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ULTRA LOW POWER CRYSTAL OSCILLATORS

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ABSTRACT

Crystal Oscillators are key components used in many electronic circuits, such as in radio frequency applications and digital and microprocessor-based devices. In order to save power, an ultra low-power oscillator circuit is often desired. In this article we will build 1MHz to 16MHz crystal oscillator circuits and demonstrate a circuit that operates at 7µW with a 4MHz oscillation frequency and operating voltage of +0.3V. An ultra low-power oscillator circuit can be built using recently introduced ultra-low voltage MOSFET arrays. The resulting circuit reduces oscillator power consumption drastically, up to over 100x reduction, and conserves system power for other critical purposes.

INTRODUCTION

There are numerous possible combinations of crystal-oscillator circuits, many of which are derivatives of one another with different references to ground potential, and different cuts of crystals suited for different operating frequencies. In general, the majority of crystal-oscillator circuits dissipate significant amounts of power and they tend to require a large portion of the power budget of many battery-operated or low-powered systems. Power savings can be particularly important for front-end or sleep-mode crystal-oscillator circuits that must be left on continuously and operated 24-7.

These ultra low power conditions can be achieved by designing very low operating voltage crystal-oscillator circuits using EPAD MOSFETs offered by Advanced Linear Devices, Inc. An ALD110900 (dual Zero-Threshold™ EPAD MOSFET) for example can be configured as the oscillator inverter in a crystal-oscillator circuit using either a passive resistor load or an ALD114904 (dual Vgs(th)= -0.4V Depletion Mode EPAD MOSFET) active load. Both circuits are described in more detail below.

Crystal Oscillator

A crystal oscillator (Figure 1) has very desirable characteristics for tuned oscillator circuit applications because the natural oscillation frequency of the crystal is very stable with changes in temperature, power supply voltage, or mechanical vibration. The oscillation frequency of a crystal oscillator can be approximated by the following equation:

$$f_{OSC} = \frac{1}{2\pi \sqrt{L_1 \times C_1}}$$

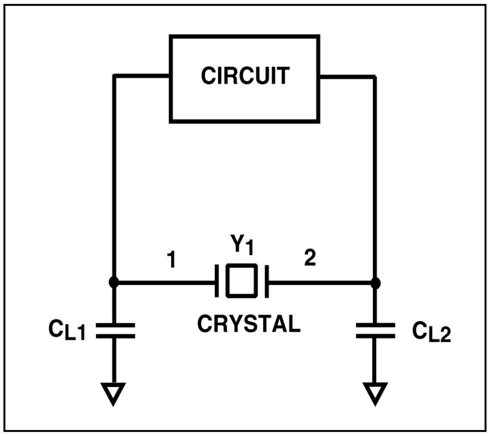


FIGURE 1: Crystal Oscillator Network.

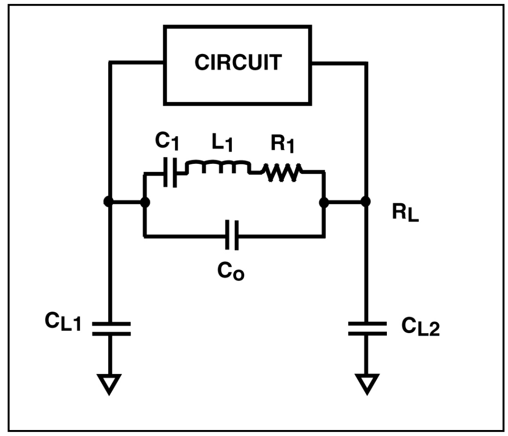


FIGURE 2: Crystal Equivalent Circuit Network.

The electrical equivalent circuit for a crystal oscillator circuit is shown in Figure 2. This electrical equivalent circuit is a model of the crystal's electrical and mechanical behaviors. It does not consist of these actual circuit elements; therefore it tends to operate under a more limited set of electrical conditions.

The crystal electrical equivalent circuit consists of C_1, L_1, R_1 and C_0. The components C_1, L_1, and R_1 are called the motion arm and they model the mechanical behavior of the crystal element. C_0 models the electrical behavior of the crystal element and its holder. C_1 models the elasticity of the quartz, the area of the electrodes on the face, and the thickness and shape of the quartz wafer. L_1 models the vibrating mechanical mass of the quartz in motion. R_1 models and represents the real resistive losses within the crystal. C_0 represents the sum of capacitance due to the electrodes on the crystal plate and stray capacitance due to the crystal holder and enclosure.

ULTRA LOW POWER CRYSTAL OSCILLATOR CIRCUIT

The design objective for this paper is to create an ultra low-power crystal-oscillator circuit. The crystal-oscillation circuit uses an inverter gate consisting of an ALD EPAD MOSFET device with a passive resistor load or an alternate design with an active EPAD MOSFET load. In implementing this crystal oscillator circuit, an ALD110900 Zero-Threshold mode MOSFET was selected for the oscillator circuit inverter, M1. For this oscillator inverter, a 10KΩ resistor acting as passive load was used (Fig. 3A). Alternatively, an active load M2 using an ALD114904 Depletion Mode MOSFET with gate connected to the source is used to create an active load inverter circuit consisting of M1 and M2 (Fig. 3B), in order to examine the effect of passive loading versus active loading on circuit performance. Many different circuit configurations using a variety of component values were found to be effective for these crystal-oscillator circuits. Furthermore, the results showed that crystal-oscillator circuits with passive loads required lower power to operate when compared to those using active loads.

A 5.6MΩ-feedback resistance R_F provides negative feedback around the inverter so that oscillation will start when power is applied to the circuit. If the value of R_F is higher and the insulation resistance of the input inverter is too low, then the oscillation will stop due to the loss of loop gain. A large R_F value will also introduce noise into the oscillation circuit. Obviously, if R_F is too low, loop gain will be decreased.

The 6Ω damping resistance R_L was added to the circuit to reduce the coupling between the inverter and the feedback circuit and to decrease the loading on the output side of the inverter. In addition, the phase of the feedback circuit is stabilized by means of reducing gain at higher frequencies, thus preventing the possibility of spurious oscillation.

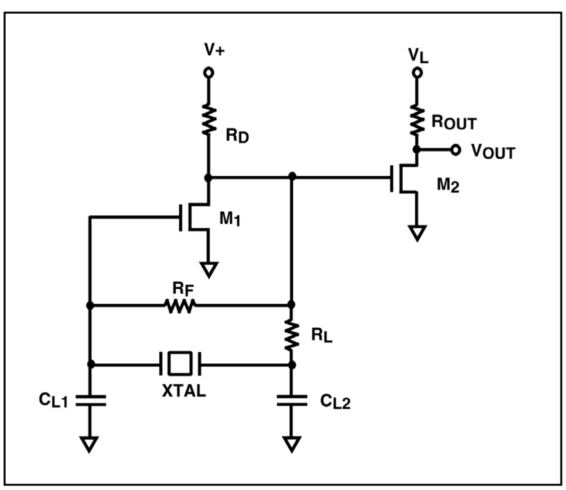


FIGURE 3A: Crystal Oscillator with Resistor Load

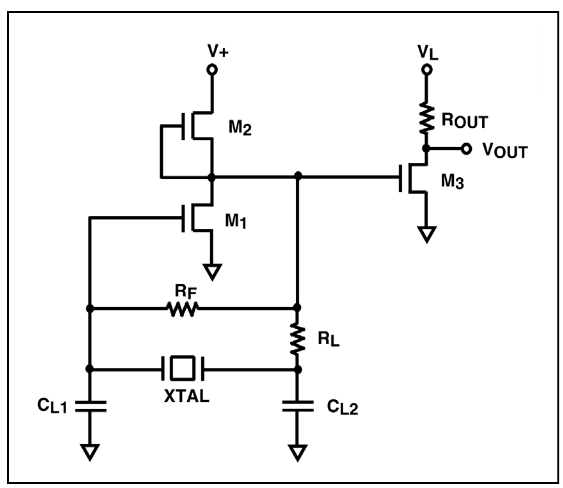


FIGURE 3B: Crystal Oscillator with Active Load

CL_1 and CL_2 are utilized to provide 180^o phase lag for the feedback network. If CL_1 and CL_2 values are too low, the loop gain at high frequency is increased, which in turn increases the probability of spurious oscillation. If CL_1 and CL_2 values are too high, the oscillation will stop. Therefore CL_1 = 10pF and CL_2 = 22pF were selected for the circuit.

A second inverter M2 (buffer inverter) using an ALD114904 with a 2.4KΩ R_{out} pull-up resistor was connected to the first oscillator inverter output as a waveform shaper and also as a buffer for the oscillator output. In order to obtain the lowest possible power dissipation, V+ (referred to as V_R in the simulation) was used to power the oscillator inverter and V_L was used to power the buffer inverter. V+ and V_L can be set independently to different voltage levels to optimize power dissipation and to provide the desired output voltage level swings. Both V+ and V_L were decreased from +5V until oscillation stops to obtain their respective minimum operating voltage levels.

The circuits in Fig. 3A and Fig. 3B were operated at oscillation frequencies ranging from 1MHz to 16MHz using various crystals from different crystal manufacturers. With passive load circuit configuration, the crystal-oscillator circuit performed from 1MHz to 16MHz with output voltage swings ranging from 10mV to 3.4V; and with V+ (V_R) range of 0.3V to 5V and V_L range of 0.1V to 5V. Minimum power dissipation of 7μW was achieved at an optimum frequency of 4MHz and at V+=0.3V and V_L=0.1V.

Optimum active-load oscillator circuit configuration was achieved by using an ALD114904 as the active load device. Oscillation frequency range for the active-load oscillator was 1MHz to 8MHz, producing output voltage swings ranging from 5mV to 0.73V with a V+ range of 0.3V to 5V and V_L range 0.1V to 5V. Minimum power dissipation of 7μW was achieved at an optimum operating frequency of 4MHz with V+=0.3V and V_L=0.1V.

SIMULATION RESULTS

The circuits depicted in Figs. 3A and 3B were simulated on a computer circuit simulator, substituting the crystal with electrical-equivalent circuit elements as shown in Figure 2. The electrical-equivalent crystal parameters to produce an oscillating frequency of 4MHz are L_1=28mH, C_1=0.054pF, R_1=22.1Ω, and C_0=2.39pF. Other device and component parameters in the crystal-oscillator circuit were selected based on simulation and experimental results, i.e. CL_1=10pF, CL_2=22pF, ALD110900 (Vgs(th)=0.00V), ALD114904 (Vgs(th)= –0.40V), R_D=10KΩ, R_{out}=2.4KΩ, R_F=5.6MΩ, and R_L=6Ω as shown in Figure 4.

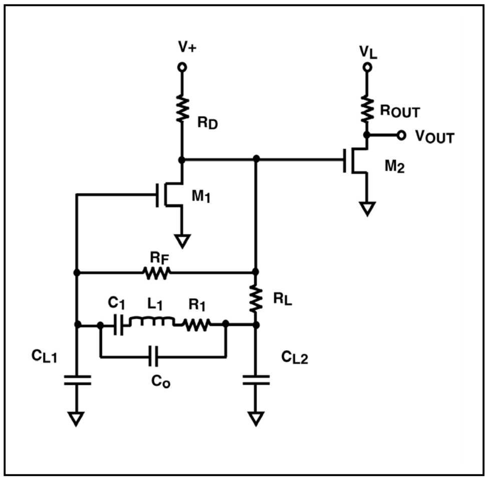


FIGURE 4: Crystal Oscillator Simulation Circuit using Passive Load Inverters.

Figure 5 and 6 show a crystal oscillator circuit oscillating at 4MHz with V+ and VL ranging from 0.3V to 5V and 0.1V to 5V, respectively. Simulation results matched the laboratory experimental results.

In an active-load crystal-oscillator inverter circuit as shown in Figure 7, the resistor R_D of the circuit in Figure 4 was replaced with an ALD114904 with Vgs(th) of –0.4V. The gate of the ALD114904 was connected to its source as an active load, while other remaining circuit elements and their respective component parameter values were kept the same as in the case of passive-load crystal-oscillator circuit. This circuit in the simulation was running at an optimum frequency of 4MHz.

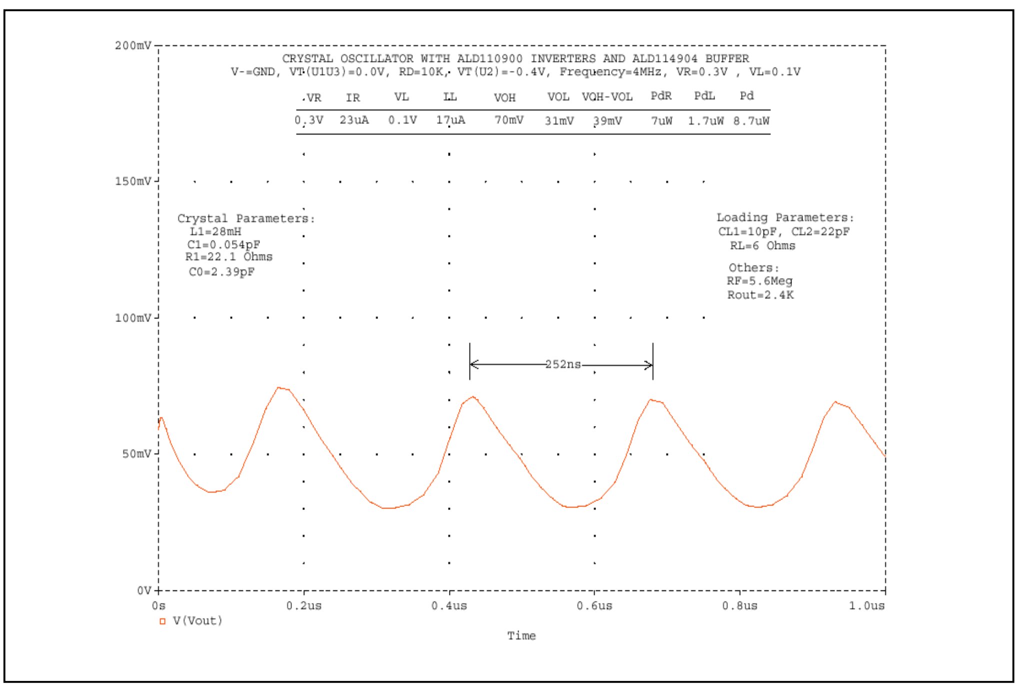
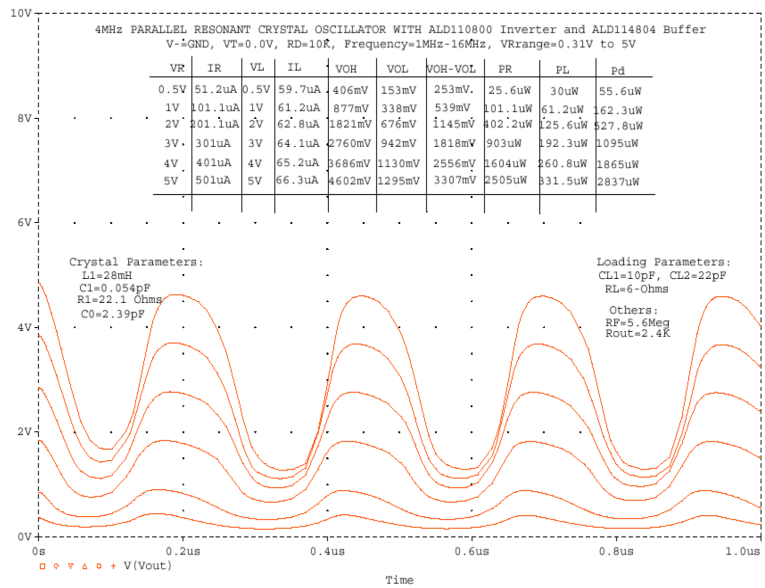


FIGURE 5: Simulation Results of Crystal Oscillator Circuit with Passive Load Inverter at V+=0.3V and V_L=0.1V



VR	IR	VL	IL	VOH	VOL	VOH-VOL	PR	PL	Pd
0.5V	51.2uA	0.5V	59.7uA	406mV	153mV	253mV	25.6uW	30uW	55.6uW
1V	101.1uA	1V	61.2uA	877mV	338mV	539mV	101.1uW	61.2uW	162.3uW
2V	201.1uA	2V	62.8uA	1821mV	676mV	1145mV	402.2uW	125.6uW	527.8uW
3V	301uA	3V	64.1uA	2760mV	942mV	1818mV	903uW	192.3uW	1095uW
4V	401uA	4V	65.2uA	3686mV	1130mV	2556mV	1604uW	260.8uW	1865uW
5V	501uA	5V	66.3uA	4602mV	1295mV	3307mV	2505uW	331.5uW	2837uW

FIGURE 6: Simulation Results of Crystal Oscillator Circuit with Passive Load at various V+(V_R) and V_L

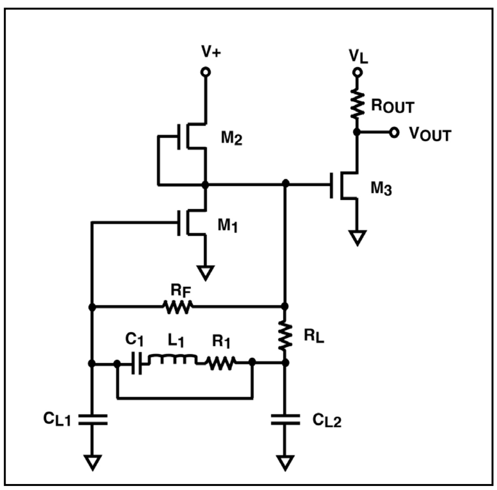


FIGURE 7: Simulation Circuit of Crystal-Oscillator Circuit using an Active Load Inverter.

Figs. 8 and 9 show simulation results of the circuit in Figure 7 oscillating at 4MHz with various V+(V_R) and V_L values ranging from 0.3V to 5V and 0.1V to 5V, respectively. Simulation results matched those of the laboratory experimental results. Both the passive loading and active loading versions of the oscillator circuits performed similarly at a low voltage minimum of about 0.3V and a minimum power of about 7 uW, although the passive loading version dissipated 20% less power when operated at 0.5V supply. However, the active load version required consistently low supply current averaging about 66 uA for a much broader voltage range.

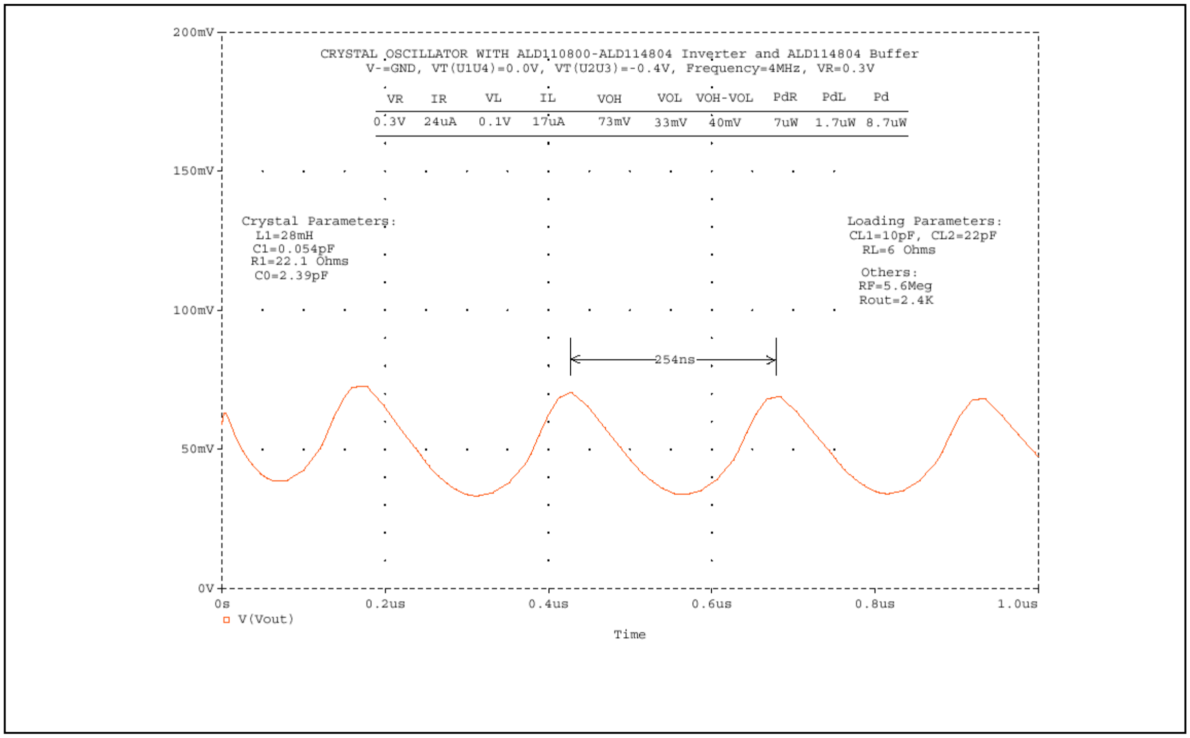


FIGURE 8: Simulation Result of Crystal Oscillator Circuit with Active Load at V+(V_R)=0.3V, V_L=0.1V.

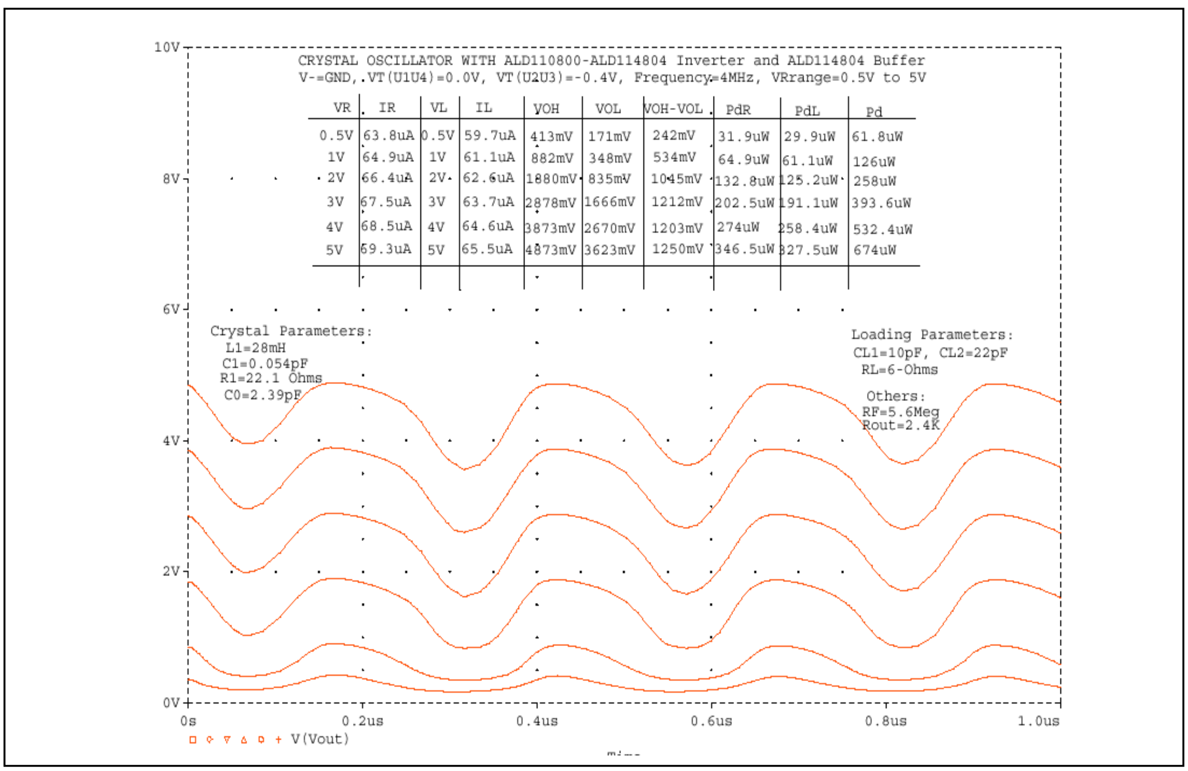


FIGURE 9: Simulation Results of Crystal Oscillator Circuit with Active Load at various V+(V_R) and V_L.

SUMMARY

Ultra low power crystal-oscillator circuit networks in parallel resonant mode were simulated and bench-tested using ALD EPAD MOSFETs. Both experimental and simulation results demonstrated that a broad range of oscillating frequencies could be achieved by using EPAD MOSFET-based low voltage crystal-oscillator circuits. Results demonstrated feasibility of operating a crystal-oscillator circuit at substantially lower operating voltages, in the 0.3V to 0.5V range, when compared to conventional oscillators operating in the 3V to 5V range. At the same time, substantially lower power dissipation is obtained for a wide range of oscillation frequencies using a variety of different crystals from different crystal manufacturers.