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UART CRYSTAL OSCILLATOR DESIGN GUIDE

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1. Frequently Asked Questions associated with UART Crystal Oscillators

- "How does a crystal oscillator work?"

- "What crystal should I use?"

- "Do we have to use the oscillator circuit specified in the UART data sheet?"

- "I want to use a different crystal. How do we adapt the circuit?"

- "How accurate must the external R's and C's be?"

- "What is the UART's on chip oscillator made up of?"

- "A second source UART's data sheet specifies different oscillator loading capacitors - will this work with the equivalent EXAR UART?"

- "Our crystal oscillator does not start up. Why?"

- "How accurate must the crystal's frequency of oscillation be for the serial communication link to work reliably?"

2. Generalized Oscillator

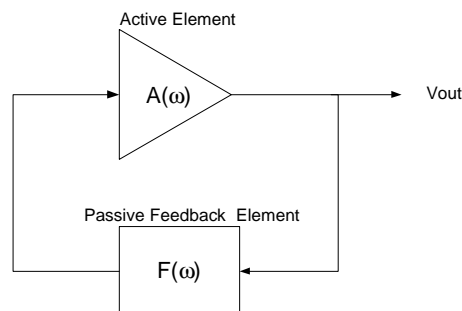An oscillator may be modeled by the block diagram shown in Figure 1.

Figure 1: Generalized Oscillator

EXAR Corporation, 48720 Kato Road, Fremont, CA 94538 Tel 510-668-7000 - Fax 510-668-7017 www.exar.com

Here $A(\omega)$ is the transfer function of the amplifier that adds enough energy to the loop in order to keep it oscillating, and $F(\omega)$ is the transfer function of a feedback element that sets the frequency selectivity.

A and F are complex quantities that can be described by a gain and phase component:

$$A(w) = |A(w)| \cdot e^{a\,jwt}$$
$$F(w) = |F(w)| \cdot e^{b\,jwt}$$

Oscillation is achieved by feeding back enough electrical energy that is delayed by nx360° such that the total loop gain is unity. Barkhausen's Criterion reflects this condition for steady state oscillation:

$$|A(\omega)| \cdot |F(\omega)| = 1 \quad \text{(amplitude condition)}$$
$$\alpha(\omega) + \beta(\omega) = 2\pi.n \quad \text{(phase condition)}$$

When both conditions are met, oscillation occurs at a frequency, $f = \omega/2\pi$.

3. Oscillator Startup

In order to get the oscillator to start up, it needs initial electrical energy. Power-up transients as well as noise can supply the needed energy. However the energy levels may not be adequately high enough. This can be complemented by large open loop gain at any frequency that boosts the energy to a necessary level.

Mathematically, this is represented by:

$$|A(\omega)| \cdot |F(\omega)| \gg 1$$

Since this condition may be met at a frequency different to the final steady state one, the start up transient occurs at a differing rate. The time until steady state oscillation is reached, will depend on how much the open loop gain is larger than unity.

4. A Simple CMOS Amplifier

The Inverter is the basic building block of CMOS digital integrated circuits. An inverter is small and its transfer characteristic is non-linear, as can be seen by the curves in Figure 2.
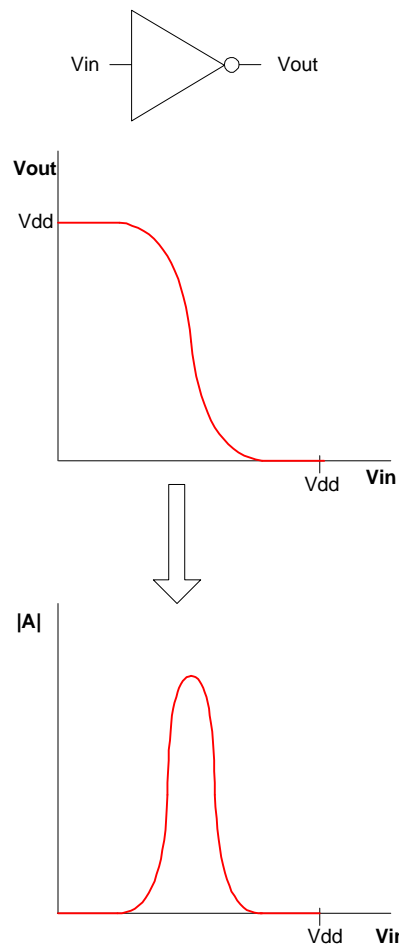

Figure 2: Inverter Characteristics

The point of maximum gain depends on the transistor characteristics. These can be designed such that the gain has its maximum near the Vdd/2 point.

By biasing and operating the inverter near the maximum gain point, amplification (with negative gain) is achieved. A resistor can be connected between the input and the output, as shown in Figure 3. Since the input impedance of an inverter is very high (mainly capacitive), the inverter autobiases to: Vin=Vout.

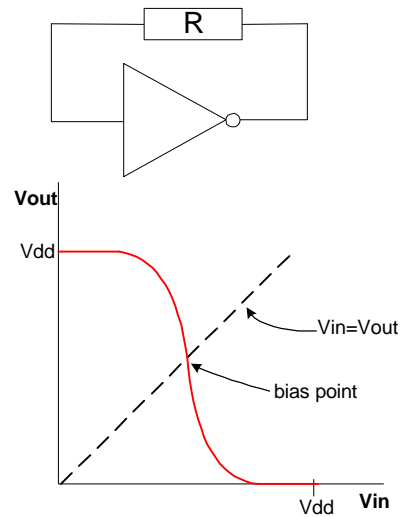Figure 3: Biassing the Inverter

The feedback resistor converts the inverter into an amplifier (Figure 4) with an absolute gain >>1 near the logic switching midpoint.
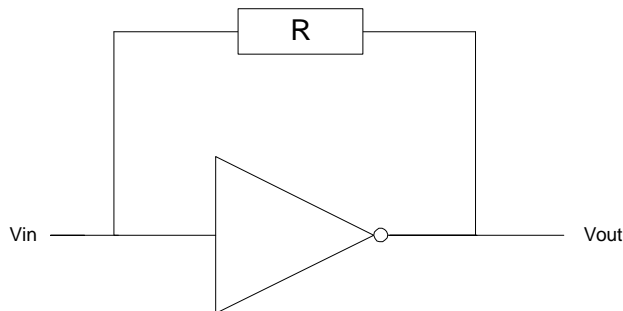

Figure 4: Converting an Inverter into an Amplifier

5. Achieving Barkhausen's Criteria

Satisfying both Barkhausen's Criteria for Oscillation is not easily achieved when one wants to design a sinusoidal oscillator with a well-defined frequency of oscillation. Fortunately digital circuits work off square wave clock, which can be produced from an amplifier whose gain is high and whose input is overdriven.

An amplifier's output voltage is limited by the supply voltage – which means that the amplifier's gain is not constant. The gain approaches zero as the input sinusoidal signal's amplitude increases. This means that the output amplitude of the amplifier/inverter is independent of both frequency and input amplitude, assuming a high gain amplifier. This makes achieve Barkhausen's Amplitude Criteria feasible.

In order to satisfy Barkhausen's Phase Condition for oscillation, a suitable feedback element, $F(\omega)$, needs to be selected. Since the inverter creates 180° phase delay (within its pass-band), an additional 180° is needed. This can be achieved with passive R, L, C elements. However frequency selectivity is limited by the accuracy of the LC components. Enter the piezo-electric quartz crystal.

6. Quartz Crystals

Electrically, a quartz crystal can be modeled by the equivalent circuit given in Figure 5.
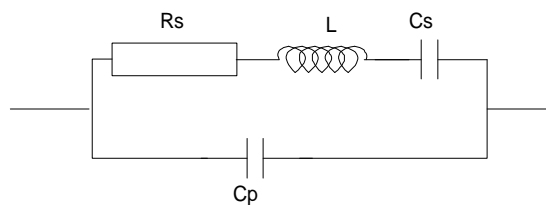

Figure 5: Crystal Equivalent Circuit

Cp represents the capacitance of the crystal electrodes plus the holder and the leads. Rs, Cs and L model the motional parameters of the crystal. The motional inductance, L, represents the vibrating mass of the crystal. The motional capacitance, Cs, represents the elasticity of the quartz. Rs represents the bulk losses that occur within the quartz. The relative magnitudes of the shunt capacitance, Cp, series capacitance, Cs, inductance, L, and series resistance, R, results in a typical crystal reactance curve shown in Figure 6.
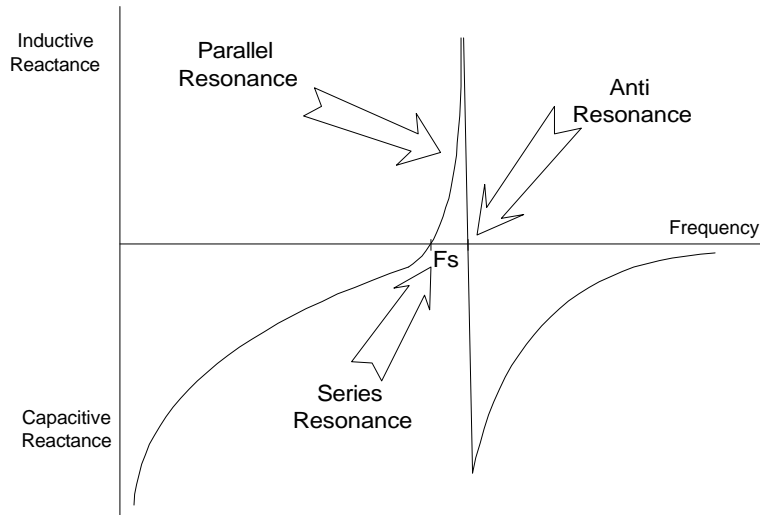
Figure 6: Quartz Reactance Characteristic

At low frequencies, the crystal is capacitive up to the series resonant point, F_s. At F_s, the crystal's impedance is purely resistive – and very small.

$$F_s = \frac{1}{2p\sqrt{L \cdot C_s}}$$

C_s = Motional capacitance
 L = Motional Inductance

Hence F_s is solely determined by the crystal's motional parameters.

At frequencies above F_s, its reactance becomes inductive, and the crystal is said to be in parallel resonance. A crystal can oscillate at higher frequencies (odd overtones) if operation above, say, 30MHz is required.

The temperature dependence of quartz crystals is relatively small even for the inexpensive consumer (AT cut) parts. The worst case frequency deviation from room temperature nominal frequency is about ±100 ppm in the loosest specification over its specified temperature range.

7. Crystal Oscillator Circuits

The attraction of a quartz crystal oscillator is its tightly controlled impedance characteristic. A crystal with a desired series resonant frequency and parallel resonance curve can be manufactured in mass production. Also, crystals have an extremely high Q factor. For instance a 4 MHz crystal commonly has a Q of about 26000.

By realizing that the impedance of a quartz crystal is solely resistive at F_s, an oscillator as shown in Figure 7 can be made. Here a second inverter creates the required total 360° phase shift.
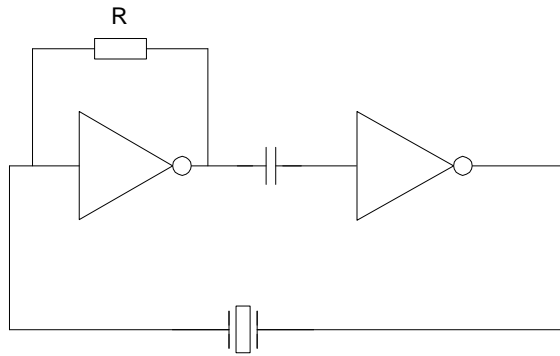
Figure 7: Series Resonant Oscillator

The oscillation frequency is strongly determined by the crystal, since only at F_s does the crystal add no phase shift. Since the crystal's resistance is very small at F_s, the oscillator's energy may damage the crystal. Hence special crystals need be selected for series resonance use.

At frequencies slightly higher than F_s, the crystal's impedance is inductive. Hence inserting the crystal in a π (pi) configuration with capacitors can achieve the additional 180° phase delay necessary when used with a single inverter. Figure 8 shows the Parallel Resonant Oscillator.
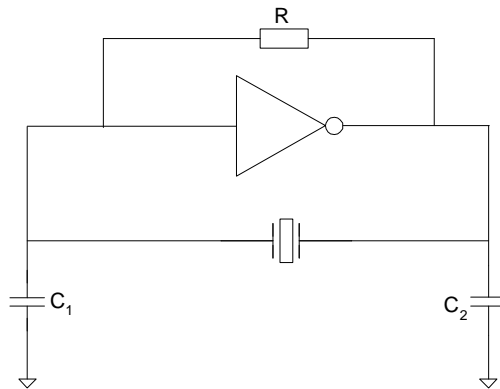
Figure 8: Parallel Resonant Oscillator

Since the capacitors become a frequency-determining element, the sensitivity to its values should be investigated. The parallel resonant portion of the crystal's reactance curve (Fig.6) is extremely steep and short.

Figure 9 shows the dependence of the oscillation frequency on the load capacitance, C_L, for a typical crystal.
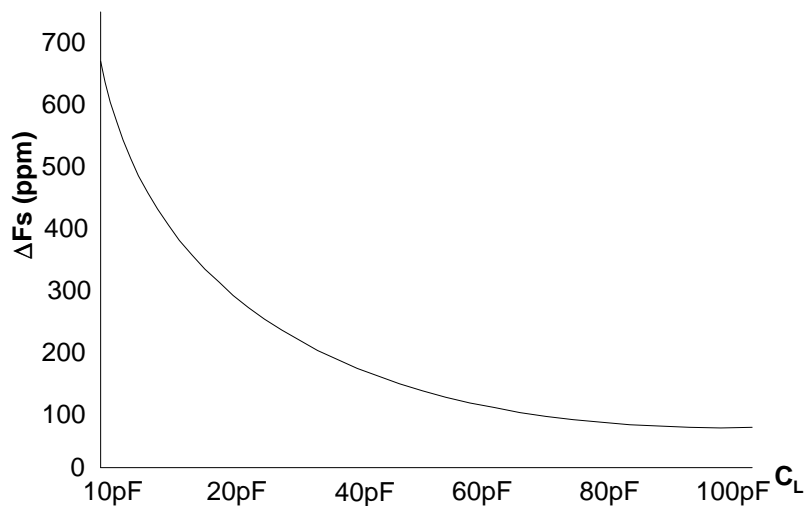
$$C_L = \frac{C_1 \cdot C_2}{C_1 + C_2}$$

Figure 9: Frequency Sensitivity

This validates the fact that:
1) A quartz crystal is an excellent frequency determining element for an oscillator, even when used in conjunction with inaccurate capacitors.
2) The capacitors allow frequency fine-tuning. A varicap used in a parallel oscillator configuration turns the circuit into a Voltage Controlled Oscillator, VCXO.

The parallel resonant configuration – also known as the PIERCE oscillator is the one suggested for EXAR UARTs.

Since crystals can be made to oscillate at higher harmonics, one can limit oscillator's bandwidth by appropriately choosing a feedback resistor. In general, the feedback resistor should have a relatively high value to keep the input impedance to the inverter ($Rin=R/(1-A)$ high. So, R is typically chosen to be in the range: $100k\Omega<R<5M\Omega$.

8. UART Oscillator Components integrated on chip

As a minimum, the inverter is always integrated on chip. However, depending on the particular UART, the feedback resistor may or may not be integrated on chip.

8.1 Off-Chip Feedback Resistors

The first generation UARTs (16C450) and its derivatives do not feature integrated feedback resistors. This includes the ST16C450, ST16C1450, ST16C550, ST16C1550, ST16C580, ST16C650A, XR16C850, ST16C2450, ST16C2550, ST16C2552, XR16C2850 and XR16C2852. These have the internal architecture as shown in Figure 10.
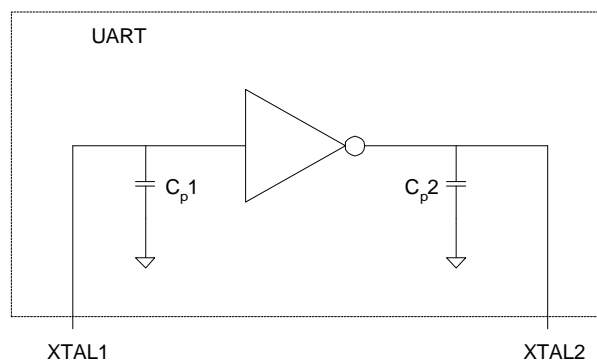

Figure 10 : UART Oscillator Circuit without feedback resistor

Here Cp1 and Cp2 represent the parasitic capacitances associated with the package, pins, bond wires etc. Each is in the range of 2pF to 5pF in magnitude.

Since the feedback resistor is not integrated on chip, it needs to be added externally to the UART, between the XTAL1 and XTAL2 pins.

8.2 Integrated Feedback Resistor

All QUARTs as well as all derivatives of the Motorola UARTs have integrated feedback resistors. This includes the XR68C681, XR88C681, XR68C92, XR68C192, XR88C92, XR88C192, ST16C454, ST16C554, ST16C654, XR16C854, XR16C864, XR16C872, XR82C684 which integrate the biasing resistor on chip as shown in Figure 11. Its nominal value is 300kΩ.
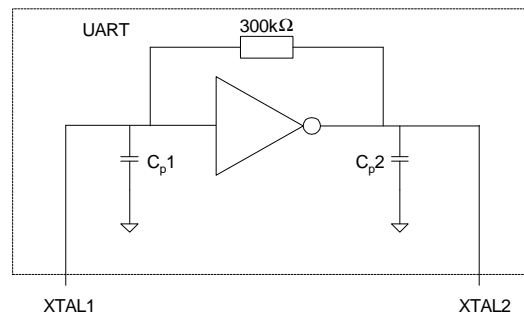

Figure 11: Integrated Feedback Resistor

Hence only a crystal with two load capacitors need be added, in order to make an oscillator.

9. Required Clock Accuracy

The required accuracy of a UART's clock oscillator can be established by understanding the UART's receiver sampling mechanism. A UART's receiver samples the received signal with the externally applied clock. This has a 16x oversampling rate in order to achieve sampling near the mid bit-period instant.
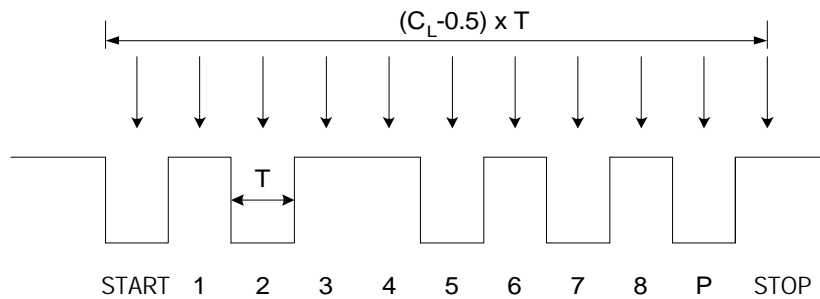
Figure 12: Receiver Mid-Bit Sampling

If the receiver's baud rate, B, deviates by $\Delta B = 1/\Delta T$, where T is the nominal bit period of the transmitter, the START bit will be sampled at $\Delta T/2$ from its nominal mid-bit instant. This deviation in sampling instant adds up by an additional ΔT every bit period.

Consider a general bit pattern that has one START bit, W_L user bits per word (word length), P parity bits and at least one STOP bit. Hence the total bit count (also called Character Length), C_L, is:

$C_L = 1 + W_L + P + 1$
$\quad = W_L + P + 2$.

If the first bit (the START bit) is sampled with a deviation of $\Delta T/2$, then the last bit (the STOP bit) is sampled with $(C_L - 0.5).\Delta T$ deviation from its mid point. Figure 13 shows an example of a long pattern with $C_L = 11$.
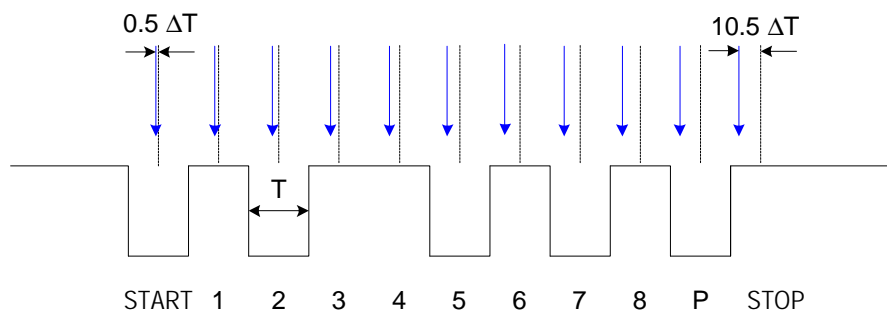

Figure 13: Deviation in Sampling from mid-bit Instant

This deviation may not be larger than half the bit time of the received sequence, or else the previous or next bits are erroneously sampled, instead of the desired STOP bit.

Thus $|(C_L-0.5).\Delta T| < T/2$
Hence $|\Delta T|/T < 1/(2.C_L-1)$

Converting this into Baud Rate terms.
Since $B=1/T$, hence $dB/dT = -B/T$.
Where B is the received signal's Baud Rate, and dB is the difference between the receiver's baud rate and the received signal's baud rate. Assuming small deviations, a linear relationship can be approximated: $\Delta B/\Delta T \approx dB/dT$

Substituting: $|\Delta B|/B < 1/(2.C_L-1)$ Equation (1)

Relating this back to the receiving UART's externally applied clock rate, $F_s = 16.n.B$.
Where,
      n = programmed baud rate divider
       = 256DLM+DLL.

DLM, DLL and n are in decimal.

Hence, $\Delta F_s/F_s = \Delta B/B$

Substituting this into Equation (1):

$$\frac{|\Delta Fs|}{Fs} < \frac{1}{(2.C_L-1)}$$

For example, an 8 bit word with parity and one STOP bit pattern, as shown in Figure 13, allows for a maximum deviation between receiving UART's clock and the transmitting UART's clock of 4.76%. The other extreme of a very short character length of 5 bit, no parity, has $C_L=7$. Here the allowable clock rate deviation is 7.69%.

If the transmitting UART's clock has the same tolerance as the receiving UART's clock, then both UART's clocks may not differ from the nominal clock rate by more than half of the calculated value.

This analysis assumes an ideal, clean transmission channel with no jitter effects, which would degrade the above analysis.

10. Choosing a Crystal for UART use

When selecting a crystal, the following issues should be considered:
1) Parallel resonant crystals are preferable – series resonant crystals are not suitable.
2) Fundamental Oscillation Mode. Since typical UART applications require clock rates of between 1 and 25MHz, fundamental mode resonant crystals are usually adequate.
3) Load Capacitance, C_L. This is the parallel combination of the capacitors: parasitic and external – as seen by the crystal:

$$C_L = \frac{C_1 \cdot C_2}{C_1 + C_2}$$

As indicated in the previous section, the required UART frequency accuracy is relatively lax, and variation in frequency with changing load capacitance is quite low. So capacitor values do not have to be very accurate. The rule is to use capacitors that conform to the values specified by the crystal manufacturer.
4) Temperature coefficients. Common crystals have temperature dependence well witin the requirements for UART usage.
5) Package: A large variety of packages are available.
6) Cost: The most common crystals are cut in the "AT" plane. These are relatively inexpensive, but well suited for UART applications.

11. Design and Debugging Hints

Besides observing the points mentioned in the previous chapter on "Choosing a Crystal", the following should be observed for reliable crystal operation.

Some crystal oscillator circuits show the use of a series resistor (about 100Ω) at the inverter's output pin. While such a series resistor is needed for series resonant oscillator circuits in order to protect the crystal from damage due to excessive energy, this is not required in a parallel oscillating circuit, as suggested in this App Note.

Supply transients can result in:
-   a lack of oscillation
-   non crystal controlled oscillation (self-oscillation)
-   crystal controlled oscillation modulated by self-oscillation frequencies

Hence supply-line bypassing techniques are important in order to ensure that the UART's higher frequencies are not within the oscillator loop's pass band.

Whilst the parasitic capacitances of the UART's chip and package (typically between 2pF and 5pF) influence the frequency of oscillation, this is so small, that the capacitive effect may be neglected.

The external components to the UART should be kept as close as possible to the UART to reduce noise coupling and reduce parasitic inductance.

In order to check the crystal oscillator with an oscilloscope, it is recommended to apply the oscilloscope's probe on the XTAL2 pin of the UART's package. This is the low impedance point in the feedback loop – which is least disturbed by the oscilloscope's input impedance. The waveform will look like a square wave if the crystal oscillates at low frequencies (say less than 5MHz). At higher frequencies the signal will look more like a sinusoid with amplitude limiting, as the oscillation frequency approaches unity open loop gain of the feedback loop.

The signal at the XTAL1 pin will be sinusoidal, since the feedback elements (capacitors and crystal) form a high Q band-pass filter. The 'scope probe may interfere with this signal due to XTAL1 being a high impedance point.

For debugging purposes, some UARTs (ST16C450, ST16C550, ST16C580, ST16C650A, XR16C850, XR16C864) have an output clock pin, called BAUDOUT. BAUDOUT's pulse rate reflects the programmed baud rate of the UART. It allows non-invasive monitoring. BAUDOUT's duty cycle is not necessarily 50%, as shown in the respective data sheets.

12. Application Example

An industrial control system shall employ a XR16C850IQ single channel UART that should operate with standard Baud Rates (50 Baud to 115.2 kBaud) as well as at quadruple these baud rates. The terminal that the XR16C850IQ will exchange data with via RS485, is specified to operate at a baud rates of within 500ppm of the nominal rates. The serial communication link uses 8bit, even parity with two stop bits protocol. Design a suitable crystal oscillator circuit for the UART.

The XR16C850 has an additional divider (divide by four) besides the standard 16C550-style baud rate generator. If this divider is used, the reference clock rate needs to be 7.3728MHz, as shown in the UART's data sheet baud rate table.

The maximum allowable tolerance of the UART's reference frequency for the specified protocol is 4.7%, as calculated in the example at the end of paragraph 9. Since this tolerance is orders of magnitude looser than 500ppm, the XR16C850 crystal should operate within 4.7% from nominal frequency (7.3728MHz). A typical loose frequency tolerance spec for a crystal is 100pm.

Hence, a parallel resonant, fundamental mode, 100ppm, -20°C to +85° temperature range crystal would suite this application.

For example, VITE Technology makes AT-cut crystals in the industry standard HC-49/U package. The crystal's data sheet shows 7.3728MHz to be a standard crystal frequency, in the VXA1 range of crystals. The data sheet allows selection of load capacitance from 16pF to 30pF. A 20pF load capacitance is arbitrarily selected here. These parameters make up the VITE part number: VXA1-1C2-7M3727.

Since the parasitic capacitances C_{1p} and C_{2p} have negligible effect on the frequency, two standard 39pF capacitors were selected for external connection – the parallel equivalent value of which is close the desired load capacitance of 20pF.

Finally, the XR16C850 UART needs a large valued feedback resistor external to the UART for biasing the inverter. A 1MΩ resistor was selected as shown in Figure 14; alternatively, a smaller one could also have been used.
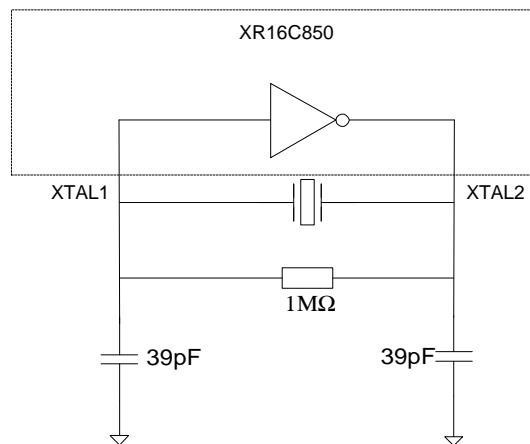

Figure 14: Example Design of a XR16C850 Crystal Oscillator

13. References

1) Parzen, Benjamin, Design of Crystal and Other Harmonic Oscillators, John Wiley and Sons, New York, 1983.
2) EXAR Corporation. XR16C850 Data Sheet. URL: www.exar.com
3) VITE Technology VXA1-1C2-7M3727 Data Sheet, URL: www.viteonline.com