

# 1A, 4MHz, Synchronous Step-Down DC/DC Converter

## FEATURES

- Uses Tiny Capacitors and Inductor
- High Frequency Operation: Up to 4MHz
- High Switch Current: 1.4A
- Low  $R_{DS(ON)}$  Internal Switches: 0.110 $\Omega$
- High Efficiency: Up to 95%
- $V_{IN}$ : 2.63V to 5.5V
- Stable with Ceramic Capacitors
- Current Mode Operation for Excellent Line and Load Transient Response
- Short-Circuit Protected
- Low Dropout Operation: 100% Duty Cycle
- Low Shutdown Current:  $I_Q \leq 1\mu A$
- Low Quiescent Current: 240 $\mu A$
- Output Voltages from 0.8V to 5V
- Low Noise Pulse-Skipping Operation
- Small 8-Pin DFN Package

## APPLICATIONS

- Wireless LAN Power
- Notebook Computers
- Digital Cameras
- Cellular Phones
- Board Mounted Power Supplies

## DESCRIPTION

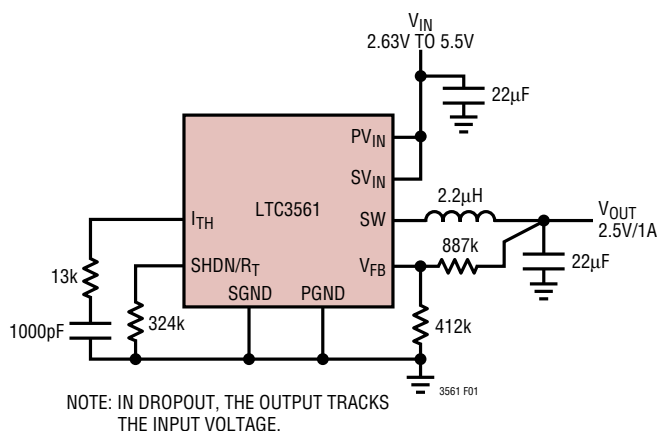
The LTC<sup>®</sup>3561 is a constant-frequency, synchronous, step-down DC/DC converter. Intended for medium power applications, it operates from a 2.63V to 5.5V input voltage range and has a user configurable operating frequency up to 4MHz, allowing the use of tiny, low cost capacitors and inductors 2mm or less in height. The output voltage is adjustable from 0.8V to 5V. Internal synchronous 0.11 $\Omega$  power switches with 1.4A peak current ratings provide high efficiency. The LTC3561's current mode architecture and external compensation allow the transient response to be optimized over a wide range of loads and output capacitors.

To further maximize battery life, the P-channel MOSFET is turned on continuously in dropout (100% duty cycle). The no-load quiescent current is only 240 $\mu A$ . In shutdown, the device draws <1 $\mu A$ .

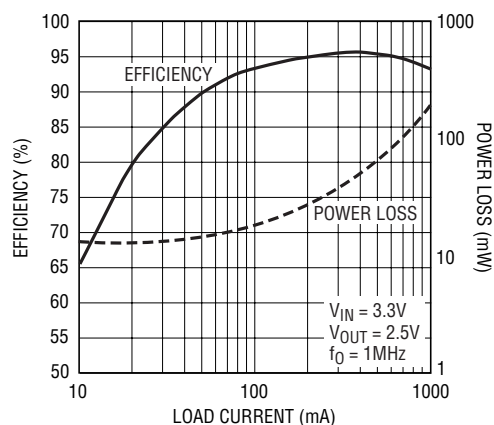
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## TYPICAL APPLICATION

Step-Down 2.5V/1A Regulator



Efficiency and Power Loss vs Load Current



3561 TA01

## ABSOLUTE MAXIMUM RATINGS

(Note 1)

$PV_{IN}$ , $SV_{IN}$ Voltages	-0.3V to 6V
$V_{FB}$ , $SHDN/R_T$ Voltages	-0.3V to ( $V_{IN} + 0.3V$ )
$I_{TH}$ Voltage	-0.3V to 1.4V
SW Voltage	-0.3V to ( $V_{IN} + 0.3V$ )
Operating Ambient Temperature Range	
(Note 2)	-40°C to 85°C
Junction Temperature (Notes 5, 8)	125°C
Storage Temperature Range	-65°C to 125°C

## PACKAGE/ORDER INFORMATION

TOP VIEW

DD PACKAGE  
8-LEAD (3mm × 3mm) PLASTIC DFN

$T_{JMAX} = 125^{\circ}C$ ,  $\theta_{JA} = 43^{\circ}C/W$ ,  $\theta_{JC} = 3^{\circ}C/W$   
EXPOSED PAD (PIN 9) MUST BE SOLDERED TO GROUND

ORDER PART NUMBER	DD PART MARKING
LTC3561EDD	LCJJ

**Order Options** Tape and Reel: Add #TR  
Lead Free: Add #PBF Lead Free Tape and Reel: Add #TRPBF  
Lead Free Part Marking: <http://www.linear.com/leadfree/>

Consult LTC Marketing for parts specified with wider operating temperature ranges.

## ELECTRICAL CHARACTERISTICS

The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at  $T_A = 25^{\circ}C$ .  $V_{IN} = 3.3V$ ,  $R_T = 324k$  unless otherwise specified. (Note 2)

SYMBOL	PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
$V_{IN}$	Operating Voltage Range		2.625		5.5	V
$I_{FB}$	Feedback Pin Input Current	(Note 3)			±0.1	μA
$V_{FB}$	Feedback Voltage	(Note 3)	● 0.784	0.8	0.816	V
$\Delta V_{LINEREG}$	Reference Voltage Line Regulation	$V_{IN} = 2.7V$ to 5V		0.04	0.2	%/V
$\Delta V_{LOADREG}$	Output Voltage Load Regulation	$I_{TH} = 0.36$ , (Note 3)	●	0.02	0.2	%
		$I_{TH} = 0.84$ , (Note 3)	●	-0.02	-0.2	%
$g_{m(EA)}$	Error Amplifier Transconductance	$I_{TH}$ Pin Load = ±5μA (Note 3)		800		μS
$I_S$	Input DC Supply Current (Note 4)					
	Active Mode	$V_{FB} = 0.75V$		240	350	μA
	Shutdown	$V_{SHDN/RT} = 3.3V$		0.1	1	μA
$V_{SHDN/RT}$	Shutdown Threshold High			$V_{IN} - 0.6$	$V_{IN} - 0.4$	V
	Active Oscillator Resistor			324k	1M	Ω
$f_{OSC}$	Oscillator Frequency	$R_T = 324k$ (Note 7)	0.85	1	1.15	MHz
					4	MHz
$I_{LIM}$	Peak Switch Current Limit	$I_{TH} = 1.3$	1.4	1.7		A
$R_{DS(ON)}$	Top Switch On-Resistance (Note 6)	$V_{IN} = 3.3V$		0.11	0.15	Ω
	Bottom Switch On-Resistance (Note 6)	$V_{IN} = 3.3V$		0.11	0.15	Ω
$I_{SW(LKG)}$	Switch Leakage Current	$V_{IN} = 6V$ , $V_{ITH/RUN} = 0V$ , $V_{FB} = 0V$		0.01	1	μA
$V_{UVLO}$	Undervoltage Lockout Threshold	$V_{IN}$ Ramping Down	2.375	2.5	2.625	V

**Note 1:** Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. Exposure to any Absolute Maximum Rating condition for extended periods may affect device reliability and lifetime. No pin shall exceed 6V.

**Note 2:** The LTC3561E is guaranteed to meet specified performance from 0°C to 85°C. Specifications over the -40°C to 85°C operating ambient

temperature range are assured by design, characterization and correlation with statistical process controls.

**Note 3:** The LTC3561 is tested in a feedback loop which serves  $V_{FB}$  to the midpoint for the error amplifier ( $V_{ITH} = 0.6V$ ).

**Note 4:** Dynamic supply current is higher due to the internal gate charge being delivered at the switching frequency.

## ELECTRICAL CHARACTERISTICS

**Note 5:**  $T_J$  is calculated from the ambient  $T_A$  and power dissipation  $P_D$  according to the following formula:

$$LTC3561EDD: T_J = T_A + (P_D \cdot 43^\circ\text{C/W})$$

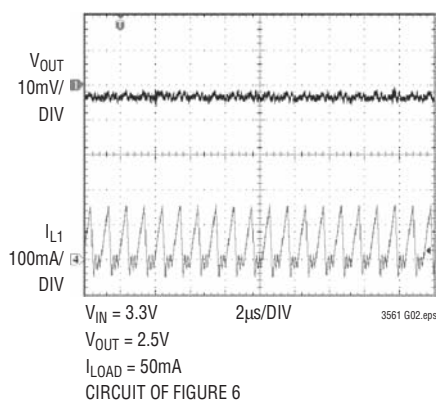
**Note 6:** Switch on-resistance is guaranteed by correlation to wafer level measurements.

**Note 7:** 4MHz operation is guaranteed by design but not production tested and is subject to duty cycle limitations (see Applications Information).

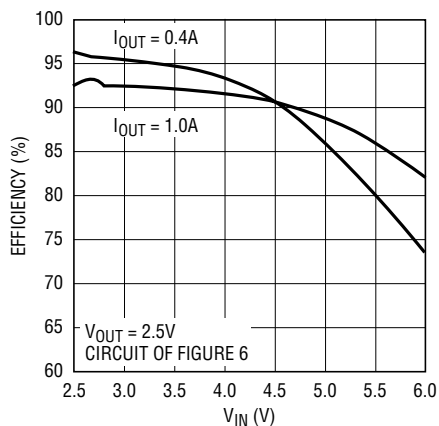
**Note 8:** This IC includes overtemperature protection that is intended to protect the device during momentary overload conditions. Junction temperature will exceed  $125^\circ\text{C}$  when overtemperature protection is active. Continuous operation above the specified maximum operating junction temperature may impair device reliability.

## TYPICAL PERFORMANCE CHARACTERISTICS

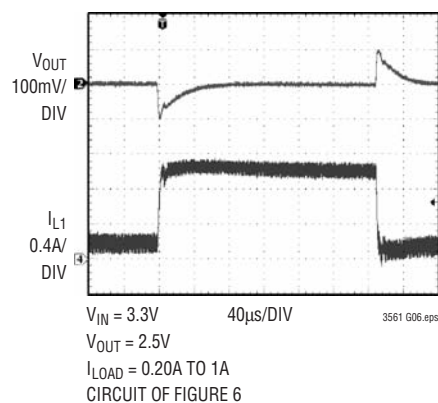
Switching Waveforms



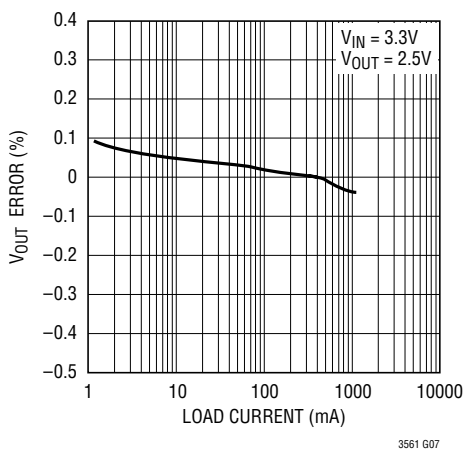
Efficiency vs  $V_{IN}$



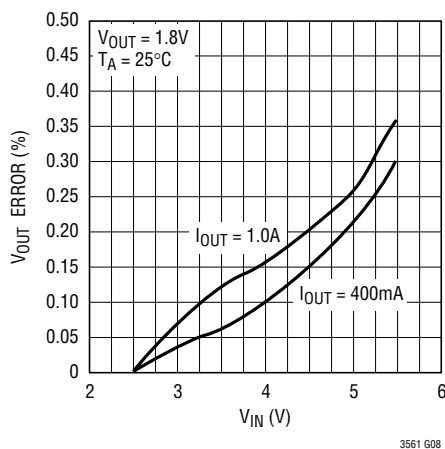
Load Step



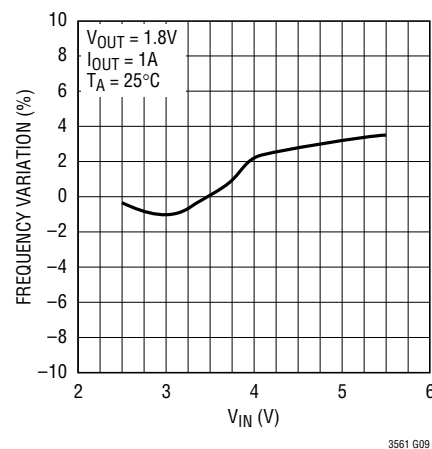
Load Regulation



Line Regulation

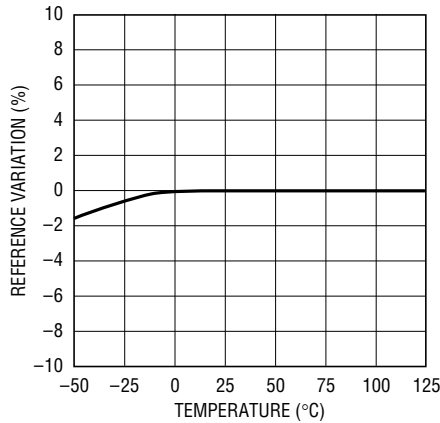


Frequency vs  $V_{IN}$



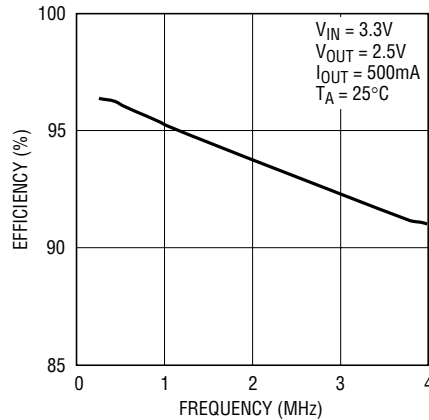
## TYPICAL PERFORMANCE CHARACTERISTICS

Frequency Variation  
vs Temperature



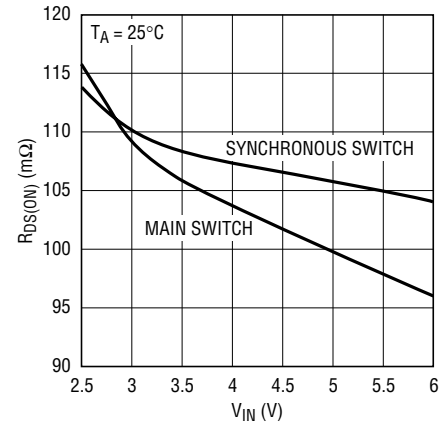
3561 G10

Efficiency vs Frequency



3561 G11

$R_{DS(ON)}$  vs  $V_{IN}$



3561 G12

## PIN FUNCTIONS

**SHDN/ $R_T$  (Pin 1):** Combination Shutdown and Timing Resistor Pin. The oscillator frequency is programmed by connecting a resistor from this pin to ground. Forcing this pin to  $SV_{IN}$  causes the device to be shut down. In shutdown all functions are disabled.

**SGND (Pin 2):** The Signal Ground Pin. All small signal components and compensation components should be connected to this ground (see Board Layout Considerations).

**SW (Pin 3):** The Switch Node Connection to the Inductor. This pin swings from  $PV_{IN}$  to PGND.

**PGND (Pin 4):** Main Power Ground Pin. Connect to the (-) terminal of  $C_{OUT}$ , and (-) terminal of  $C_{IN}$ .

**$PV_{IN}$  (Pin 5):** Main Supply Pin. Must be closely decoupled to PGND.

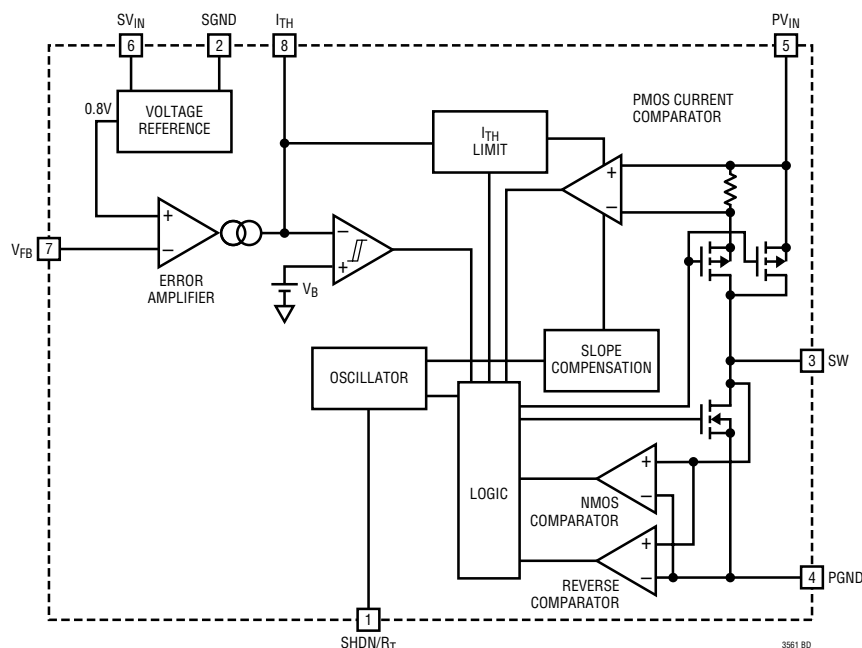
**$SV_{IN}$  (Pin 6):** The Signal Power Pin. All active circuitry is powered from this pin. Must be closely decoupled to SGND.  $SV_{IN}$  must be greater than or equal to  $PV_{IN}$ .

**$V_{FB}$  (Pin 7):** Receives the feedback voltage from the external resistive divider across the output. Nominal voltage for this pin is 0.8V.

**$I_{TH}$  (Pin 8):** Error Amplifier Compensation Point. The current comparator threshold increases with this control voltage. Nominal voltage range for this pin is 0V to 1.5V.

**Exposed Pad (Pin 9):** Thermal Connection to PCB. This pin should be soldered to ground to achieve rated thermal performance.

## BLOCK DIAGRAM



## OPERATION

The LTC3561 uses a constant frequency, current mode architecture. The operating frequency is determined by the value of the  $R_T$  resistor.

The output voltage is set by an external divider returned to the  $V_{FB}$  pin. An error amplifier compares the divided output voltage with a reference voltage of 0.8V and adjusts the peak inductor current accordingly.

### Main Control Loop

During normal operation, the top power switch (P-channel MOSFET) is turned on at the beginning of a clock cycle when the  $V_{FB}$  voltage is below the reference voltage. The current into the inductor and the load increases until the current limit is reached. The switch turns off and energy stored in the inductor flows through the bottom switch (N-channel MOSFET) into the load until the next clock cycle.

The peak inductor current is controlled by the voltage on the  $I_{TH}$  pin, which is the output of the error amplifier. This amplifier compares the  $V_{FB}$  pin to the 0.8V reference. When the load current increases, the  $V_{FB}$  voltage decreases slightly below the reference. This decrease causes the error amplifier to increase the  $I_{TH}$  voltage until the average inductor current matches the new load current. At

low load currents, the inductor current becomes discontinuous, and pulses may be skipped to maintain regulation.

The main control loop is shut down by pulling the SHDN/ $R_T$  pin to  $S_{VIN}$ . A digital soft-start is enabled after shutdown, which will slowly ramp the peak inductor current up over 1024 clock cycles or until the output reaches regulation, whichever is first. Soft-start can be lengthened by ramping the voltage on the  $I_{TH}$  pin (see Applications Information section).

### Dropout Operation

When the input supply voltage decreases toward the output voltage, the duty cycle increases to 100% which is the dropout condition. In dropout, the PMOS switch is turned on continuously with the output voltage being equal to the input voltage minus the voltage drops across the internal P-channel MOSFET and the inductor.

### Low Supply Operation

The LTC3561 incorporates an undervoltage lockout circuit which shuts down the part when the input voltage drops below about 2.5V to prevent unstable operation.

## APPLICATIONS INFORMATION

A general LTC3561 application circuit is shown in Figure 4. External component selection is driven by the load requirement, and begins with the selection of the inductor L1. Once L1 is chosen, C<sub>IN</sub> and C<sub>OUT</sub> can be selected.

### Operating Frequency

Selection of the operating frequency is a tradeoff between efficiency and component size. High frequency operation allows the use of smaller inductor and capacitor values. Operation at lower frequencies improves efficiency by reducing internal gate charge losses but requires larger inductance values and/or capacitance to maintain low output ripple voltage.

The operating frequency, f<sub>O</sub>, of the LTC3561 is determined by an external resistor that is connected between the R<sub>T</sub> pin and ground. The value of the resistor sets the ramp current that is used to charge and discharge an internal timing capacitor within the oscillator and can be calculated by using the following equation:

$$R_T = 9.78 \cdot 10^{11} (f_O)^{-1.08} (\Omega)$$

or can be selected using Figure 1.

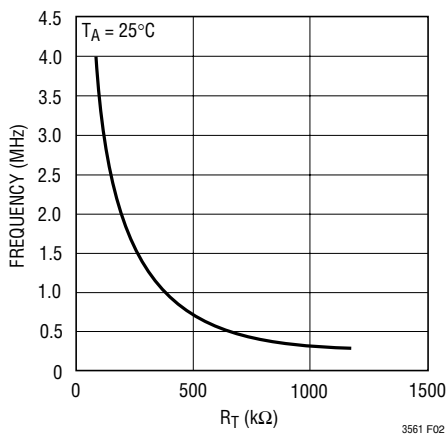


Figure 1. Frequency vs R<sub>T</sub>

The maximum usable operating frequency is limited by the minimum on-time and the duty cycle. This can be calculated as:

$$f_{O(\text{MAX})} \approx 6.67 \cdot (V_{\text{OUT}} / V_{\text{IN}(\text{MAX})}) \text{ (MHz)}$$

The minimum frequency is limited by leakage and noise coupling due to the large resistance of R<sub>T</sub>.

### Inductor Selection

Although the inductor does not influence the operating frequency, the inductor value has a direct effect on ripple current. The inductor ripple current ΔI<sub>L</sub> decreases with higher inductance and increases with higher V<sub>IN</sub> or V<sub>OUT</sub>:

$$\Delta I_L = \frac{V_{\text{OUT}}}{f_O \cdot L} \cdot \left( 1 - \frac{V_{\text{OUT}}}{V_{\text{IN}}} \right)$$

Accepting larger values of ΔI<sub>L</sub> allows the use of low inductances, but results in higher output voltage ripple, greater core losses, and lower output current capability.

A reasonable starting point for setting ripple current is ΔI<sub>L</sub> = 0.4 × I<sub>OUT(MAX)</sub>, where I<sub>OUT(MAX)</sub> is 1A. The largest ripple current ΔI<sub>L</sub> occurs at the maximum input voltage. To guarantee that the ripple current stays below a specified maximum, the inductor value should be chosen according to the following equation:

$$L = \frac{V_{\text{OUT}}}{f_O \cdot \Delta I_L} \cdot \left( 1 - \frac{V_{\text{OUT}}}{V_{\text{IN}(\text{MAX})}} \right)$$

### Inductor Core Selection

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 do not radiate much energy, but generally cost more than powdered iron 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 LTC3561 requires to operate. Table 1 shows some typical surface mount inductors that work well in LTC3561 applications.



## APPLICATIONS INFORMATION

Table 1. Representative Surface Mount Inductors

MANUFACTURER	PART NUMBER	VALUE	MAX DC CURRENT	DCR	HEIGHT
Toko	A914BYW-2R2M-D52LC	2.2 $\mu$ H	2.05A	49m $\Omega$	2mm
Coilcraft	D01608C-222	2.2 $\mu$ H	2.3A	70m $\Omega$	3mm
Coilcraft	LP01704-222M	2.2 $\mu$ H	2.4A	120m $\Omega$	1mm
Sumida	CDRH2D18/HP-2R2	2.2 $\mu$ H	1.6A	48m $\Omega$	2mm
Taiyo Yuden	N05DB2R2M	2.2 $\mu$ H	2.9A	32m $\Omega$	2.8mm
Murata	LQN6C2R2M04	2.2 $\mu$ H	3.2A	24m $\Omega$	5mm
Cooper	SD3112-2R2	2.2 $\mu$ H	1.1A	140m $\Omega$	1.2mm
TDK	VLF3010AT-2R2M1R0	2.2 $\mu$ H	1.0A	100m $\Omega$	1.0mm
EPCO	B82470A1222M	2.2 $\mu$ H	1.6A	90m $\Omega$	1.2mm

### Input Capacitor ( $C_{IN}$ ) Selection

In continuous mode, the input current of the converter is a square wave with a duty cycle of approximately  $V_{OUT}/V_{IN}$ . To prevent large voltage transients, a low equivalent series resistance (ESR) input capacitor sized for the maximum RMS current must be used. The maximum RMS capacitor current is given by:

$$I_{RMS} \approx I_{MAX} \frac{\sqrt{V_{OUT}(V_{IN} - V_{OUT})}}{V_{IN}}$$

where the maximum average output current  $I_{MAX}$  equals the peak current minus half the peak-to-peak ripple current,  $I_{MAX} = I_{LIM} - \Delta I_L/2$ .

This formula has a maximum at  $V_{IN} = 2V_{OUT}$ , where  $I_{RMS} = I_{OUT}/2$ . This simple worst case is commonly used to design because even significant deviations do not offer much relief. Note that capacitor manufacturer's ripple current ratings are often based on only 2000 hours lifetime. This makes it advisable to further derate the capacitor, or choose a capacitor rated at a higher temperature than required. Several capacitors may also be paralleled to meet the size or height requirements of the design. An additional 0.1 $\mu$ F to 1 $\mu$ F ceramic capacitor is also recommended on  $V_{IN}$  for high frequency decoupling, when not using an all ceramic capacitor solution.

### Output Capacitor ( $C_{OUT}$ ) Selection

The selection of  $C_{OUT}$  is driven by the required ESR to minimize voltage ripple and load step transients. Typically, once the ESR requirement is satisfied, the capacitance is adequate for filtering. The output ripple ( $\Delta V_{OUT}$ ) is determined by:

$$\Delta V_{OUT} \approx \Delta I_L \left( ESR + \frac{1}{8f_0 C_{OUT}} \right)$$

where  $f$  = operating frequency,  $C_{OUT}$  = output capacitance and  $\Delta I_L$  = ripple current in the inductor. The output ripple is highest at maximum input voltage since  $\Delta I_L$  increases with input voltage. With  $\Delta I_L = 0.3 \cdot I_{LIM}$  the output ripple will be less than 100mV at maximum  $V_{IN}$  and  $f_0 = 1$ MHz with:

$$ESR_{C_{OUT}} < 150m\Omega$$

Once the ESR requirements for  $C_{OUT}$  have been met, the RMS current rating generally far exceeds the  $I_{RIPPLE(P-P)}$  requirement, except for an all ceramic solution.

In surface mount applications, multiple capacitors may have to be paralleled to meet the capacitance, ESR or RMS current handling requirement of the application. Aluminum electrolytic, special polymer, ceramic and dry tantalum capacitors are all available in surface mount packages. The OS-CON semiconductor dielectric capacitor available from Sanyo has the lowest ESR(size) product of any aluminum electrolytic at a somewhat higher price. Special polymer capacitors, such as Sanyo POSCAP, offer very low ESR, but have a lower capacitance density than other types. Tantalum capacitors have the highest capacitance density, but it has a larger ESR and it is critical that the capacitors are surge tested for use in switching power supplies. An excellent choice is the AVX TPS series of surface mount tantalums, available in case heights ranging from 2mm to 4mm. Aluminum electrolytic capacitors have a significantly larger ESR, and is often used in extremely cost-sensitive applications provided that consideration is given to ripple current ratings and long term reliability. Ceramic capacitors have the lowest ESR and cost but also have the lowest capacitance density, a high voltage and temperature coefficient and exhibit audible

## APPLICATIONS INFORMATION

piezoelectric effects. In addition, the high Q of ceramic capacitors along with trace inductance can lead to significant ringing. Other capacitor types include the Panasonic specialty polymer (SP) capacitors.

In most cases, 0.1 $\mu$ F to 1 $\mu$ F of ceramic capacitors should also be placed close to the LTC3561 in parallel with the main capacitors for high frequency decoupling.

### Ceramic Input and Output Capacitors

Higher value, lower cost ceramic capacitors are now becoming available in smaller case sizes. These are tempting for switching regulator use because of their very low ESR. Unfortunately, the ESR is so low that it can cause loop stability problems. Solid tantalum capacitor ESR generates a loop “zero” at 5kHz to 50kHz that is instrumental in giving acceptable loop phase margin. Ceramic capacitors remain capacitive to beyond 300kHz and usually resonate with their ESL before ESR becomes effective. Also, ceramic caps are prone to temperature effects which requires the designer to check loop stability over the operating temperature range. To minimize their large temperature and voltage coefficients, only X5R or X7R ceramic capacitors should be used. A good selection of ceramic capacitors is available from Taiyo Yuden, TDK and Murata.

Great care must be taken when using only ceramic input and output capacitors. When a ceramic capacitor is used at the input and the power is being supplied through long wires, such as from a wall adapter, a load step at the output can induce ringing at the  $V_{IN}$  pin. At best, this ringing can couple to the output and be mistaken as loop instability. At worst, the ringing at the input can be large enough to damage the part.

Since the ESR of a ceramic capacitor is so low, the input and output capacitor must instead fulfill a charge storage requirement. During a load step, the output capacitor must instantaneously supply the current to support the load until the feedback loop raises the switch current enough to support the load. The time required for the feedback loop to respond is dependent on the compensation components and the output capacitor size. Typically, 3 to 4 cycles

are required to respond to a load step, but only in the first cycle does the output drop linearly. The output droop,  $V_{DROOP}$ , is usually about 2 to 3 times the linear drop of the first cycle. Thus, a good place to start is with the output capacitor size of approximately:

$$C_{OUT} \approx 2.5 \frac{\Delta I_{OUT}}{f_0 \cdot V_{DROOP}}$$

More capacitance may be required depending on the duty cycle and load step requirements.

In most applications, the input capacitor is merely required to supply high frequency bypassing, since the impedance to the supply is very low. A 10 $\mu$ F ceramic capacitor is usually enough for these conditions.

### Setting the Output Voltage

The LTC3561 develops a 0.8V reference voltage between the feedback pin,  $V_{FB}$ , and the signal ground as shown in Figure 4. The output voltage is set by a resistive divider according to the following formula:

$$V_{OUT} \approx 0.8V \left( 1 + \frac{R2}{R1} \right)$$

Keeping the current small (<5 $\mu$ A) in these resistors maximizes efficiency, but making them too small may allow stray capacitance to cause noise problems and reduce the phase margin of the error amp loop.

To improve the frequency response, a feed-forward capacitor  $C_F$  may also be used. Great care should be taken to route the  $V_{FB}$  line away from noise sources, such as the inductor or the SW line.

### Shutdown and Soft-Start

The SHDN/ $R_T$  pin is a dual purpose pin that sets the oscillator frequency and provides a means to shut down the LTC3561. This pin can be interfaced with control logic in several ways, as shown in Figure 2(a) and Figure 2(b).

The  $I_{TH}$  pin is primarily for loop compensation, but it can also be used to increase the soft-start time. Soft-start



## APPLICATIONS INFORMATION

reduces surge currents from  $V_{IN}$  by gradually increasing the peak inductor current. Power supply sequencing can also be accomplished using this pin. The LTC3561 has an internal digital soft-start which steps up a clamp on  $I_{TH}$  over 1024 clock cycles, as can be seen in Figure 3.

The soft-start time can be increased by ramping the voltage on  $I_{TH}$  during start-up as shown in Figure 2(c). As the voltage on  $I_{TH}$  ramps through its operating range the internal peak current limit is also ramped at a proportional linear rate.

### Checking Transient Response

The OPTI-LOOP compensation allows the transient response to be optimized for a wide range of loads and output capacitors. The availability of the  $I_{TH}$  pin not only allows optimization of the control loop behavior but also provides a DC coupled and AC filtered closed loop response test point. The DC step, rise time and settling at this test point truly reflects the closed loop response. Assuming a predominantly second order system, phase margin and/or damping factor can be estimated using the percentage of overshoot seen at this pin. The bandwidth can also be estimated by examining the rise time at the pin.

The  $I_{TH}$  external components shown in the front page circuit will provide an adequate starting point for most applications. The series R-C filter sets the dominant pole-zero loop compensation. The values can be modified slightly (from 0.5 to 2 times their suggested values) to optimize transient response once the final PC layout is

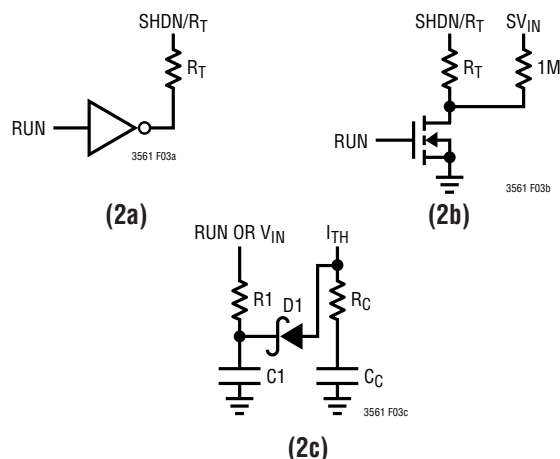


Figure 2. SHDN/R<sub>T</sub> Pin Interfacing and External Soft-Start

done and the particular output capacitor type and value have been determined. The output capacitors need to be selected because the various types and values determine the loop feedback factor gain and phase. An output current pulse of 20% to 100% of full load current having a rise time of  $1\mu\text{s}$  to  $10\mu\text{s}$  will produce output voltage and  $I_{TH}$  pin waveforms that will give a sense of the overall loop stability without breaking the feedback loop.

Switching regulators take several cycles to respond to a step in load current. When a load step occurs,  $V_{OUT}$  immediately shifts by an amount equal to  $\Delta I_{LOAD} \cdot \text{ESR}$ , where ESR is the effective series resistance of  $C_{OUT}$ .  $\Delta I_{LOAD}$  also begins to charge or discharge  $C_{OUT}$  generating a feedback error signal used by the regulator to return  $V_{OUT}$  to its steady-state value. During this recovery time,  $V_{OUT}$  can be monitored for overshoot or ringing that would indicate a stability problem.

The initial output voltage step may not be within the bandwidth of the feedback loop, so the standard second order overshoot/DC ratio cannot be used to determine phase margin. The gain of the loop increases with R and the bandwidth of the loop increases with decreasing C. If R is increased by the same factor that C is decreased, the zero frequency will be kept the same, thereby keeping the phase the same in the most critical frequency range of the feedback loop. In addition, a feedforward capacitor  $C_F$  can be added to improve the high frequency response, as shown in Figure 5. Capacitor  $C_F$  provides phase lead by creating a high frequency zero with R2 which improves the phase margin.

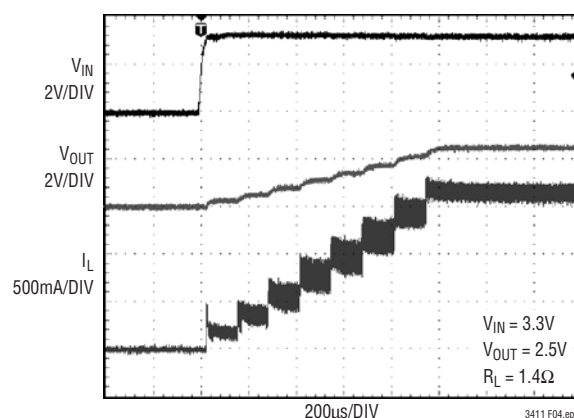


Figure 3. Digital Soft-Start

## APPLICATIONS INFORMATION

The output voltage settling behavior is related to the stability of the closed-loop system and will demonstrate the actual overall supply performance. For a detailed explanation of optimizing the compensation components, including a review of control loop theory, refer to Linear Technology Application Note 76.

Although a buck regulator is capable of providing the full output current in dropout, it should be noted that as the input voltage  $V_{IN}$  drops toward  $V_{OUT}$ , the load step capability does decrease due to the decreasing voltage across the inductor. Applications that require large load step capability near dropout should use a different topology such as SEPIC, Zeta or single inductor, positive buck/boost.

In some applications, a more severe transient can be caused by switching in loads with large ( $>1\mu\text{F}$ ) input capacitors. The discharged input capacitors are effectively put in parallel with  $C_{OUT}$ , causing a rapid drop in  $V_{OUT}$ . No regulator can deliver enough current to prevent this problem, if the switch connecting the load has low resistance and is driven quickly. The solution is to limit the turn-on speed of the load switch driver. A hot swap controller is designed specifically for this purpose and usually incorporates current limiting, short-circuit protection, and soft-starting.

### Efficiency Considerations

The percent efficiency of a switching regulator is equal to the output power divided by the input power times 100%. It is often useful to analyze individual losses to determine what is limiting the efficiency and which change would

produce the most improvement. Percent efficiency can be expressed as:

$$\% \text{Efficiency} = 100\% - (L1 + L2 + L3 + \dots)$$

where  $L1$ ,  $L2$ , etc. are the individual losses as a percentage of input power.

Although all dissipative elements in the circuit produce losses, four main sources usually account for most of the losses in LTC3561 circuits: 1) LTC3561  $V_{IN}$  current, 2) switching losses, 3)  $I^2R$  losses, 4) other losses.

- 1) The  $V_{IN}$  current is the DC supply current given in the electrical characteristics which excludes MOSFET driver and control currents.  $V_{IN}$  current results in a small ( $<0.1\%$ ) loss that increases with  $V_{IN}$ , even at no load.
- 2) The switching current is the sum of the MOSFET driver and control currents. The MOSFET driver current results from switching the gate capacitance of the power MOSFETs. Each time a MOSFET gate is switched from low to high to low again, a packet of charge  $dQ$  moves from  $V_{IN}$  to ground. The resulting  $dQ/dt$  is a current out of  $V_{IN}$  that is typically much larger than the DC bias current. In continuous mode,  $I_{\text{GATECHG}} = f_D(Q_T + Q_B)$ , where  $Q_T$  and  $Q_B$  are the gate charges of the internal top and bottom MOSFET switches. The gate charge losses are proportional to  $V_{IN}$  and thus their effects will be more pronounced at higher supply voltages.
- 3)  $I^2R$  Losses are calculated from the DC resistances of the internal switches,  $R_{\text{SW}}$ , and external inductor,  $R_L$ . In continuous mode, the average output current flowing through inductor  $L$  is "chopped" between the internal top and bottom switches. Thus, the series resistance

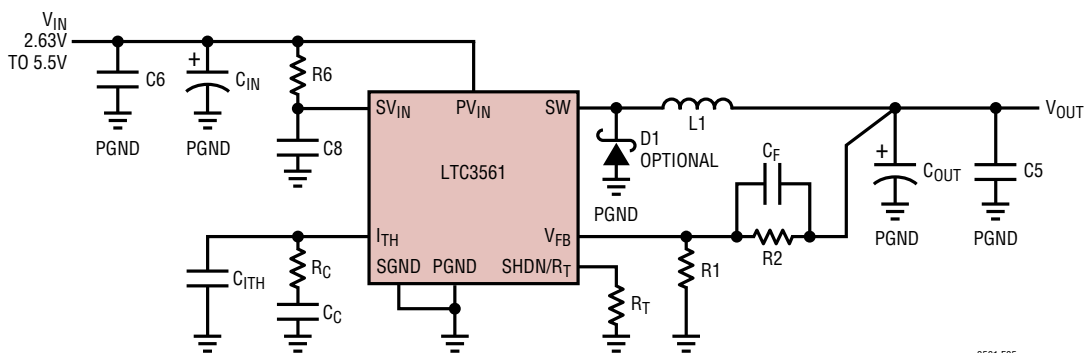


Figure 4. LTC3561 General Schematic

## APPLICATIONS INFORMATION

looking into the SW pin is a function of both top and bottom MOSFET  $R_{DS(ON)}$  and the duty cycle (DC) as follows:

$$R_{SW} = (R_{DS(ON)TOP})(DC) + (R_{DS(ON)BOT})(1 - DC)$$

The  $R_{DS(ON)}$  for both the top and bottom MOSFETs can be obtained from the Typical Performance Characteristics curves. Thus, to obtain  $I^2R$  losses:

$$I^2R \text{ losses} = I_{OUT}^2(R_{SW} + R_L)$$

- 4) Other “hidden” losses such as copper trace and internal battery resistances can account for additional efficiency degradations in portable systems. It is very important to include these “system” level losses in the design of a system. The internal battery and fuse resistance losses can be minimized by making sure that  $C_{IN}$  has adequate charge storage and very low ESR at the switching frequency. Other losses including diode conduction losses during dead-time and inductor core losses generally account for less than 2% total additional loss.

### Thermal Considerations

In a majority of applications, the LTC3561 does not dissipate much heat due to its high efficiency. However, in applications where the LTC3561 is running at high ambient temperature with low supply voltage and high duty cycles, such as in dropout, the heat dissipated may exceed the maximum junction temperature of the part. If the junction temperature reaches approximately 150°C, both power switches will be turned off and the SW node will become high impedance.

To avoid the LTC3561 from exceeding the maximum junction temperature, the user will need to do some thermal analysis. The goal of the thermal analysis is to determine whether the power dissipated exceeds the maximum junction temperature of the part. The temperature rise is given by:

$$T_{RISE} = P_D \cdot \theta_{JA}$$

where  $P_D$  is the power dissipated by the regulator and  $\theta_{JA}$  is the thermal resistance from the junction of the die to the ambient temperature.

The junction temperature,  $T_J$ , is given by:

$$T_J = T_{RISE} + T_{AMBIENT}$$

As an example, consider the case when the LTC3561 is in dropout at an input voltage of 3.3V with a load current of 1A. From the Typical Performance Characteristics graph of Switch Resistance, the  $R_{DS(ON)}$  resistance of the P-channel switch is 0.11Ω. Therefore, power dissipated by the part is:

$$P_D = I^2 \cdot R_{DS(ON)} = 110\text{mW}$$

The DD8 package junction-to-ambient thermal resistance,  $\theta_{JA}$ , will be in the range of about 43°C/W. Therefore, the junction temperature of the regulator operating in a 70°C ambient temperature is approximately:

$$T_J = 0.11 \cdot 43 + 70 = 74.7^\circ\text{C}$$

Remembering that the above junction temperature is obtained from an  $R_{DS(ON)}$  at 25°C, we might recalculate the junction temperature based on a higher  $R_{DS(ON)}$  since it increases with temperature. However, we can safely assume that the actual junction temperature will not exceed the absolute maximum junction temperature of 125°C.

### Design Example

As a design example, consider using the LTC3561 in a portable application with a Li-Ion battery (refer to Figure 4 for reference designation). The battery provides a  $V_{IN} = 2.5\text{V}$  to 4.2V. The load requires a maximum of 1A in active mode and 10mA in standby mode. The output voltage is  $V_{OUT} = 2.5\text{V}$ .

First, calculate the timing resistor:

$$R_T = 9.78 \cdot 10^{11} (1\text{MHz})^{-1.08} = 323.8\text{k}$$

Use a standard value of 324k. Next, calculate the inductor value for about 40% ripple current at maximum  $V_{IN}$ :

$$L = \frac{2.5\text{V}}{1\text{MHz} \cdot 400\text{mA}} \cdot \left(1 - \frac{2.5\text{V}}{4.2\text{V}}\right) = 2.5\mu\text{H}$$

Choosing the closest inductor from a vendor of 2.2μH, results in a maximum ripple current of:

$$\Delta I_L = \frac{2.5\text{V}}{1\text{MHz} \cdot 2.2\mu} \cdot \left(1 - \frac{2.5\text{V}}{4.2\text{V}}\right) = 460\text{mA}$$

## APPLICATIONS INFORMATION

For cost reasons, a ceramic capacitor will be used.  $C_{OUT}$  selection is then based on load step droop instead of ESR requirements. For a 5% output droop:

$$C_{OUT} \approx 2.5 \frac{1A}{1MHz \cdot (5\% \cdot 2.5V)} = 20\mu F$$

The closest standard value is 22 $\mu$ F. Since the output impedance of a Li-Ion battery is very low,  $C_{IN}$  is typically 10 $\mu$ F. In noisy environments, decoupling  $SV_{IN}$  from  $PV_{IN}$  with an R6/C8 filter of 1 $\Omega$ /0.1 $\mu$ F may help, but is typically not needed.

The output voltage can now be programmed by choosing the values of R1 and R2. To maintain high efficiency, the current in these resistors should be kept small. Choosing 2 $\mu$ A with the 0.8V feedback voltage makes R1~400k. A close standard 1% resistor is 412k and R2 is then 887k.

The compensation should be optimized for these components by examining the load step response but a good place to start for the LTC3561 is with a 13k $\Omega$  and 1000pF filter. The output capacitor may need to be increased depending on the actual undershoot during a load step.

The circuit in Figure 6 shows the complete schematic for this design example.

### Board Layout Considerations

When laying out the printed circuit board, the following checklist should be used to ensure proper operation of the LTC3561. These items are also illustrated

graphically in the layout diagram of Figure 5. Check the following in your layout:

1. Does the capacitor  $C_{IN}$  connect to the power  $V_{IN}$  (Pin 5) and power GND (Pin 4) as close as possible? This capacitor provides the AC current to the internal power MOSFETs and their drivers.
2. Are the  $C_{OUT}$  and L1 closely connected? The (–) plate of  $C_{OUT}$  returns current to PGND and the (–) plate of  $C_{IN}$ .
3. The resistor divider, R1 and R2, must be connected between the (+) plate of  $C_{OUT}$  and a ground line terminated near SGND (Pin 2). The feedback signal  $V_{FB}$  should be routed away from noisy components and traces, such as the SW line (Pin 3), and its trace should be minimized.
4. Keep sensitive components away from the SW pin. The input capacitor  $C_{IN}$ , the compensation capacitor  $C_C$  and  $C_{ITH}$  and all the resistors R1, R2,  $R_T$ , and  $R_C$  should be routed away from the SW trace and the inductor L1.
5. A ground plane is preferred, but if not available, keep the signal and power grounds segregated with small signal components returning to the SGND pin at one point which is then connected to the PGND pin.
6. Flood all unused areas on all layers with copper. Flooding with copper will reduce the temperature rise of power components. These copper areas should be connected to one of the input supplies:  $PV_{IN}$ , PGND,  $SV_{IN}$  or SGND.

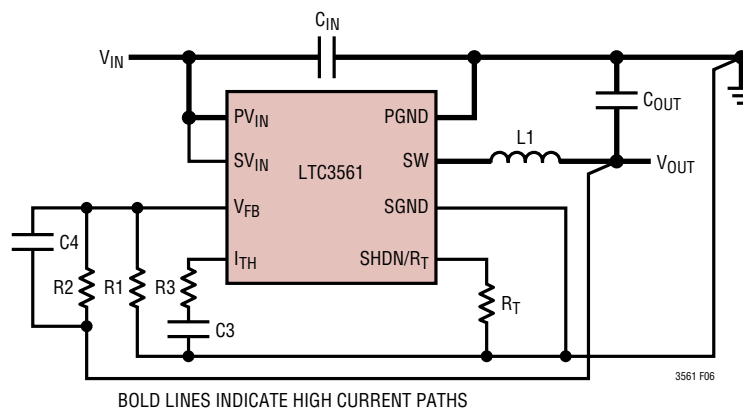
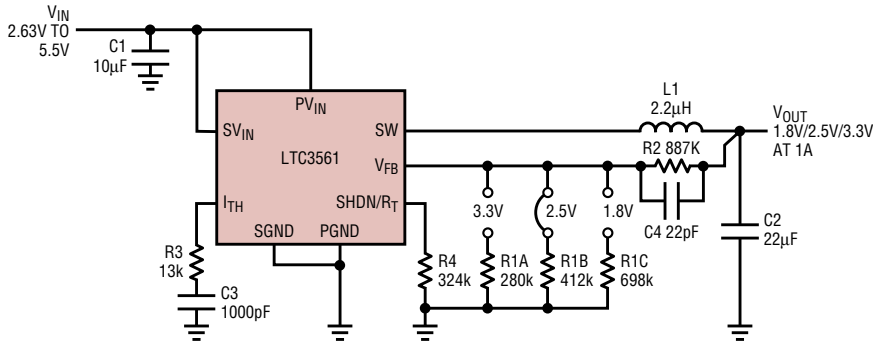


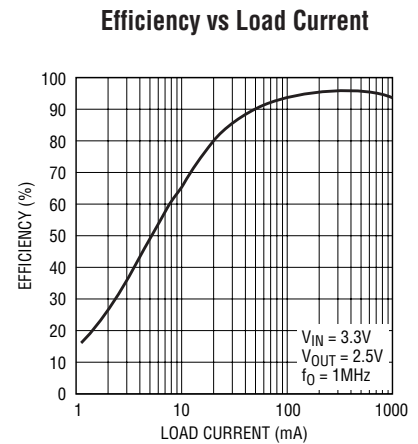
Figure 5. LTC3561 Layout Diagram (See Board Layout Checklist)

# TYPICAL APPLICATIONS



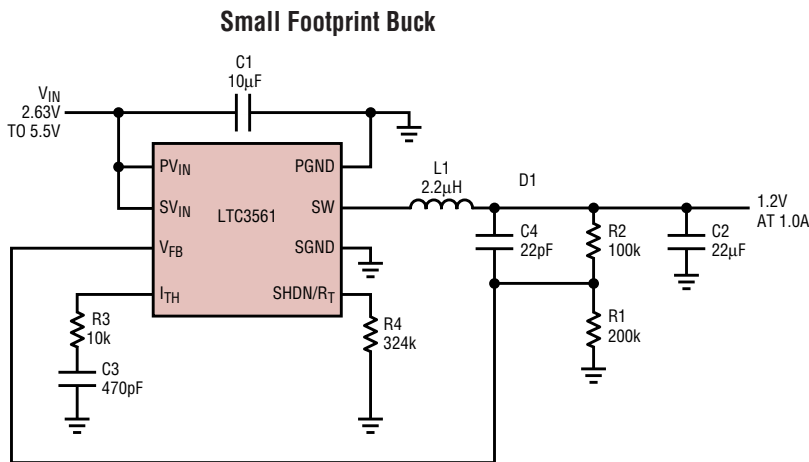
NOTE: IN DROPOUT, THE OUTPUT TRACKS THE INPUT VOLTAGE  
 C1, C2: TAIYO YUDEN JMK325BJ226MM  
 L1: TOKO A914BYW-2R2M (D52LC SERIES)

3561 F07a



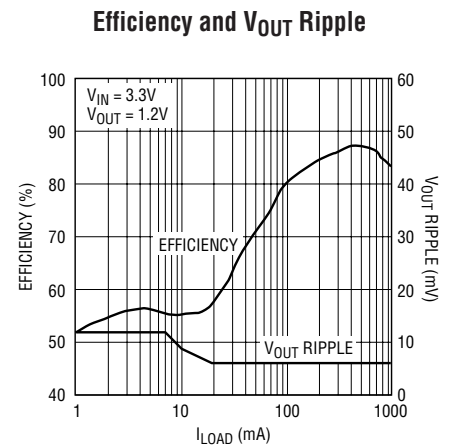
3561 F07b

Figure 6. General Purpose Buck Regulator Using Ceramic Capacitors



C1: AVX 06034D106M  
 C2: AVX 08054D226M  
 L1: SUMIDA CDRH2D18/HP-2R2

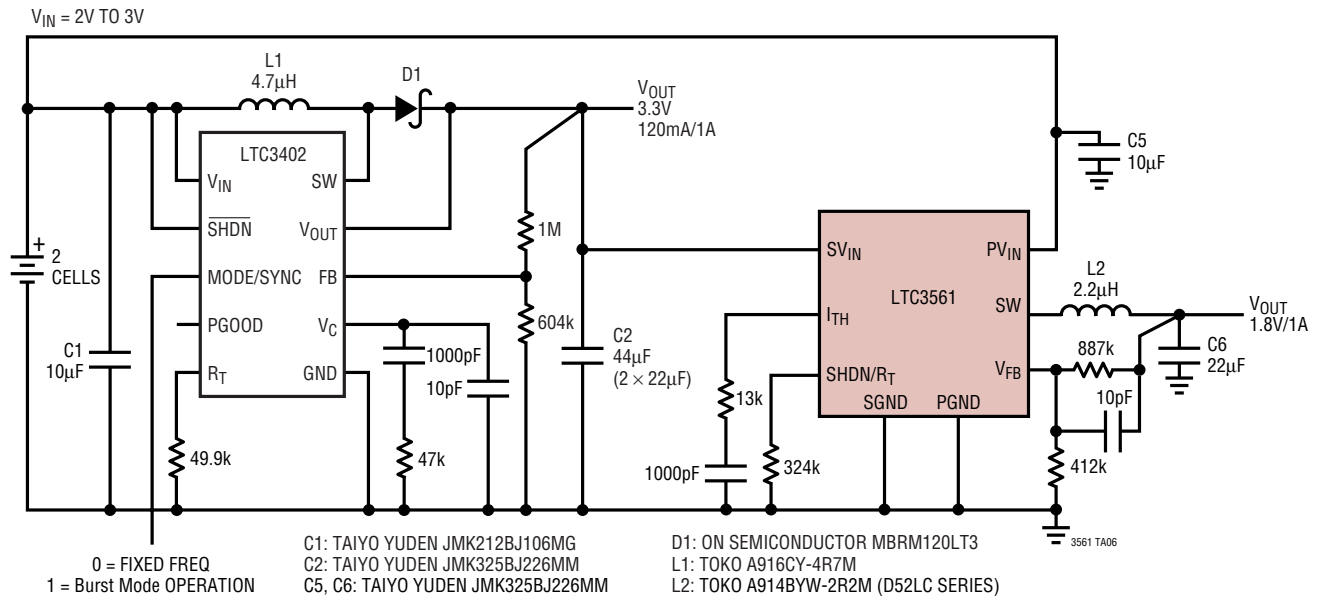
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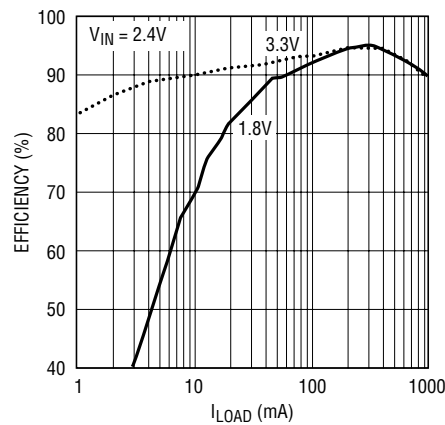
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## TYPICAL APPLICATIONS

All Ceramic 2-Cell to 3.3V and 1.8V Converters



Efficiency and  $V_{OUT}$  Ripple



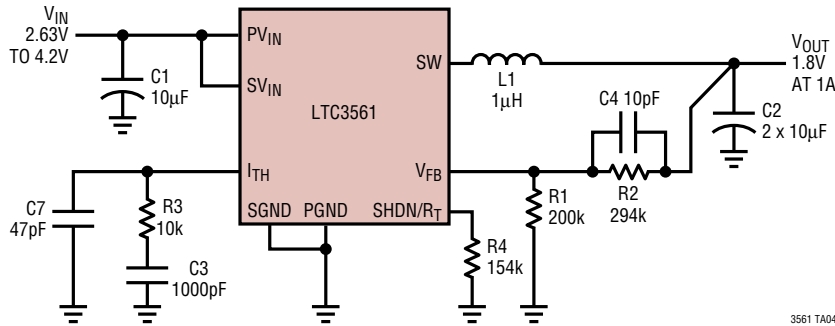
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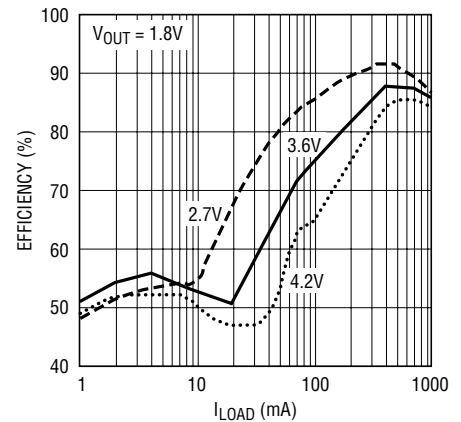
## TYPICAL APPLICATION

1mm Height, 2MHz, Li-Ion to 1.8V Converter



C1, C2: AVX 08056D106M  
L1: TDK VLF3010ATIR5NIRZ

Efficiency vs Load Current



3561 TA05

## RELATED PARTS

PART NUMBER	DESCRIPTION	COMMENTS
LTC1879	1.2A (I <sub>OUT</sub> ) 550kHz Synchronous Step-Down DC/DC Converter	95% Efficiency, V <sub>IN</sub> : 2.7V to 10V, V <sub>OUT(MIN)</sub> : 0.8V, I <sub>Q</sub> : 15µA, I <sub>SD</sub> : <1µA, TSSOP16
LTC3405/LTC3405A	300mA (I <sub>OUT</sub> ) 1.5MHz Synchronous Step-Down DC/DC Converters	95% Efficiency, V <sub>IN</sub> : 2.7V to 6V, V <sub>OUT(MIN)</sub> : 0.8V, I <sub>Q</sub> : 20µA, I <sub>SD</sub> : <1µA, ThinSOT™
LTC3406/LTC3406B	600mA (I <sub>OUT</sub> ) 1.5MHz Synchronous Step-Down DC/DC Converters	95% Efficiency, V <sub>IN</sub> : 2.5V to 5.5V, V <sub>OUT(MIN)</sub> : 0.6V, I <sub>Q</sub> : 20µA, I <sub>SD</sub> : <1µA, ThinSOT
LTC3407	600mA (I <sub>OUT</sub> ) 1.5MHz Dual Synchronous Step-Down DC/DC Converters	95% Efficiency, V <sub>IN</sub> : 2.5V to 5.5V, V <sub>OUT(MIN)</sub> : 0.6V, I <sub>Q</sub> : 40µA, I <sub>SD</sub> : <1µA, 10-Lead MS or DFN
LTC3407-2	800mA (I <sub>OUT</sub> ) 2.25MHz, Dual Synchronous Step-Down DC/DC Converters	95% Efficiency, V <sub>IN</sub> : 2.5V to 5.5V, V <sub>OUT(MIN)</sub> : 0.6V, I <sub>Q</sub> : 40µA, I <sub>SD</sub> : <1µA, 10-Lead MS or DFN
LTC3410	300mA (I <sub>OUT</sub> ) 2.25MHz Synchronous Step-Down DC/DC Converters	96% Efficiency, V <sub>IN</sub> : 2.5V to 5.5V, V <sub>OUT(MIN)</sub> : 0.8V, I <sub>Q</sub> : 26µA, I <sub>SD</sub> : <1µA, 6-Lead SC70
LTC3411	1.25A (I <sub>OUT</sub> ) 4MHz Synchronous Step-Down DC/DC Converters	95% Efficiency, V <sub>IN</sub> : 2.5V to 5.5V, V <sub>OUT(MIN)</sub> : 0.8V, I <sub>Q</sub> : 60µA, I <sub>SD</sub> : <1µA, 10-Lead MS or DFN
LTC3412	2.5A (I <sub>OUT</sub> ) 4MHz Synchronous Step-Down DC/DC Converter	95% Efficiency, V <sub>IN</sub> : 2.5V to 5.5V, V <sub>OUT(MIN)</sub> : 0.8V, I <sub>Q</sub> : 60µA, I <sub>SD</sub> : <1µA, TSSOP16E
LTC3413	3A (I <sub>OUT</sub> Sink/Source) 2MHz Monolithic Synchronous Regulator for DDR/QDR Memory Termination	90% Efficiency, V <sub>IN</sub> : 2.25V to 5.5V, V <sub>OUT(MIN)</sub> : V <sub>REF</sub> /2, I <sub>Q</sub> : 280µA, I <sub>SD</sub> : <1µA, TSSOP16E
LTC3440	600mA (I <sub>OUT</sub> ) 2MHz Synchronous Buck-Boost DC/DC Converter	95% Efficiency, V <sub>IN</sub> : 2.5V to 5.5V, V <sub>OUT(MIN)</sub> : 2.5V, I <sub>Q</sub> : 25µA, I <sub>SD</sub> : <1µA, 10-Lead MS

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