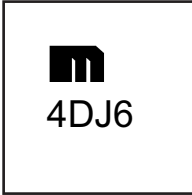
TABLE 6-1: BILL OF MATERIALS

Item	Part Number	Manufacturer	Description	Qty.
C1, C2	C2012JB0J106K	TDK	10 μ F Ceramic Capacitor X5R 0805 6.3V	2
	GRM219R60J106KE19	Murata		
	08056D106MAT	AVX		
C7	0402ZD104MAT	AVX	0.1 μ F Ceramic Capacitor X5R 0402 10V	1
C9	CGA3E1X5R0J475K080AC	TDK	4.7 μ F Ceramic Capacitor X5R 0603 6.3V	1
	GRM188R60J475KE19	Murata		
	06036D475MAT	AVX		
C8	VJ0402A820KXXPW1BC	Vishay VT	82 pF Ceramic Capacitor 0402	1
D1	SSA33L	Vishay Semi	3A Schottky 30V SMA	1
L1	IHLP2525AHER1R0M01	Vishay Dale	1 μ H Inductor 17.5 m Ω (L)6.47 mm x (W)6.86 mm x (H)1.8 mm	1
R1, R4	CRCW040210K0FKTD	Vishay Dale	10 k Ω 1% 0402 resistor	2
R2	CRCW04026K65FKTD	Vishay Dale	6.65 k Ω 1% 0402 For 2.5V _{OUT}	1
	CRCW040212K4FKTD		12.4 k Ω 1% 0402 For 1.8V _{OUT}	
	CRCW040220K0FKTD		20 k Ω 1% 0402 For 1.5V _{OUT}	
	CRCW040240K2FKTD		40.2 k Ω 1% 0402 For 1.2V _{OUT}	
R3	CRCW040210R0F	Vishay Dale	Open For 1.0V _{OUT}	1
U1	MIC4721YMM	Microchip Technology Inc.	1.5A 2 MHz Integrated Switch Buck Regulator	1

MIC4721

7.0 PACKAGING INFORMATION

7.1 Package Marking Information

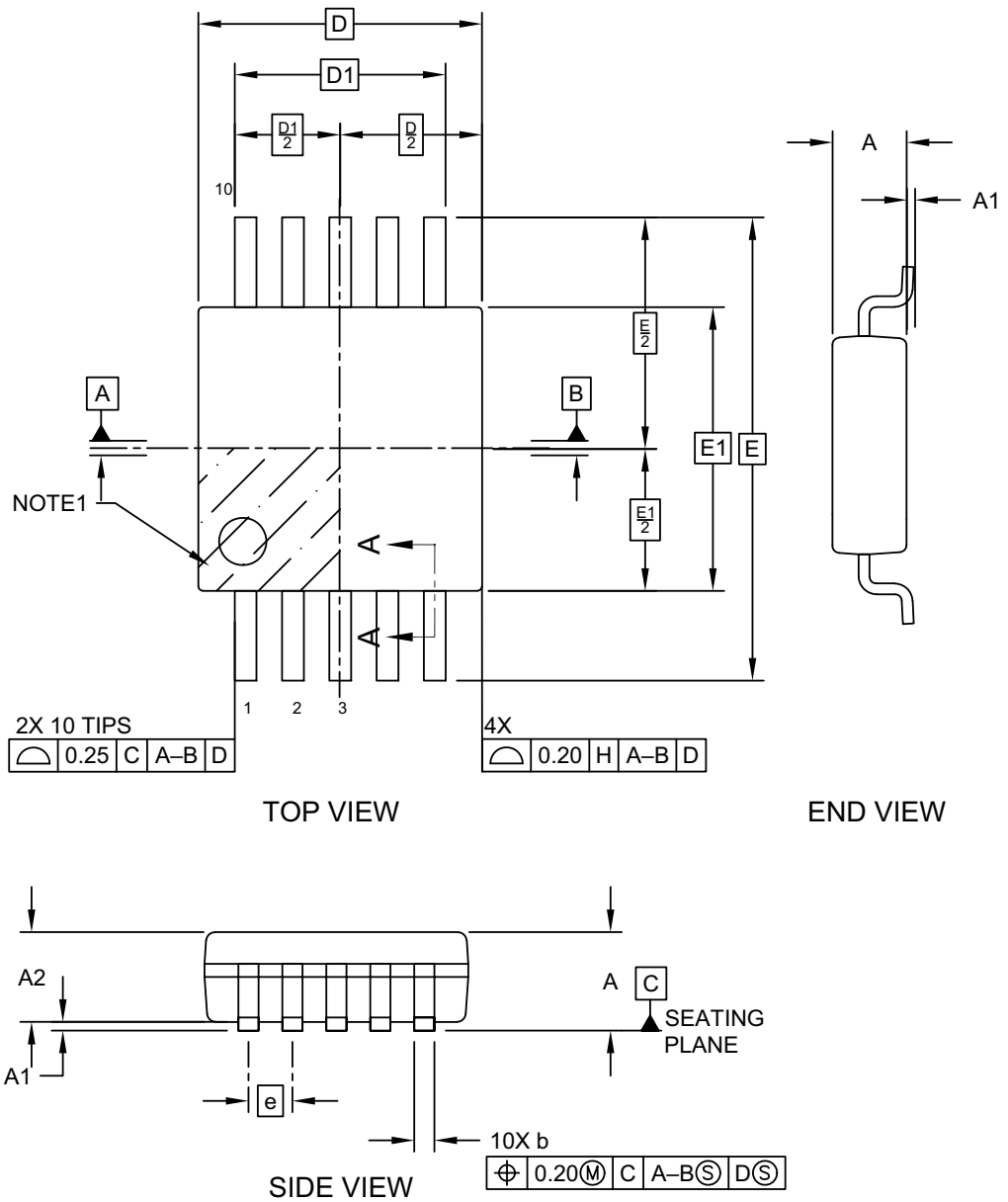
10-Lead MSOP* (Front)	Example	10-Lead MSOP* (Back)	Example
			

Legend:	XX...X	Product code or customer-specific information
	Y	Year code (last digit of calendar year)
	YY	Year code (last 2 digits of calendar year)
	WW	Week code (week of January 1 is week '01')
	NNN	Alphanumeric traceability code
	(e3)	Pb-free JEDEC® designator for Matte Tin (Sn)
	*	This package is Pb-free. The Pb-free JEDEC designator ((e3)) can be found on the outer packaging for this package.
	•, ▲, ▼	Pin one index is identified by a dot, delta up, or delta down (triangle mark).
Note:	In the event the full Microchip part number cannot be marked on one line, it will be carried over to the next line, thus limiting the number of available characters for customer-specific information. Package may or may not include the corporate logo.	
	Underbar (_) and/or Overbar (¯) symbol may not be to scale.	

Note: If the full seven-character YYWWNNN code cannot fit on the package, the following truncated codes are used based on the available marking space:
6 Characters = YWWNNN; 5 Characters = WWNNN; 4 Characters = WNNN; 3 Characters = NNN;
2 Characters = NN; 1 Character = N

10-Lead Plastic Micro Small Outline Package (DQA)- 3x3x1.0 mm Body [MSOP]

Note: For the most current package drawings, please see the Microchip Packaging Specification located at <http://www.microchip.com/packaging>

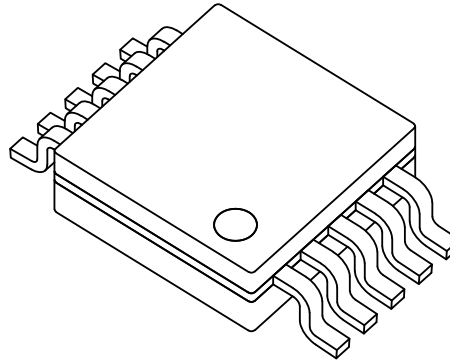
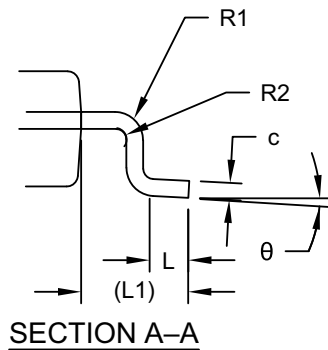


Microchip Technology Drawing C04-01081 Rev A Sheet 1 of 2

MIC4721

10-Lead Plastic Micro Small Outline Package (DQA)- 3x3x1.0 mm Body [MSOP]

Note: For the most current package drawings, please see the Microchip Packaging Specification located at <http://www.microchip.com/packaging>



		Units	MILLIMETERS		
Dimension Limits			MIN	NOM	MAX
Number of Terminals	N		10		
Pitch	e		0.50 BSC		
Overall Height	A		0.94	1.02	1.10
Standoff	A1		0.05	0.10	0.15
Molded Package Thickness	A2		0.91	0.92	0.95
Overall Length	D		3.00 BSC		
Molded Package Length	D1		2.23 BSC		
Overall Width	E		4.90 BSC		
Molded Package Width	E1		3.00 BSC		
Terminal Width	b		0.16	0.23	0.30
Terminal Thickness	c		0.13	0.15	0.23
Footprint	L		0.40	0.55	0.70
Terminal Length	L1		0.95 REF		
Lead Bend Radius	R1		0.08	-	-
Lead Bend Radius	R2		0.08	-	0.20
Foot Angle	θ		0°	3°	6°

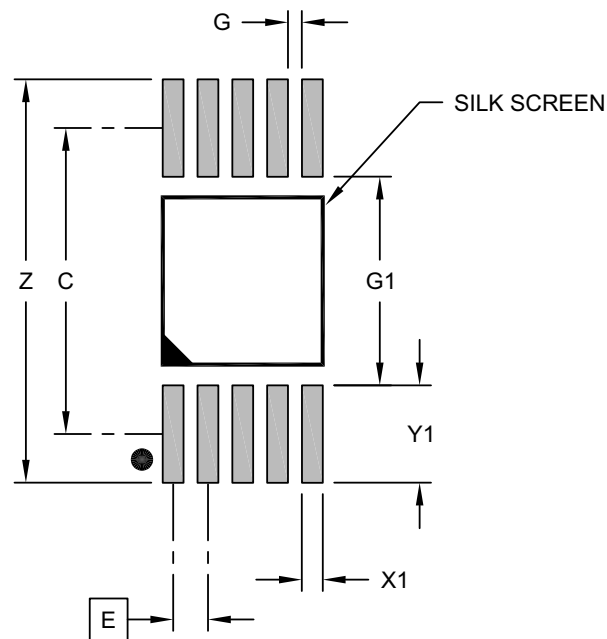
Notes:

- Pin 1 visual index feature may vary, but must be located within the hatched area.
- Dimensioning and tolerancing per ASME Y14.5M
BSC: Basic Dimension. Theoretically exact value shown without tolerances.
REF: Reference Dimension, usually without tolerance, for information purposes only.

Microchip Technology Drawing C04-01081 Rev A Sheet 2 of 2

10-Lead Plastic Micro Small Outline Package (DQA)- 3x3x1.0 mm Body [MSOP]

Note: For the most current package drawings, please see the Microchip Packaging Specification located at <http://www.microchip.com/packaging>



RECOMMENDED LAND PATTERN

Units		MILLIMETERS		
Dimension Limits		MIN	NOM	MAX
Contact Pitch	E	0.50 BSC		
Contact Pad Spacing	C		4.40	
Overall Width	Z			6.06
Contact Pad Width (X10)	X1	0.28	0.30	0.32
Contact Pad Length (X10)	Y1	1.24	1.26	1.28
Distance Between Pads (X5)	G1	3.00		
Distance Between Pads (X8)	G	0.20		

Notes:

1. Dimensioning and tolerancing per ASME Y14.5M

BSC: Basic Dimension. Theoretically exact value shown without tolerances.

Microchip Technology Drawing No. C04-03081 Rev A

MIC4721

NOTES:

APPENDIX A: REVISION HISTORY

Revision A (October 2025)

- Converted Micrel document MIC4721 to Microchip data sheet DS20007053A.
- Minor text changes throughout.

MIC4721

NOTES:

PRODUCT IDENTIFICATION SYSTEM

To order or obtain information, e.g., on pricing or delivery, contact your local Microchip representative or sales office.

<u>Part Number</u>	<u>X</u>	<u>X</u>	<u>[-XX]</u>
Device	Temp. Range	Package	Media Type
Device:	MIC4721:	1.5A, 2 MHz Integrated Switch Buck Regulator	
Temperature Range:	Y	= -40°C to +125°C	
Package:	MM	= 10-Lead 3 mm x 3 mm MSOP	
Media Type:	<blank> TR	= 100/Tube = 2,500/Reel	

Examples:

a) MIC7421YMM:
MIC7421, -40°C to +125°C Temp. Range,
10-Lead MSOP, 100/Tube

a) MIC7421YMM-TR:
MIC7421, -40°C to +125°C Temp. Range,
10-Lead MSOP, 2,500/Reel

Note: Tape and Reel identifier only appears in the catalog part number description. This identifier is used for ordering purposes and is not printed on the device package. Check with your Microchip Sales Office for package availability with the Tape and Reel option.

MIC4721

NOTES:

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- Neither Microchip nor any other semiconductor manufacturer can guarantee the security of its code. Code protection does not mean that we are guaranteeing the product is “unbreakable”. Code protection is constantly evolving. Microchip is committed to continuously improving the code protection features of our products.