

# 500mA Low Voltage Step-Down Synchronous Switching Regulator

## FEATURES

- 500mA Output Current at 3.3V Output
- Up to 92% Peak Efficiency
- Internal Reference Trimmed to 1%
- Output Can Source or Sink Current
- Requires as Few as Four External Components
- Input Voltage Range: 4V to 10V
- Adjustable Current Limit
- Small SO-8 Package
- 200kHz Switching Frequency Can be Synchronized Up to 500kHz

## APPLICATIONS

- Small Portable Digital Systems
- Active Termination
- Auxiliary Output Voltage Supplies
- Minimum Part Count/Size Switchers

## DESCRIPTION

The LTC<sup>®</sup>1504 is a self-contained, high efficiency synchronous buck switching regulator. It includes a pair of on-chip 1.5Ω power switches, enabling it to supply up to 500mA of load current. Efficiency peaks at 92%, minimizing heat and wasted power. The synchronous buck architecture allows the output to source or sink current as required to keep the output voltage in regulation.

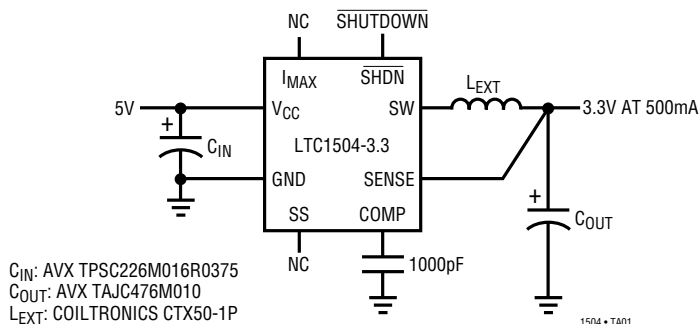
The LTC1504 is available in adjustable and fixed 3.3V output versions. An adjustable current limit circuit provides protection from overloads. The internal 1% reference combined with a sophisticated voltage feedback loop provides optimum output voltage accuracy and fast load transient response. The LTC1504 is specified to operate with input voltages between 4V and 10V. Contact the LTC factory for guaranteed specifications at 2.7V supply.

The LTC1504 is available in a plastic SO-8 package.

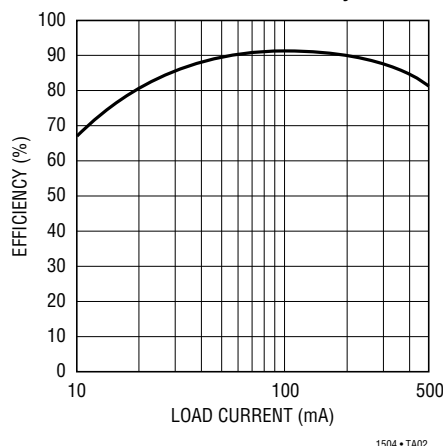
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## TYPICAL APPLICATION

Minimum Part Count 5V to 3.3V Regulator



5V to 3.3V Efficiency



## ABSOLUTE MAXIMUM RATINGS

(Note 1)

|                                            |                                  |
|--------------------------------------------|----------------------------------|
| Supply Voltage ( $V_{CC}$ to GND) .....    | 10V                              |
| Peak Output Current (SW) .....             | $\pm 1A$                         |
| Input Voltage (All Other Pins) .....       | $-0.3V$ to $V_{CC} + 0.3V$       |
| Operating Temperature Range .....          | $0^{\circ}C$ to $70^{\circ}C$    |
| Storage Temperature Range .....            | $-65^{\circ}C$ to $150^{\circ}C$ |
| Lead Temperature (Soldering, 10 sec) ..... | $300^{\circ}C$                   |

## PACKAGE/ORDER INFORMATION

|  |                              |
|--|------------------------------|
|  | ORDER PART NUMBER            |
|  | LTC1504CS8<br>LTC1504CS8-3.3 |
|  | S8 PART MARKING              |
|  | 1504<br>15043                |

Consult factory for Industrial and Military grade parts.

ELECTRICAL CHARACTERISTICS  $V_{CC} = 5V$ ,  $T_A = 25^{\circ}C$  unless otherwise specified. (Note 2)

| SYMBOL             | PARAMETER                            | CONDITIONS                                                                           | MIN | TYP       | MAX                 | UNITS     |
|--------------------|--------------------------------------|--------------------------------------------------------------------------------------|-----|-----------|---------------------|-----------|
| $V_{CC}$           | Minimum Supply Voltage               | (Note 7)                                                                             | ●   | 4         |                     | V         |
| $V_{FB}$           | Feedback Voltage                     | LTC1504CS8                                                                           | ●   | 1.25      | 1.265 1.28          | V         |
| $\Delta V_{FB}$    | Feedback Voltage PSRR                | Figure 1, $4V \leq V_{CC} \leq 10V$ , LTC1504CS8                                     | ●   | 1.1       | 1.6                 | %         |
| $V_{SENSE}$        | Sense Pin Voltage                    | LTC1504CS8-3.3                                                                       | ●   | 3.20      | 3.30 3.40           | V         |
| $\Delta V_{SENSE}$ | Sense Voltage PSRR                   | Figure 1, $4V \leq V_{CC} \leq 10V$ , LTC1504CS8-3.3                                 | ●   | 1.2       | 1.8                 | %         |
| $I_{CC}$           | Supply Current                       | Figure 1, $V_{SHDN} = V_{CC}$ , $I_{OUT} = 0$ (Note 4)                               | ●   | 3         |                     | mA        |
|                    |                                      | Figure 1, $V_{SHDN} = V_{CC}$ , $I_{OUT} = 0$ , $V_{FB}/V_{SENSE} = V_{CC}$ (Note 4) | ●   | 0.3       | 0.6                 | mA        |
|                    |                                      | $V_{SHDN} = 0V$                                                                      | ●   | 1.0       | 20                  | $\mu A$   |
| $f_{OSC}$          | Internal Oscillator Frequency        |                                                                                      | ●   | 150       | 200 250             | kHz       |
| $R_{SW}$           | Internal Switch Resistance           |                                                                                      | ●   | 1.3       | 2.0                 | $\Omega$  |
| $V_{IH}$           | $\overline{SHDN}$ Input High Voltage |                                                                                      | ●   | 2.4       |                     | V         |
| $V_{IL}$           | $\overline{SHDN}$ Input Low Voltage  |                                                                                      | ●   |           | 0.8                 | V         |
| $I_{IN}$           | $\overline{SHDN}$ Input Current      |                                                                                      | ●   | $\pm 0.1$ | $\pm 1$             | $\mu A$   |
| $V_{OH}$           | Error Amplifier Positive Swing       | Figure 2                                                                             | ●   | 4.5       | 4.95                | V         |
| $V_{OL}$           | Error Amplifier Negative Swing       | Figure 2                                                                             | ●   | 0.05      | 0.5                 | V         |
| $I_{OH}, I_{OL}$   | Error Amplifier Output Current       | Figure 2                                                                             | ●   | $\pm 50$  | $\pm 100$ $\pm 200$ | $\mu A$   |
| $g_{mV}$           | Error Amplifier Transconductance     | (Note 5)                                                                             | ●   | 350       | 600 1100            | $\mu mho$ |
| $A_V$              | Error Amplifier DC Gain              | (Note 5)                                                                             | ●   | 40        | 48                  | dB        |
| $g_{mI}$           | $I_{LIM}$ Amplifier Transconductance | (Note 6)                                                                             |     | 1000      | 2000 3000           | $\mu mho$ |
| $I_{MAX}$          | $I_{MAX}$ Sink Current               | $V_{IMAX} = V_{CC}$                                                                  | ●   | 8         | 12 16               | $\mu A$   |
| $I_{SS}$           | Soft Start Source Current            | $V_{SS} = 0V$                                                                        | ●   | -8        | -12 -16             | $\mu A$   |
| $t_r, t_f$         | Output Switch Rise/Fall Time         |                                                                                      | ●   | 5         | 50                  | ns        |
| $DC_{MAX}$         | Maximum Duty Cycle                   | $V_{COMP} = V_{CC}$                                                                  | ●   | 84        | 90                  | %         |

## ELECTRICAL CHARACTERISTICS

The ● denotes specifications which apply over the full operating temperature range.

**Note 1:** Absolute Maximum Ratings are those values beyond which the life of the device may be impaired.

**Note 2:** All currents into device pins are positive; all currents out of device pins are negative. All voltages are referenced to ground unless otherwise specified.

**Note 3:** This parameter is guaranteed by correlation and is not tested directly.

**Note 4:** LTC1504 quiescent current is dominated by the gate drive current drawn by the onboard power switches. With FB or SENSE pulled to  $V_{CC}$

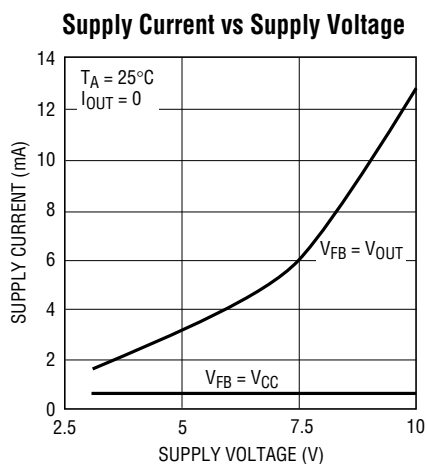
the output stage will stop switching and the static quiescent current can be observed. With FB or SENSE hooked up normally, the output stage will be switching and total dynamic supply current can be measured.

**Note 5:** Fixed output parts will appear to have  $g_{mV}$  and  $A_V$  values 2.6 times lower than the specified values, due to the internal divider resistors.

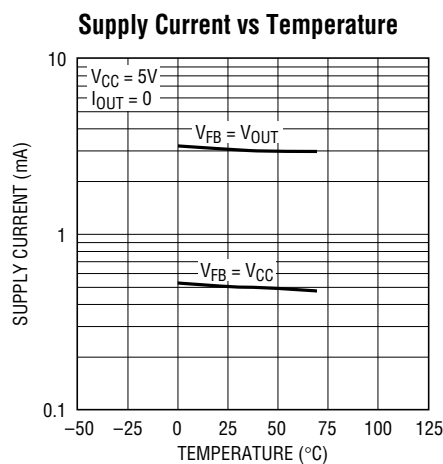
**Note 6:** The  $I_{LIM}$  amplifier can sink but not source current. Under normal (not current limited) operation, the  $I_{LIM}$  output current will be zero.

**Note 7:** Contact factory for guaranteed specifications at 2.7V supply.

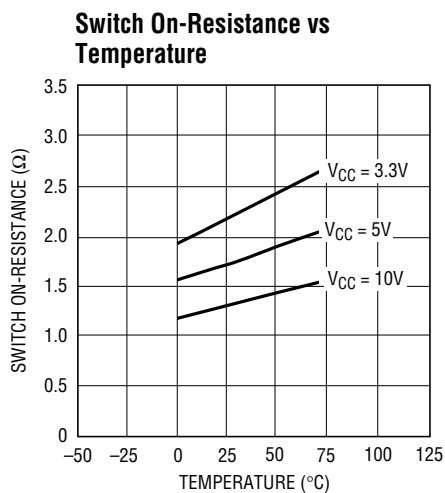
## TYPICAL PERFORMANCE CHARACTERISTICS



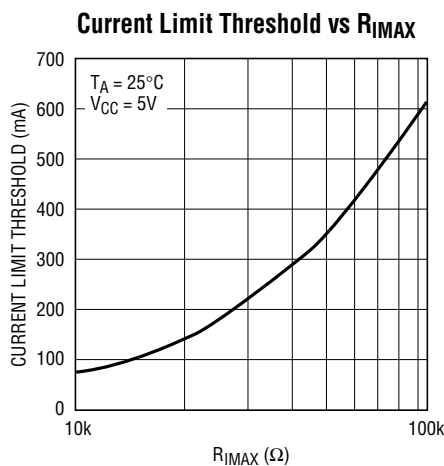
1504 • TPC01



1504 • TPC02

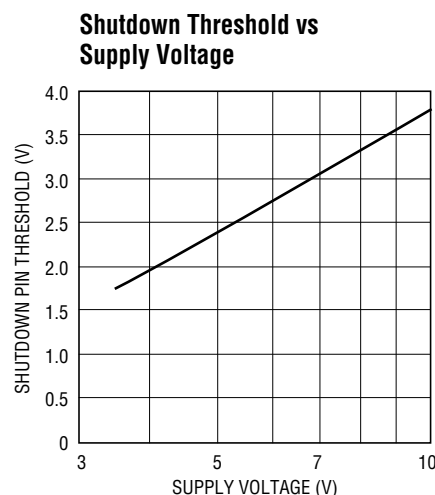
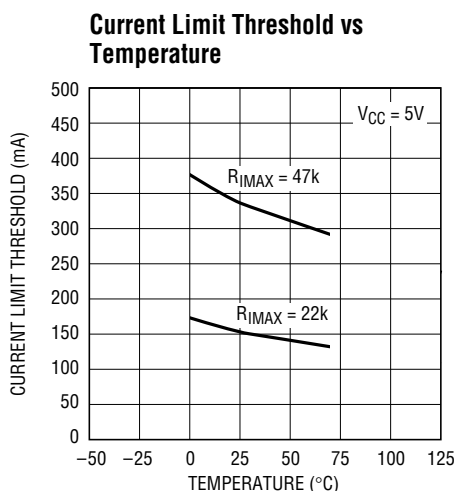


1504 • TPC03



1504 • TPC04

## TYPICAL PERFORMANCE CHARACTERISTICS



## PIN FUNCTIONS

**$I_{MAX}$  (Pin 1):** Current Limit Set. Connect a resistor from  $V_{CC}$  to  $I_{MAX}$  to set the current limit threshold. An internal  $12\mu A$  current source from  $I_{MAX}$  to GND sets the voltage drop across this resistor. This voltage is compared to the voltage drop across the internal high-side switch (Q1) while it is turned on. See the Applications Information section for more information. To disable current limit, leave  $I_{MAX}$  floating.

**$V_{CC}$  (Pin 2):** Power Supply Input. Connect to a power supply voltage between 4V and 10V.  $V_{CC}$  requires a low impedance bypass capacitor to ground, located as close as possible to the LTC1504. See the Applications Information section for details on capacitor selection and placement.

**SW (Pin 3):** Power Switch Output. This is the switched node of the buck circuit. Connect SW to one end of the external inductor. The other end of the inductor should be connected to  $C_{OUT}$  and becomes the regulated output voltage. Avoid shorting SW to GND or  $V_{CC}$ .

**GND (Pin 4):** Ground. Connect to a low impedance ground. The input and output bypass capacitors and the feedback resistor divider (adjustable parts only) should be grounded as close to this pin as possible. Pin 4 acts as a heat sink in the LTC1504 S0-8 package and should be connected to

as large a copper area as possible to improve thermal dissipation. See the Thermal Considerations section for more information.

**FB (LTC1504CS8) (Pin 5):** Feedback. Connect FB to a resistor divider from  $V_{OUT}$  to GND to set the regulated output voltage. The LTC1504CS8 feedback loop will servo the FB pin to 1.265V.

**SENSE (LTC1504CS8-3.3) (Pin 5):** Output Voltage Sense. Connect directly to the output voltage node. The LTC1504CS8-3.3 feedback loop will servo SENSE to 3.3V. SENSE is connected to an internal resistor divider which will load any external dividers. For output voltages other than 3.3V, use the LTC1504CS8.

**$\overline{SHDN}$  (Pin 6):** Shutdown, Active Low. When  $\overline{SHDN}$  is at a logic High, the LTC1504 will operate normally. When  $\overline{SHDN}$  is Low, the LTC1504 ceases all internal operation and supply current drops below  $1\mu A$ . In shutdown, the SW pin is pulled low. This ensures that the output is actively shut off when  $\overline{SHDN}$  is asserted, but it prevents other supplies from providing power to the output when the LTC1504 is inactive. See the Applications Information section for more details.

**SS (Pin 7):** Soft Start. Connect an external capacitor (usually  $0.1\mu F$ ) from SS to GND to limit the output rise time

## PIN FUNCTIONS

during power-up.  $C_{SS}$  also compensates the current limit loop, allowing the LTC1504 to enter and exit current limit cleanly. See the Applications Information section for more details.

**COMP (Pin 8):** External Compensation. An external RC network should be connected to COMP to compensate the feedback loop. COMP is connected to the output of the internal error amplifier.

## BLOCK DIAGRAM

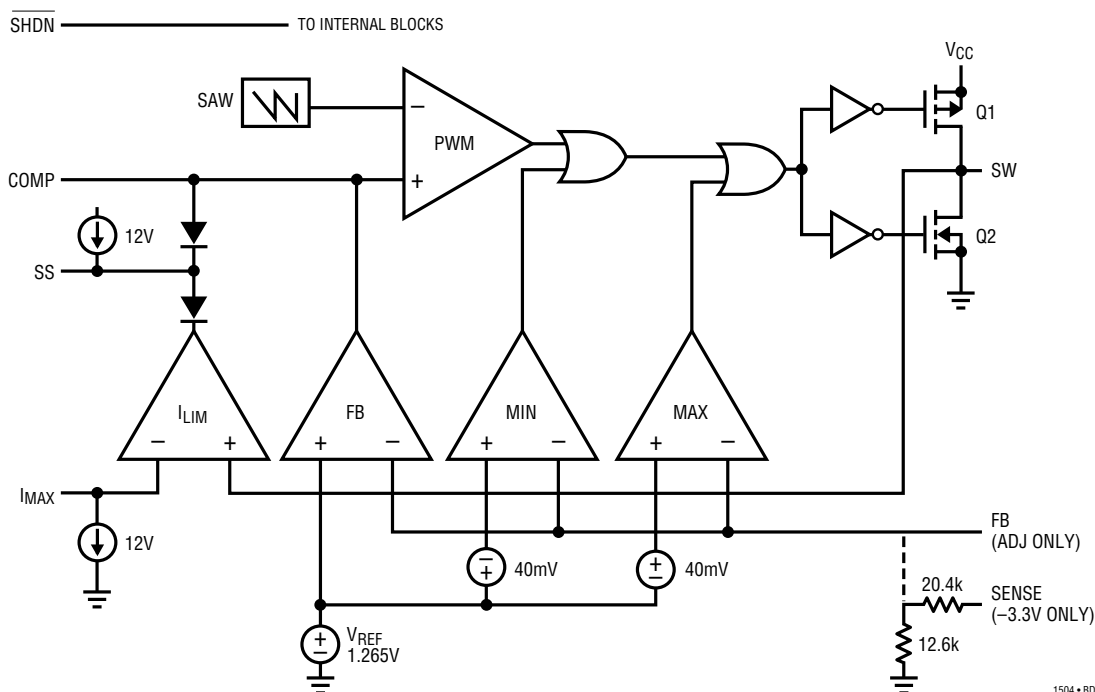


Figure 3. Block Diagram

## TEST CIRCUITS

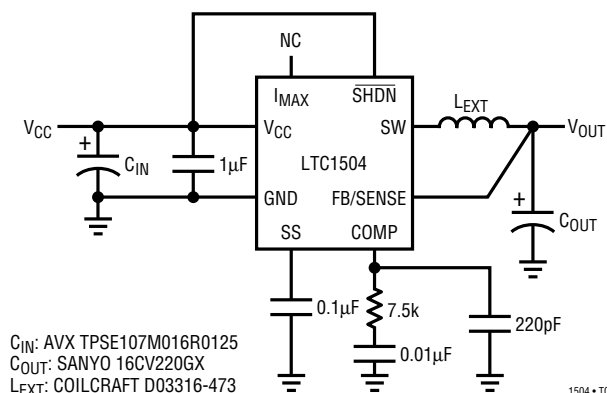


Figure 1

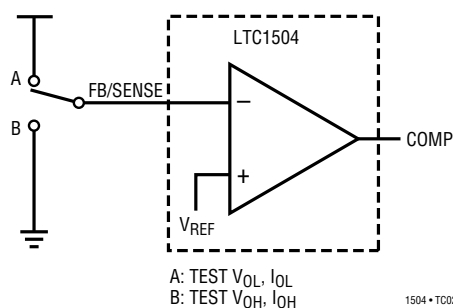


Figure 2

## APPLICATIONS INFORMATION

### OVERVIEW

The LTC1504 is a complete synchronous switching regulator controller (see Block Diagram). It includes two on-chip  $1.5\Omega$  power MOSFETs, eliminating the need for external power devices and minimizing external parts count. The internal switches are set up as a synchronous buck converter with a P-channel device (Q1) from the input supply to the switching node and an N-channel device (Q2) as the synchronous rectifier device from the switching node to ground. An external inductor, input and output bypass capacitors and the compensation network complete the control loop. The LTC1504 adjustable output parts require an additional pair of resistors to set the output voltage. The LTC1504-3.3 parts include an onboard resistor divider preset to a 3.3V output voltage. A functional 3.3V output regulator can be constructed with an LTC1504-3.3 and as few as four external components.

The LTC1504 feedback loop includes a precision reference trimmed to 1% ( $V_{REF}$ ), a wide bandwidth transconductance feedback amplifier (FB) and an onboard PWM generator (SAW and PWM). Two additional feedback comparators (MIN and MAX) monitor the feedback voltage and override the primary feedback amplifier when the regulated out falls outside a  $\pm 3\%$  window, improving transient response. The internal sawtooth oscillator typically runs at 200kHz.

Q1 and Q2 are capable of carrying peak currents in excess of 500mA, with the continuous output power level limited primarily by the thermal dissipation of the SO-8 package. With a 5V input and a 3.3V output, the LTC1504 can supply 500mA of continuous output current with an appropriate layout. An on-chip current limit circuit, set with a single external resistor, can be used to help limit power dissipation. See the Thermal Considerations section for more information.

### Theory of Operation

The LTC1504 primary feedback loop consists of the main error amplifier FB, the PWM generator, the output drive logic and the power switches. The loop is closed with the external inductor and the output bypass capacitor. The feedback amplifier senses the output voltage directly at the SENSE pin for fixed output versions or through an external

resistor divider in the adjustable output version. This feedback voltage is compared to the 1.265V internal reference voltage by FB and an error signal is generated at the COMP pin. COMP is a high impedance node that is brought out to an external pin for optimizing the loop compensation.

COMP is compared to a 200kHz sawtooth wave by comparator PWM. This raw pulse-width modulated signal is logically combined with the outputs of the transient comparators MIN and MAX before reaching the output stage. The output stage generates nonoverlapping drive for the onboard P- and N-channel power MOSFETs, which drive the SW pin with a low impedance image of the PWM waveform. Typical open-loop output impedance at SW is between  $1\Omega$  and  $3\Omega$ , depending on supply voltage. This high power pulse train is filtered by the external inductor and capacitor, providing a steady DC value at the output node. This node returns to FB or SENSE, closing the loop.

The MIN and MAX comparators in the feedback loop provide high speed fault correction in situations where the FB amplifier may not respond quickly enough. MIN compares the feedback signal to a voltage 40mV (3%) below the internal reference. At this point, MIN overrides the FB amplifier and forces the loop to full duty cycle. Similarly, MAX monitors the output voltage at 3% above the internal reference and forces the output to 0% duty cycle when tripped. These two comparators prevent extreme output perturbations with fast output transients, while allowing the main feedback loop to be optimally compensated for stability.

The LTC1504 includes yet another feedback loop that controls operation in current limit. The  $I_{LIM}$  amplifier monitors the voltage at the SW pin while Q1 is on. It compares this voltage to the voltage at the  $I_{MAX}$  pin. As the peak current through Q1 rises, the voltage drop across it due to its  $R_{ON}$  increases proportionally. When SW drops below  $I_{MAX}$ , indicating the current through Q1 has increased beyond the desired value,  $I_{LIM}$  starts pulling a controlled amount of current out of SS, the external soft start pin. As SS falls, it pulls COMP down with it, limiting the duty cycle and reducing the output voltage to control the current. The speed at which the current limit circuit reacts is set by the value of the external soft start capacitor.

## APPLICATIONS INFORMATION

### EXTERNAL COMPONENT SELECTION

External components required by the LTC1504 fall into three categories: input bypass, output filtering and compensation. Additional components to set up soft start and current limit are usually included as well. A minimum LTC1504 circuit can be constructed with as few as four external components; a circuit that utilizes all of the LTC1504s functionality usually includes eight or nine external components, with two additional feedback resistors required for adjustable parts. See the Typical Applications section for examples of external component hookup.

#### Input Bypass

The input bypass capacitor is critical to proper LTC1504 operation. The LTC1504 includes a precision reference and a pair of high power switches feeding from the same  $V_{CC}$  pin. If  $V_{CC}$  does not have adequate bypassing, the switch pulses introduce enough ripple at  $V_{CC}$  to corrupt the reference voltage and the LTC1504 will not regulate accurately. Symptoms of inadequate bypassing include poor load regulation and/or erratic waveforms at the SW pin. If an oscilloscope won't trigger cleanly when looking at the SW pin, there isn't adequate input bypass.

Ideally, the LTC1504 requires a low impedance bypass right at the chip and a larger reservoir capacitor that can be located somewhat farther away. This requirement usually can be met with a ceramic capacitor right next to the LTC1504 and an electrolytic capacitor (usually 10 $\mu$ F to 100 $\mu$ F, depending on expected load current) located somewhere nearby. In certain cases, the bulk capacitance requirement can be met by the output bypass of the input supply. Applications running at very high load currents or at input supply voltages greater than 6V may require the local ceramic capacitor to be 1 $\mu$ F or greater. In some cases, both the low impedance and bulk capacitance requirements can be met by a single capacitor, mounted very close to the LTC1504. Low ESR organic semiconductor (OS-CON) electrolytic capacitors or surge tested surface mount tantalum capacitors can have low enough impedance to keep the LTC1504 happy in some circuits.

Often the RMS current capacity of the input bypass capacitors is more important to capacitor selection than value.

Buck converters like the LTC1504 are hard on input capacitors, since the current flow alternates between the full load current and near zero during every clock cycle. In the worst case (50% duty cycle or  $V_{OUT} = 0.5V_{IN}$ ) the RMS current flow in the input capacitor is half of the total load current plus half the ripple current in the inductor—perhaps 300mA in a typical 500mA load current application. This current flows through the ESR of the input bypass capacitor, heating it up and shortening its life, sometimes dramatically. Many ordinary electrolytic capacitors that look OK at first glance are not rated to withstand such currents—check the RMS current rating before you specify a device! If the RMS current rating isn't specified, it should not be used as an input bypass capacitor. Again, low ESR electrolytic and surge tested tantalums usually do well in LTC1504 applications and have high RMS current ratings. The local ceramic bypass capacitor usually has negligible ESR allowing it to withstand large RMS currents without trouble. Table 1 shows typical surface mount capacitors that make acceptable input bypass capacitors in LTC1504 applications.

**Table 1. Representative Surface Mount Input Bypass Capacitors**

| PART             | VALUE       | ESR           | MAX RMS | TYPE         | HEIGHT |
|------------------|-------------|---------------|---------|--------------|--------|
| <b>AVX</b>       |             |               |         |              |        |
| TPSC226M016R0375 | 22 $\mu$ F  | 0.38 $\Omega$ | 0.54A   | Tantalum     | 2.6mm  |
| TPSD476M016R0150 | 47 $\mu$ F  | 0.15 $\Omega$ | 0.86A   | Tantalum     | 2.9mm  |
| TPSE107M016R0125 | 100 $\mu$ F | 0.13 $\Omega$ | 1.15A   | Tantalum     | 4.1mm  |
| 1206YC105M       | 1 $\mu$ F   | Low           | >1A     | X7R Ceramic  | 1.5mm  |
| 1210YG106Z       | 10 $\mu$ F  | Low           | >1A     | Y5V Ceramic  | 1.7mm  |
| <b>Sanyo</b>     |             |               |         |              |        |
| 16SN33M          | 33 $\mu$ F  | 0.15 $\Omega$ | 1.24A   | OS-CON       | 7mm    |
| 16SN68M          | 68 $\mu$ F  | 0.1 $\Omega$  | 1.65A   | OS-CON       | 7mm    |
| 16CV100GX        | 100 $\mu$ F | 0.44 $\Omega$ | 0.23A*  | Electrolytic | 6mm    |
| 16CV220GX        | 220 $\mu$ F | 0.34 $\Omega$ | 0.28A*  | Electrolytic | 7.7mm  |
| <b>Sprague</b>   |             |               |         |              |        |
| 593D476X0016D2W  | 47 $\mu$ F  | 0.17 $\Omega$ | 0.93A   | Tantalum     | 2.8mm  |
| 593D107X0016E2W  | 100 $\mu$   | 0.15 $\Omega$ | 1.05A   | Tantalum     | 4mm    |

\*Note: Use multiple devices in parallel or limit output current to prevent capacitor overload.

#### Inductor

The LTC1504 requires an external inductor to be connected from the switching node SW to the output node where the load is connected. Inductor requirements are fairly straightforward; it must be rated to handle continuous DC current equal to the maximum load current plus

## APPLICATIONS INFORMATION

half the ripple current and its value should be chosen based on the desired ripple current and/or the output current transient requirements. Large value inductors lower ripple current and decrease the required output capacitance, but limit the speed that the LTC1504 can change the output current, limiting output transient response. Small value inductors result in higher ripple currents and increase the demands on the output capacitor, but allow faster output current slew rates and are often smaller and cheaper for the same DC current rating. A typical inductor used in an LTC1504 application might have a maximum current rating between 500mA and 1A and an inductance between 33 $\mu$ H and 220 $\mu$ H.

Different core materials and shapes will change the size/current and price/current relationship of an inductor. Toroid or shielded pot cores in ferrite or permalloy materials are small and don't radiate much energy, but generally cost more than powdered iron rod core inductors with similar electrical characteristics. The choice of which style inductor to use often depends more on the price vs size requirements and any radiated field/EMI requirements than on what the LTC1504 requires to operate. Table 2 shows some typical surface mount inductors that work well in LTC1504 applications.

**Table 2. Representative Surface Mount Inductors**

| PART               | VALUE       | MAX DC | CORE TYPE | CORE MATERIAL | HEIGHT |
|--------------------|-------------|--------|-----------|---------------|--------|
| <b>CoilCraft</b>   |             |        |           |               |        |
| DT3316-473         | 47 $\mu$ H  | 1A     | Shielded  | Ferrite       | 5.1mm  |
| DT3316-104         | 100 $\mu$ H | 0.8A   | Shielded  | Ferrite       | 5.1mm  |
| DO1608-473         | 47 $\mu$ H  | 0.5A   | Open      | Ferrite       | 3.2mm  |
| DO3316-224         | 220 $\mu$ H | 0.8A   | Open      | Ferrite       | 5.5mm  |
| <b>Coiltronics</b> |             |        |           |               |        |
| CTX50-1            | 50 $\mu$ H  | 0.65A  | Toroid    | KoolM $\mu$ ® | 4.2mm  |
| CTX100-2           | 100 $\mu$ H | 0.63A  | Toroid    | KoolM $\mu$   | 6mm    |
| CTX50-1P           | 50 $\mu$ H  | 0.66A  | Toroid    | Type 52       | 4.2mm  |
| CTX100-2P          | 100 $\mu$ H | 0.55A  | Toroid    | Type 52       | 6mm    |
| <b>Sumida</b>      |             |        |           |               |        |
| CDRH62-470         | 47 $\mu$ H  | 0.54A  | Shielded  | Ferrite       | 3mm    |
| CDRH73-101         | 100 $\mu$ H | 0.50A  | Shielded  | Ferrite       | 3.4mm  |
| CD43-470           | 47 $\mu$ H  | 0.54A  | Open      | Ferrite       | 3.2mm  |
| CD54-101           | 100 $\mu$ H | 0.52A  | Open      | Ferrite       | 4.5mm  |

### Output Capacitor

The output capacitor affects the performance of the LTC1504 in a couple of ways: it provides the first line of

defense during a transient load step and it has a large effect on the compensation required to keep the LTC1504 feedback loop stable. Transient load response of an LTC1504 circuit is controlled almost entirely by the output capacitor and the inductor. In steady load operation, the average current in the inductor will match the load current. When the load current changes suddenly, the inductor is suddenly carrying the wrong current and requires a finite amount of time to correct itself—at least several switch cycles with typical LTC1504 inductor values. Even if the LTC1504 had psychic abilities and could instantly assume the correct duty cycle, the rate of change of current in the inductor is still related to its value and will not change instantaneously.

Until the inductor current adjusts to match the load current, the output capacitor has to make up the difference. Applications that require exceptional transient response (2% or better for instantaneous full-load steps) will require relatively large value, low ESR output capacitors. Applications with more moderate transient load requirements can often get away with traditional standard ESR electrolytic capacitors at the output and can use larger valued inductors to minimize the required output capacitor value. Note that the RMS current in the output capacitor is slightly more than half of the inductor ripple current—much smaller than the RMS current in the input bypass capacitor. Output capacitor lifetime is usually not a factor in typical LTC1504 applications.

Large value ceramic capacitors used as output bypass capacitors provide excellent ESR characteristics but can cause loop compensation difficulties. See the Loop Compensation section.

### Loop Compensation

Loop compensation is strongly affected by the output capacitor. From a loop stability point of view, the output inductor and capacitor form a series RLC resonant circuit, with the L set by the inductor value, the C by the value of the output capacitor and the R dominated by the output capacitor's ESR. The amplitude response and phase shift due to these components is compensated by a network of Rs and Cs at the COMP pin to (hopefully) close the feedback loop in a stable manner. Qualitatively, the L and

Kool M $\mu$  is a registered trademark of Magnetics, Inc..

## APPLICATIONS INFORMATION

C of the output stage form a 2nd order roll-off with  $180^\circ$  of phase shift; the R due to ESR forms a single zero at a somewhat higher frequency that reduces the roll-off to first order and reduces the phase shift to  $90^\circ$ .

If the output capacitor has a relatively high ESR, the zero comes in well before the initial phase shift gets all the way to  $180^\circ$  and the loop only requires a single small capacitor from COMP to GND to remain stable (Figure 4a). If, on the other hand, the output capacitor is a low ESR type to maximize transient response, the ESR zero can increase in frequency by a decade or more and the output stage phase shift can get awfully close to  $180^\circ$  before it turns around and comes back to  $90^\circ$ . Large value ceramic, OS-CON electrolytic and low impedance tantalum capacitors fall into this category. These loops require an additional zero to be inserted at the COMP pin; a series RC in parallel with a smaller C to ground will usually ensure stability. Figure 4b shows a typical compensation network which will optimize transient response with most output capacitors. Adjustable output parts can add a feedforward capacitor across the feedback resistor divider to further improve phase margin. The typical applications in this data sheet

show compensation values that work with several combinations of external components—use them as a starting point. For complex cases or stubborn oscillations, contact the LTC Applications Department.

### External Schottky Diode

An external Schottky diode can be included across the internal N-channel switch (Q2) to improve efficiency at heavy loads. The diode carries the inductor current during the nonoverlap time while the LTC1504 turns Q1 off and Q2 on and prevents current from flowing in the intrinsic body diode in parallel with Q2. This diode will improve efficiency by a percentage point or two as output current approaches 500mA and can help minimize erratic behavior at very high peak current levels caused by excessive parasitic current flow through Q2. A Motorola MBRS0530L is usually adequate, with the cathode connected to SW and the anode connected to GND. Note that this diode is not required for normal operation and has a negligible effect on efficiency at low ( $< 250\text{mA}$ ) output currents.

### Soft Start and Current Limit

Soft start and current limit are linked in the LTC1504. Soft start works in a straightforward manner. An internal  $12\mu\text{A}$  current source connected to the SS pin will pull up an external capacitor connected from SS to GND at a rate determined by the capacitor value. COMP is clamped to a voltage one diode drop above SS; as SS rises, COMP will rise at the same rate. When COMP reaches roughly 2V below  $V_{CC}$ , the duty cycle will slowly begin to increase until the output comes into regulation. As SS continues to rise, the feedback amplifier takes over at COMP, the clamp releases and SS rises to  $V_{CC}$ . During a soft start cycle, the MIN feedback comparator is disabled to prevent it from overriding the COMP pin and forcing the output to maximum duty cycle.

Current limit operates by pulling down on the soft start pin when it senses an overload condition at the output. The current limit amplifier ( $I_{LIM}$ ) compares the voltage drop across the internal P-channel switch (Q1) during its on time to the voltage at the  $I_{MAX}$  pin.  $I_{MAX}$  includes an internal  $12\mu\text{A}$  pull-down, allowing the voltage to be set by a single resistor between  $V_{CC}$  and  $I_{MAX}$ . When the IR drop across

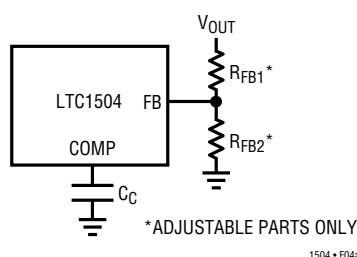


Figure 4a. Minimum Compensation Network

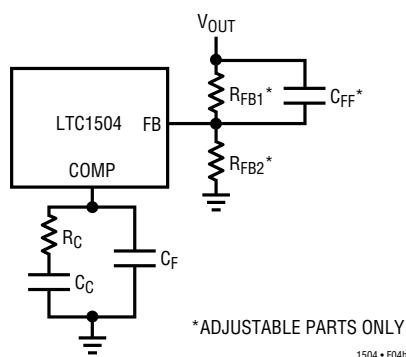


Figure 4b. Optimum Compensation Network

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Q1 exceeds the drop across the  $I_{MAX}$  resistor,  $I_{LIM}$  pulls current out of the external soft start capacitor, reducing the voltage at SS. A soft start capacitor should always be used if current limit is enabled. SS, in turn, pulls down on COMP, limiting the output duty cycle and controlling the output current. When the current overload is removed, the  $I_{LIM}$  amplifier lets go of SS and allows it to rise again as if it were completing a soft start cycle. The size of the external soft start capacitor controls both how fast the current limit responds once an overload is detected and how fast the output recovers once the overload is removed. The soft start capacitor also compensates the feedback loop created by the  $I_{LIM}$  amplifier. Because the  $I_{LIM}$  loop is a current feedback loop, the additional phase shift due to the output inductor and capacitor do not come into play and the loop can be adequately compensated with a single capacitor. Usually a 0.1 $\mu$ F ceramic capacitor from SS to GND provides adequate soft start behavior and acceptable current limit response.

This type of current limit circuit works well with mild current overloads and eliminates the need for an external current sensing resistor, making it attractive for LTC1504 applications. These same features also handicap the current limit circuit under severe short circuits when the output voltage is very close to ground. Under this condition, the LTC1504 must run at extremely narrow duty cycles (<5%) to keep the current under control. When the on-time falls below the time required to sense the current in Q1, the LTC1504 responds by reducing the oscillator frequency, increasing the off-time to decrease the duty cycle and allow it to maintain some control of the output current. The oscillator frequency may drop by as much as a factor of 10 under severe current overloads.

Under extreme short circuits (e.g., screwdriver to ground) the on-time will reduce to the point where the LTC1504 will lose control of the output current. At this point, output current will rise until the inductor saturates, and the current will be limited by the parasitic ESL of the inductor and the  $R_{ON}$  of Q2 inside the LTC1504. This current is usually nondestructive and dissipates a limited amount of power since the output voltage is very low. A typical LTC1504 circuit can withstand such a short for many seconds without damage. The test circuit in Figure 1 will

typically withstand a direct output short for more than 30 seconds without damage to the LTC1504. Eventually, however, a continuous short may cause the die temperature to rise to destructive levels.

Note that the current limit is primarily designed to protect the LTC1504 from damage and is not intended to be used to generate an accurate constant-current output. As the die temperature varies in a current limited condition, the  $R_{ON}$  of the internal switches will change and the current limit threshold will move around.  $R_{ON}$  will also vary from part-to-part due to manufacturing tolerance. The external  $I_{MAX}$  resistor should be chosen to allow enough room to account for these variations without allowing the current limit to engage at the maximum expected load current. A current limit setting roughly double the expected load is often a good compromise, eliminating unintended current limit operation while preventing circuit destruction under actual fault conditions. If desired, current limit can be disabled by floating the  $I_{MAX}$  pin; the internal current source will pull  $I_{MAX}$  to GND and the  $I_{LIM}$  amplifier will be disabled.

### Shutdown

The LTC1504 includes a micropower shutdown mode controlled by the logic level at  $\overline{SHDN}$ . A logic High at  $\overline{SHDN}$  allows the part to operate normally. A logic Low at  $\overline{SHDN}$  stops all internal switching, pulls COMP, SS and SW to GND and drops quiescent current below 1 $\mu$ A typically. Note that the internal N-channel power MOSFET from SW to GND turns on when  $\overline{SHDN}$  is asserted. This ensures that the output voltage drops to zero when the LTC1504 is shut down, but prevents other devices from powering the output when the LTC1504 is disabled.

### External Clock Synchronization

The LTC1504  $\overline{SHDN}$  pin can double as an external clock input for applications that require a synchronized clock or a faster switching speed. The  $\overline{SHDN}$  pin terminates the internal sawtooth wave and resets the oscillator immediately when it goes low, but waits 50 $\mu$ s before shutting down the rest of the internal circuitry. A clock signal applied directly to the  $\overline{SHDN}$  pin will force the LTC1504 internal oscillator to lock to its frequency as long as the external clock runs faster than the internal oscillator

## APPLICATIONS INFORMATION

frequency. Attempting to synchronize to a frequency lower than the 250kHz maximum internal frequency may result in inconsistent pulse widths and is not recommended.

Because the sawtooth waveform rises at a fixed rate internally, terminating it early by synchronizing to a fast external clock will reduce the amplitude of the sawtooth wave that the PWM comparator sees, effectively raising the gain from COMP to SW. 500kHz is the maximum recommended synchronization frequency; higher frequencies will reduce the sawtooth amplitude to the point that the LTC1504 may run erratically.

### THERMAL CONSIDERATIONS

Each of the LTC1504 internal power switches has approximately  $1.5\Omega$  of resistance at room temperature and will happily carry more than the rated maximum current if the current limit is set very high or is not connected. Since the inductor current is always flowing through one or the other of the internal switches, a typical application supplying 500mA of load current will cause a continuous dissipation of approximately 375mW. The SO-8 package has a thermal resistance of approximately  $90^{\circ}\text{C}/\text{W}$ , meaning that the die will begin to rise toward  $34^{\circ}\text{C}$  above ambient at this power level. The  $R_{\text{ON}}$  of the internal power switches increases as the die temperature rises, increasing the power dissipation as the feedback loop continues to keep the output current at 500mA. At high ambient temperatures, this cycle may continue until the chip melts, since the LTC1504 does not include any form of thermal shutdown. Applications can safely draw peak currents above the 500mA level, but the average power dissipation should be carefully calculated so that the maximum  $115^{\circ}\text{C}$  die temperature is not exceeded.

The LTC1504 dissipates the majority of its heat through its pins, especially GND (Pin 4). Thermal resistance to ambient can be optimized by connecting GND to a large copper region on the PCB, which will serve as a heat sink. Applications which will operate the LTC1504 near maximum power levels or which must withstand short circuits of extended duration should maximize the copper area at all pins and ensure that there is some airflow over the part to carry away excess heat. For layout assistance in situa-

tions where power dissipation may be a concern, contact the LTC Applications Department.

The current limit circuit can be used to limit the power under mild overloads to a safe level, but severe overloads where the output is shorted to ground may still cause the die temperature to rise dangerously. For more information on current limit behavior, see the Current Limit section.

### LAYOUT CONSIDERATIONS

Like all precision switching regulators, the LTC1504 requires special care in layout to ensure optimum performance. The large peak currents coupled with significant DC current flow will conspire to keep the output from regulating properly if the layout is not carefully planned. A poorly laid out op amp or data converter circuit will fail to give the desired performance, but will usually still act like an op amp or data converter. A poorly laid out LTC1504 circuit may look nothing at all like a regulator. *Wire-wrap or plug-in prototyping boards are not useful for breadboarding LTC1504 circuits!*

Perhaps most critical to proper LTC1504 performance is the layout of the ground node and the location of the input and output capacitors. The negative terminals of both the input and output bypass capacitors should come together at the same point, as close as possible to the LTC1504 ground pin. The compensation network and soft start capacitor can be connected together on their own trace, which should come directly back to this same common ground point. The input supply ground and the load return should also connect to this common point. Each ground line should come to a star connection with Pin 4 at the center of the star. This node should be a fairly large copper region to act as a heat sink if required.

Second in importance is the proximity of the low ESR (usually ceramic) input bypass capacitor. It should be located as close to the LTC1504  $V_{\text{CC}}$  and GND pins as physically possible. Ideally, the capacitor should be located right next to the package, straddling the SW pin. High peak current applications or applications with  $V_{\text{CC}}$  greater than 6V may require a  $1\mu\text{F}$  or larger ceramic capacitor in this position.

One node that isn't quite so critical is SW. Extra lead length or narrow traces at this pin will only add parasitic induc-

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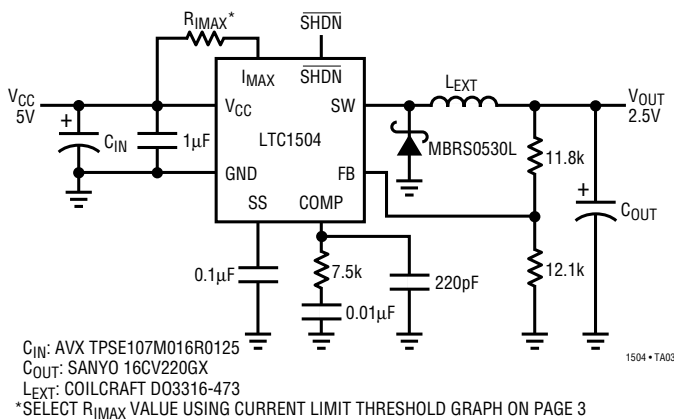
tance in series with the external inductor, slightly raising its value. The SW trace need only be wide enough to support the maximum peak current under short circuit conditions—perhaps 1A. If a trace needs to be compromised to make the layout work, this is the one. Note that long traces at the SW node may aggravate EMI considerations—don't get carried away. If a Schottky diode is used at the SW node, it should be located at the LTC1504 end of the trace, close to the device pins.

The LTC Applications Department has constructed literally hundreds of layouts for the LTC1504 and related

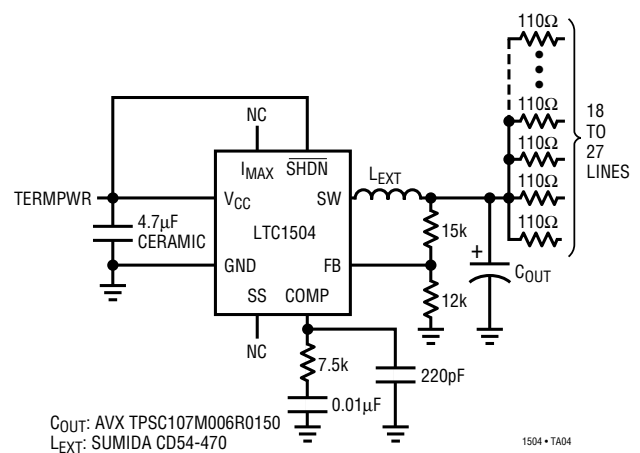
parts, many of which worked and some of which are now archived in the Bad Layout Hall of Fame. If you need layout assistance or you think you have a candidate layout for the Hall of Fame, give Applications a call at (408) 954-8400. Demo boards with properly designed layouts are available and specialized layouts can be designed if required. The applications team is also experienced in external component selection for a wide variety of applications, and they have a never-ending selection of tall tales to tell as well. When in doubt, give them a call.

## TYPICAL APPLICATIONS

High Efficiency 5V to 2.5V Converter with Current Limit



SCSI-2 Active Terminator



## RELATED PARTS

| PART NUMBER     | DESCRIPTION                                        | COMMENTS                                   |
|-----------------|----------------------------------------------------|--------------------------------------------|
| LTC1174         | 600mA, High Efficiency Step-Down Converter         | Nonsynchronous, Better Low Load Efficiency |
| LT®1307         | Single Cell 600kHz DC/DC Converter                 | Boost Mode, Micropower                     |
| LT1372          | 1.5A, 500kHz Step-Up Switching Regulator           | Boost Mode, High Power                     |
| LT1376          | 1.5A, 500kHz Step-Down Switching Regulator         | Nonsynchronous, 1.5A Max Current           |
| LTC1433/LTC1434 | 450mA, Low Noise Current Mode Step-Down Converters | Nonsynchronous, Better Low Load Efficiency |
| LT1507          | 1.5A, 500kHz Monolithic Buck Regulator             | Nonsynchronous, 1.5A Max Current           |