Technical Note

TN235

External 32.768 kHz Oscillator Circuits

An external 32.768 kHz clock is an essential part of any Rabbit-based system. Besides driving the real-time clock, the 32.768 kHz clock is used by various processor and peripheral subsystems that are used extensively by Dynamic C software. It is therefore recommended that an external 32.768 kHz oscillator circuit always be implemented. It is possible to operate the Rabbit without a 32.768 kHz clock, but several key features will not be available. Without the 32.768 kHz clock, the real-time clock, the watchdog timer, the periodic interrupt, and asynchronous remote bootstrap will not function. Neither will any of the low-power features that run off the 32.768 kHz clock.

Figure 1 shows the basic concept behind the external CMOS crystal oscillator circuits used in Rabbit-based products. The crystal used in the circuit is a parallel resonant crystal.

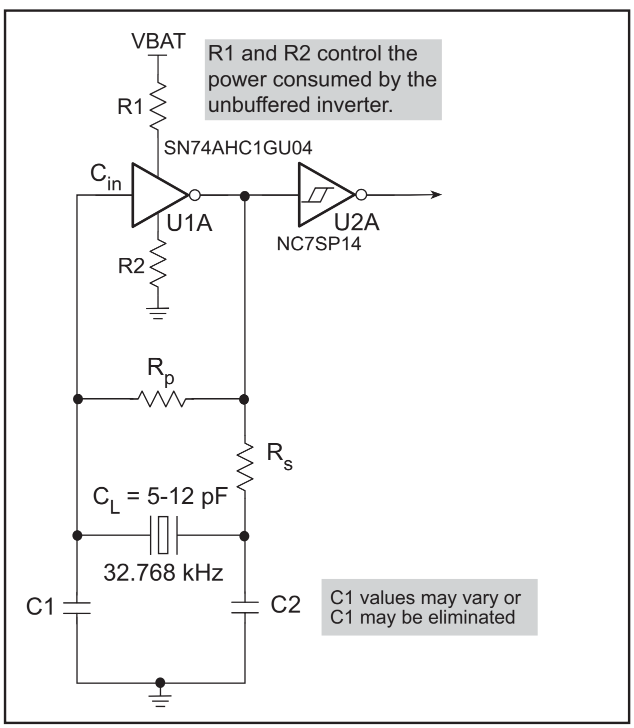

Figure 1. Basic 32.768 kHz Oscillator Circuit

> **NOTE:** The value of C1 may vary from system to system, or C1 may be completely eliminated depending on the crystal C_L, the amount of frequency deviation from 32.768 kHz, and the measured drive through the crystal.

The oscillator is constructed using low-cost single-gate logic. An unbuffered gate is used for the oscillator because buffered inverters have a tendency to oscillate at higher frequencies and are prone to startup problems. The output of the oscillator is fed to the Rabbit through a Schmitt trigger buffer. The Schmitt trigger serves two primary functions. First, it prevents power supply or high-frequency switching noise (primarily from address lines) from getting coupled into the slow rising clock signal generated by the oscillator; and second, it buffers the output of the oscillator to generate fast rising/falling (4 ns) square waves.

Internal and External 32.768 kHz Oscillators

The 32.768 kHz oscillator circuit implemented in Rabbit-based systems may vary depending on the Rabbit processor's revision and version, low-power requirements, and the type of crystal used. Table 1 lists the types of crystal oscillator circuits that can be used with each type of Rabbit microprocessor.

Table 1. 32.768 kHz Crystal Oscillator Circuit Types

Microprocessor	32.768 kHz Oscillator		Internal Schmitt Trigger
	Internal	External	
Rabbit 2000, A–C	Yes	Yes*	Yes†
Rabbit 3000	No	Yes	**No**
Rabbit 3000A	No	Yes	Yes

* External oscillator is used in low-power applications with battery backup.

† The Schmitt trigger is part of the on-chip oscillator buffer.

Note that the Rabbit 2000 family of microprocessors contain an internal 32.768 kHz oscillator. Refer to Chapter 14 of the ***Rabbit 2000 Microprocessors User's Manual*** for more information on circuit requirements. The internal circuit does not offer the same flexibility as the external circuit for low-power operation mainly because resistors cannot be placed in series with the power or ground of the oscillator to limit the switching (crossover) current.

The rest of this technical note will concentrate on external oscillator circuits.

Rabbit-2000-Based Oscillator and Battery-Backup Circuits

Figure 2 shows the external 32.768 kHz oscillator and battery-backup, and battery-switchover circuits used in Rabbit-2000-based systems. The circuits were designed for low-power operation.

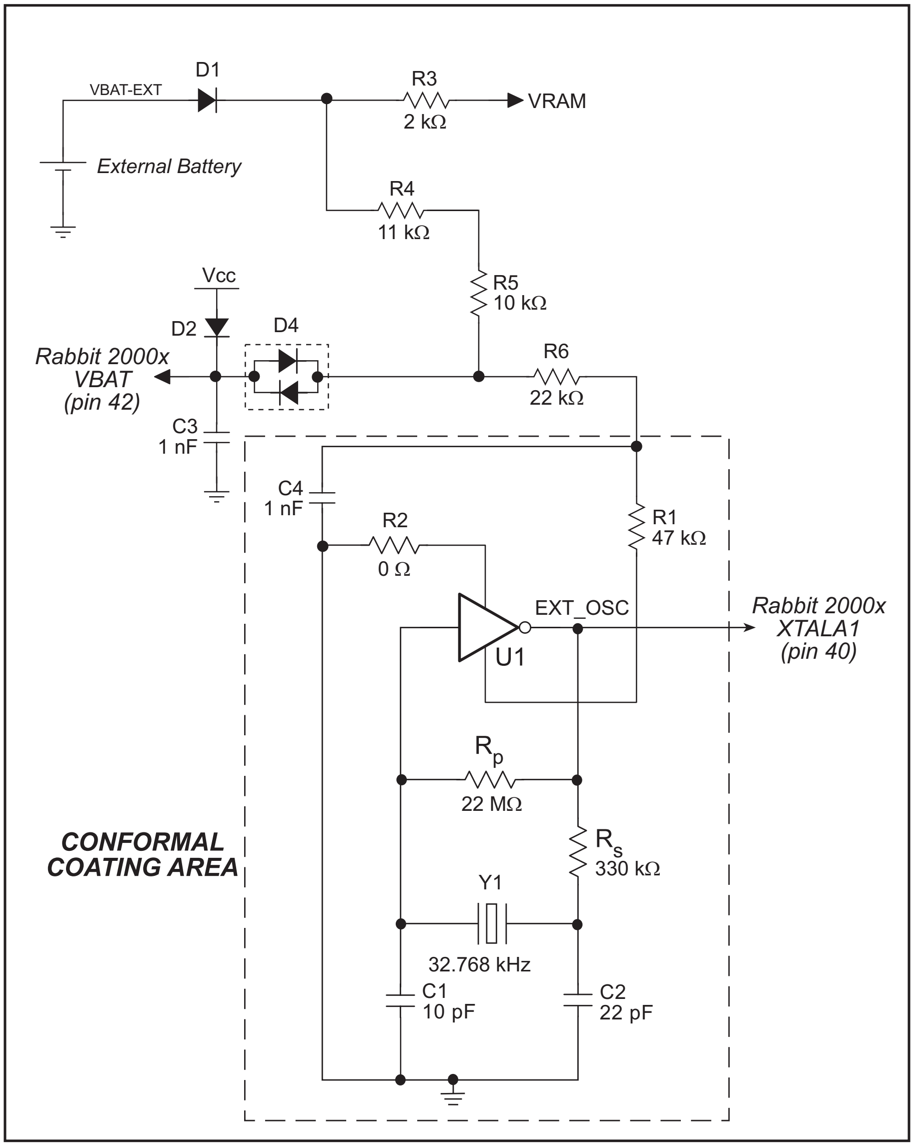

Figure 2. Rabbit 2000x 32.768 kHz Oscillator and Battery-Backup Circuits

The current consumption of the circuit is about 4 µA with a 2 V supply. Using this circuit, oscillation continues even when the voltage drops to 0.8 V, and oscillation is still very strong at 1.2 V. Note that the internal Schmitt trigger of the Rabbit 2000 family of processors does not operate reliably at voltages below 0.9 V. Furthermore, the oscillator should have its exposed circuit traces conformally coated to prevent the possibility of loading the circuit by conduction on the PC board surface in a moist atmosphere. (Rabbit Semiconductor has published an application note on conformal coating, Technical Note TN303, ***Conformal Coatings***.)

Figure 3 shows the external battery-switchover circuits used in Rabbit-2000-based systems.

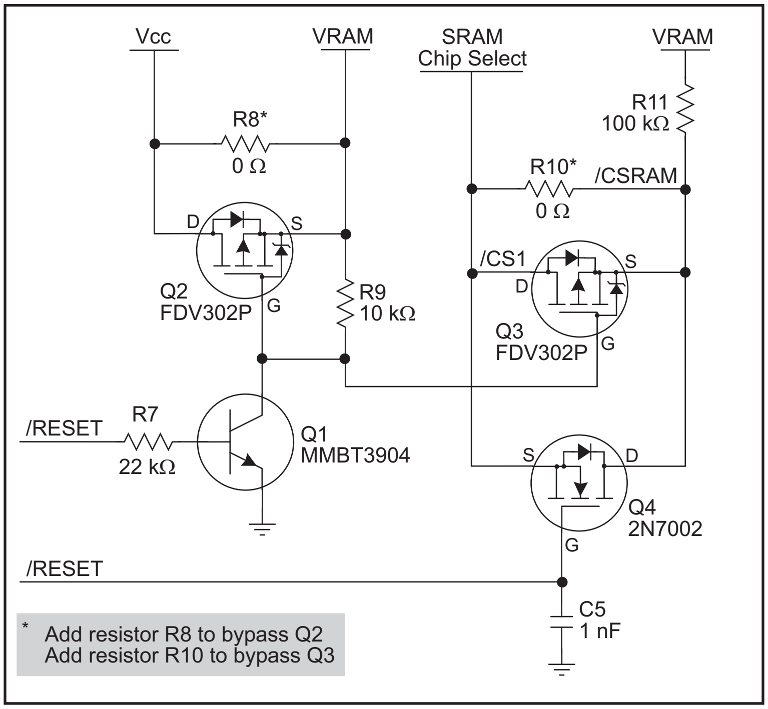

Figure 3. Rabbit 2000x Battery-Switchover Circuit

Rabbit-3000-Based Oscillator and Battery-Backup Circuits

Figure 4 shows the external 32.768 kHz oscillator, battery-backup, and battery-switchover circuits used in Rabbit-3000-based systems found in Z-World and Rabbit Semiconductor board-level products.

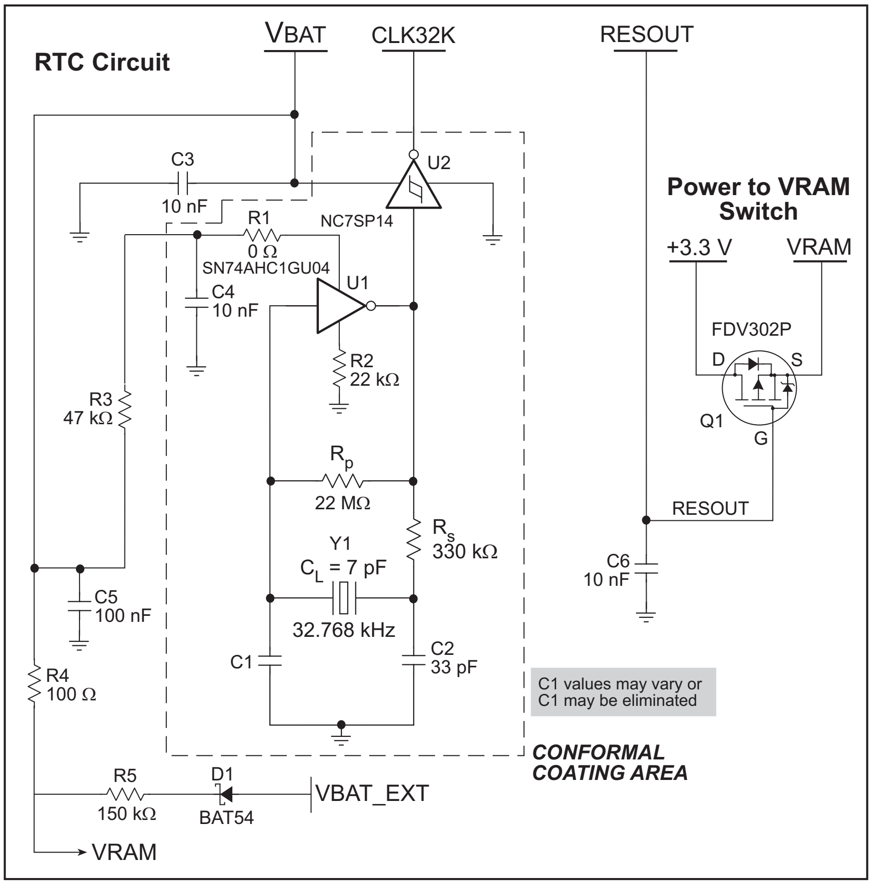

Figure 4. 32.768 kHz Oscillator and Battery-Backup Circuit for Rabbit-3000-Based Systems

The circuit in Figure 4 consumes about 8 µA for a Rabbit 3000 with U2 present and VBAT_EXT = 3.0 V.

Rabbit-3000A-based systems have special power-up requirements. In these systems, the oscillator may not start oscillating when the battery is connected for the first time. The input to the internal Schmitt trigger gets stuck in a region where the Schmitt trigger is unable to latch the data high or low. Since the oscillator is not running, the output gets stuck somewhere in the linear region because of R_p. This cycle continues until some amount of random noise disrupts the stability of the system and kick-starts the oscillator. The stuck condition results in a drop in the battery voltage and an increase in current draw. For the circuit in Figure 4, the current draw measured at R8 increases to 13 µA with the majority of the current going through VBAT. This occurs because R8 is large and is used to provide current to the SRAM, oscillator, and VBAT. The Schmitt trigger requires a large amount of current at startup, and R8 limits the amount of current available to the circuit.

This is not a problem with the circuit in Figure 4 because powering a system only at VBAT_EXT for a prolonged period doesn't make any sense and is not normally done. If for some reason a system is only powered at VBAT_EXT (the first time) for a long period of time, the current draw will not drain the battery significantly. Once main power is applied to the system. the oscillator begins operating, and when main power is removed, the circuit will switch over to the battery and will continue to operate reliably.

Note that the circuit in Figure 4 is used for low-power systems. If a Rabbit-3000A-based system is not battery-backed and the oscillator power consumption is not an issue, the circuit can be simplified as shown in Figure 5 below.

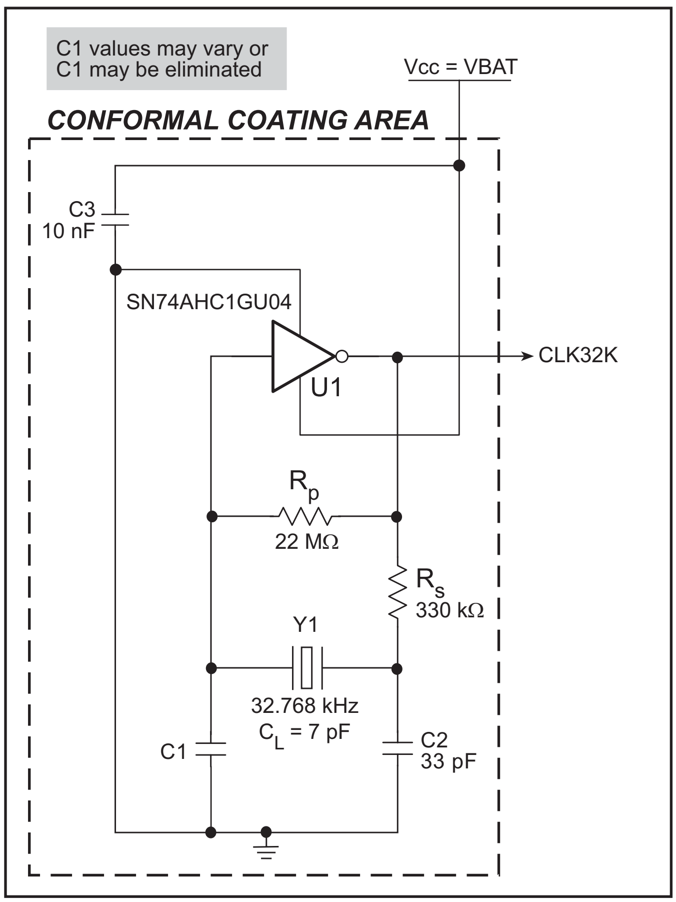

Figure 5. 32.768 kHz Circuit for Applications not Battery-Backed

For low power circuits, an alternative circuit can be designed that does not exhibit the startup issue present in the standard circuit shown in Figure 4.

The circuit in Figure 6 provides separate supplies for the oscillator (VOSC), SRAM (VRAM), and RTC (VBAT). The circuit consumes about 6.5 µA for VBAT_EXT = 3.0 V, and oscillation starts at 1.25 V. This solution does not have the startup issue, but is more expensive primarily because of the extra PMOS transistors.

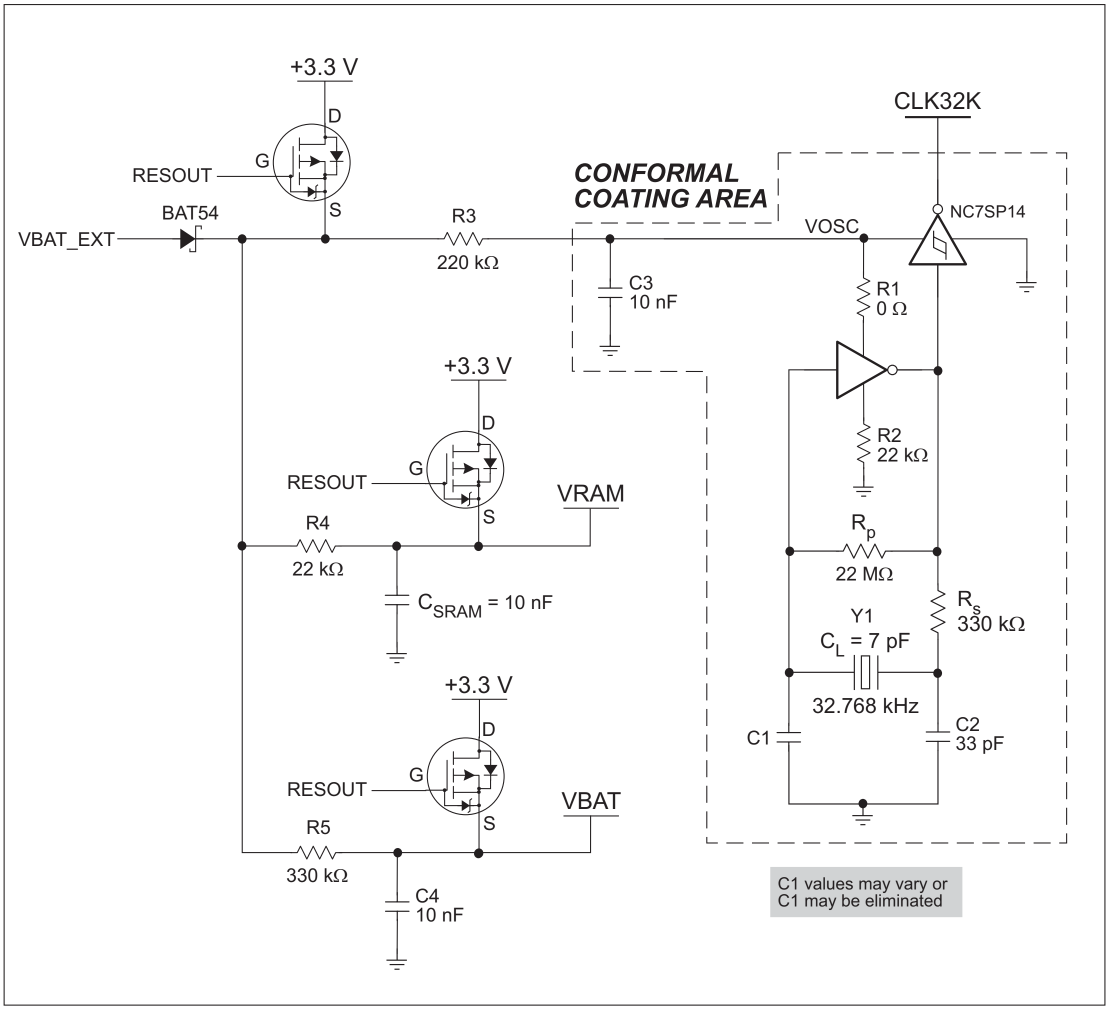

Figure 6. Alternative Low-Power Circuit for Rabbit-3000A-Based Systems

Component Selection Guidelines

R_p

The bias resistor, R_p, biases the oscillator buffer (amplifier) to operate in the linear region ($V_{DD}/2$). When biased this way, the amplifier has a high gain and will oscillate at the specified frequency. The recommended value for R_p is between 10 MΩ and 25 MΩ. As the value of R_p increases, the gain of the amplifier will also increase, enabling the oscillator to start faster and continue operating at a lower voltage.

R_p also limits the short-circuit current when the CMOS gate is switching and thus the overall current consumption.

It is important to note that the 32.768 kHz oscillator circuit draws a very low operating current and has a high input impedance. The circuit is thus susceptible to noise from nearby high-speed switching traces and board level contaminants such as dirt and moisture. It is therefore necessary to protect the oscillator circuit from high-speed switching signals by keeping the oscillator traces short and using guard traces and copper pours appropriately. Furthermore, the exposed circuit traces should be conformally coated to protect the circuit from environmental contaminants. Refer to technical Note TN303, ***Conformal Coating***, for more information.

R_s

The purpose of R_s is to increase the output impedance of the oscillator buffer and limit its drive current. R_s also affects the amplitude of the voltage swing going into the crystal, and is thus limited by the operating voltage. The value of R_s has to be large enough to prevent the crystal from being overdriven, but not too large to kill the swing going back into the oscillator. An excessively large R_s may also cause the circuit to oscillate at an overtone other than that of the fundamental frequency.

Moderate overdrive of the crystal may be acceptable. However, excessive overdrive may increase the aging of the crystal and may possibly damage the crystal.

It is somewhat difficult to predict a suitable value for R_s with which to begin. As a starting point, select a value for R_s such that it has the same impedance as C2 at the operating frequency. From this point, the value can then be modified to achieve the desired drive level or voltage swing:

$$R_s = \frac{1}{2\pi f_{osc} * C2}$$

C1, C2

For parallel resonant circuits, the phase shift/load capacitors provide the phase shift and load capacitance necessary for the oscillator to operate at the tuned frequency. The values of C1 and C2 can be modified to adjust the oscillator frequency.

The value of the load capacitors can be calculated in the following manner.

$$C_L = \frac{(C1 + C_{in})^* C2}{(C1 + C_{in}) + C2} + C_s$$

In the above equation, C_{in} represents the input capacitance of the oscillator buffer (roughly 6 to 6.5 pF), C_L represents the specified load capacitance of the parallel resonant frequency crystal, and C_s represents the stray circuit capacitance, which is usually in the range of 2 to 5 pF. Note that C_{in} is not constant, but rather is a function of frequency—any measurements of C_{in} should be done using a sine wave generator operating at 32.768 kHz.

Ideally C1 and C2 would have equal values because the inverter output introduces a phase shift of 180° and the combination of C1, C2, and the crystal would provide the additional 180° phase shift required for the phase shift of the loop to equal 360°. However, in reality, the inverter also introduces a phase delay, which creates a phase shift that is somewhat greater than 180°. The capacitors compensate for this phase difference by changing their impedance. This change in impedance can only occur if the circuit oscillates at a slightly higher frequency than that of the series resonant frequency of the crystal, which is about 32.765 kHz. In effect, the capacitors pull the oscillation frequency. The capacitors serve several functions.

- First and foremost, they provide the appropriate load capacitance for the crystal to oscillate at the correct frequency.
- The capacitors provide the correct amount of phase shift for the circuit to oscillate. Note that oscillation will not occur if the loop gain is not greater than 1 and if the loop phase shift does not add up to 360°.
- The RC circuit and the input capacitance of the oscillator buffer control the swing into the buffer, and the input side capacitance also affects the crystal drive. This affects the power consumption and the maximum operating voltage.
- The capacitors are used to tune the crystal frequency. This is called pullability, and is a function of the load capacitors.

R1, R2

For low-power applications, these two resistors limit the power consumption of the oscillator buffer (U1 in Figure 4) by limiting the crossover current during switching. The slower the switching speed, the longer the transistors stay in the transition region, and thus the greater the crossover current. Note that the Schmitt trigger does not consume as much current because of its fast switching speed. The key to controlling the current through the oscillator buffer is to limit the amount of switching current by placing resistors in series with the power and ground of the inverter. These resistors not only limit the current, but also affect the gain of the oscillator, the startup and stop voltages, the output duty cycle, and output rise and fall times. The circuit also becomes more susceptible to noise, necessitating the use of the Schmitt trigger. The layout of the oscillator circuit is therefore extremely important when dealing with such low-current, low-gain, high-input-impedance circuits. The distances between the Rabbit processor, oscillator buffer, and Schmitt trigger must be minimized to prevent noise from getting coupled into the circuit.

Crystal

The 32.768 kHz crystal used in Rabbit-based systems is the same type of crystal as the tuning-fork quartz crystals used in wristwatches. Table 2 outlines the specifications for these 32.768 kHz crystals.

Table 2. 32.768 kHz Crystal Specifications

Type	—	Through Hole or SMD Tuning-Fork Crystal
Nominal Frequency	F	32.768 kHz
Frequency Tolerance at +25°C	df/F	± 20 ppm
Load Capacitance	C_L	7.0–12.5 pF
Series Resistance	RS	50 kΩ (max.)
Drive Level	P	1 µW (max.)
Quality Factor	Q	50,000 (min.)
Turnover Temperature	TT	+ 25°C ± 5°C
Parabolic Curvature Constant	K	-0.04 ppm/°C^2 (max.)
Shunt Capacitance	C0	1.4 pF (typical)
Capacitance Ratio	C0/C1	~400 (typical)
Motional Capacitance	C1	0.0035 pF (typical)
Aging	df/F	First year: ± 3 ppm max. at +25°C
Operating Temperature Range	T0	-40°C to +85°C
Storage Temperature Range	TS	-50°C to +125°C
Shock	df/F	5 ppm max.
Vibration	df/F	3 ppm max.
Cut	—	X-Cut

X-cut crystals have a parabolic temperature curve. The maximum frequency variation in tuning-fork crystals is roughly -0.04 ppm/°C^2. The frequency tolerance at 25°C is typically ± 20 ppm.

Frequency drift per day at 85°C

According to the parabolic temperature curve, the change in frequency at +85°C is -144 ppm.

Since 1 day = 86400 seconds,

86400 seconds/day * (-144 ppm) = -12.44 seconds/day

Frequency drift per day at -45°C

According to the parabolic temperature curve, the change in frequency at -45°C is -196 ppm.

86400 seconds/day * (-196 ppm) = -16.93 seconds/day

NOTE: The -0.04ppm/°C^2 parabolic curvature constant is a maximum value. Actual tests of the crystal yield a drift of -140 ppm (-12.13 seconds/day) at the temperature extremes (-40°C and +85°C).

Crystal Drive Level

Typical 32.768 kHz crystals are specified for a maximum drive level of 1 µW. A modest overdrive, perhaps 100% over this limit, will most likely not have any adverse effect except to cause the crystal to age more rapidly. Aging in a crystal is exhibited as a gradual change of frequency, about 3 parts per million, and is most significant in the first few months of operation.

The drive power can be computed from $P = (I^2)*R$, where I is the rms AC current and R is the effective resistance of the crystal. Typical values for R are 25 kΩ for 32.768 kHz turning-fork crystals. Maximum values are often specified as 35 kΩ or 50 kΩ. If the effective resistance is 25 kΩ, then 1 µW of power is reached when I = 6.3 µA (rms). It is logical to use the typical effective resistance rather than the maximum total resistance in computing drive-power. If a particular crystal has a higher resistance, it requires more power to sustain the same amplitude of physical flexure of the quartz. This indicates that the stress on the quartz will not be greater even though the drive power is greater for a unit that happens to have an effective resistance of 35 kΩ rather than the typical value of 25 kΩ.

In calculating the current through the crystal, the output capacitance of the buffer is not relevant because the resistor R_s isolates it from the crystal. C1, however, is very important. If C1 is made smaller, this will increase the voltage swing on the gate input of the oscillator buffer and will allow the oscillator to operate at a lower voltage. This oscillator will start at about 1.2 V and operate down to about 0.75 V.

The current can be measured directly with a sensitive current probe, but it is easier to calculate the current by measuring the voltage swing at the gate input with a low-capacitance oscilloscope probe. The rms voltage at this point is related to the rms current by the relationship

$$I = V_{rms}*\omega*C_{tot}$$

where

$$C_{tot} = C1 + C_{In} + C_{probe}$$

$$\omega = 2\pi(32768)$$

$$V_{rms} = 0.707(V_{p-p})$$

If C_{tot} = 12 pF (assuming C_{probe} = 1 pF) and the effective resistance is 25 kΩ, then the current in (µA) and the drive power in (µW) are given by the following approximation.

$$I = 2.5*V_{rms}$$

$$P = 0.1*(V_{rms})^2$$

or

$$I = 1.75*V_{p-p}$$

$$P = 0.05*(V_{p-p})^2$$

Based on the above equations and calculations,

P = 1.25 µW for a 5.0 V (p-p) swing,

P = 0.65 µW for a 3.6 V (p-p) swing, and

P = 0.45 µW for a 3.0 V (p-p) swing.

From the above analysis it is clear that the value of C1 greatly affects the crystal drive level. The value of C1 depends on the crystal load capacitance, C_L. For this reason, Rabbit-based systems use crystals with low C_L requirements. Currently, Rabbit-2000 and 3000-based systems use crystals with a load capacitance of 7 pF.

Summary of Values for Rabbit-Based 32.768 kHz Oscillators

Component	Value	Notes
R_p	10–25 MΩ	Affects gain
R_s	330–680 kΩ	Limits drive current (crystal-drive level ~ 1 µW)
C_L	6.0–12.5 pF	Parallel resonant crystal load capacitance
C1	0–15 pF	The values can be used to tune the oscillator frequency, and may vary depending on the crystal load capacitance used. Appropriate values can be determined through calculations and optimized through experimentation.
C2	15–33 pF	
R1, R2	2–22 kΩ	

Approved Manufacturers List

Component	Manufacturer	Part Number	Contact
Crystal	ECS	ECS-0327-6-17	http://www.ecsxtal.com
	ILSI	IL3R-HX5F7-32.768	http://www.ilsiamerica.com
	Seiko Instruments	SSPT7-.032768-7pF	http://www.siielectroniccomponents.com
Unbuffered Inverter	Texas Instruments	SN74AHC1GU04DBVR	http://www.ti.com
	Fairchild Semiconductor	NC7SU04M5 NC7SZU04P5	http://www.fairchildsemi.com
	On Semiconductor	NL17SZU04DF	http://www.onsemi.com/home
Schmitt Trigger	Fairchild Semi.	NC7SP14P5	http://www.fairchildsemi.com

References

Marvin E. Ferking, ***Crystal Oscillator Design and Temperature Compensation***, Van Norstrand Reinhold Company, New York, 1978.

Benjamin Parzen, ***Design of Crystal and other Harmonic Oscillators***, John Wiley and Sons, Inc., New York, 1983.

Norman L. Rogers, Rabbit Semiconductor.

David Salt, ***HY-Q Handbook of Quartz Crystal Devices***, Van Norstrand Reinhold (UK) Co. Ltd., 1987.

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