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LINEAR
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ULTRA LOW POWER OSCILLATORS

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ABSTRACT

ALD110900, ALD110804 and ALD114904 devices were utilized as inverters and buffers to create a low power oscillator circuit with various configurations. This article covers three basic oscillator configurations namely RC, LC (Colpitts) and crystal oscillators. The basic crystal and LC Feedback configurations in parallel resonant operating mode were implemented in the test circuits running at 1MHz-16MHz for the crystal and 1MHz-10MHz for the LC Feedback configurations, respectively. Simulations of both basic crystal and LC Feedback configurations confirmed the test circuit with successful results. The RC configuration was modeled and simulated with successful result. The lowest power crystal oscillator was achieved at optimum frequency of 4MHz at 0.3V operating voltage with power dissipation of 7µW. On the other hand, the LC Feedback configuration dissipated power of 0.8µW at 0.17V operating voltage running at optimum frequency of 1MHz. The lowest power dissipation achieved in this article was 1.2nW at 0.14V operating voltage running at optimum frequency of 40Hz by RC configuration.

I. INTRODUCTION

Oscillators are one of the key components in radio frequency world and digital devices. There are unlimited circuit combinations that make up oscillators. Many of these circuits are derivatives of one another with different references of ground points. In general, majorities of oscillators normally dissipate significant amounts of powers. In order to save power, a very low operating voltage to drive the oscillator is desired. This very low operating voltage condition can only be achieved by ALD110900 (dual zero-threshold MOSFET) device configured with both active and passive loads ALD114904 (dual 0.4V-threshold MOSFET) inverter configurations for the LC (Colpitts) and crystal oscillator. On the other hand, in the RC oscillator circuit, ALD110804 (quad 0.4V-threshold MOSFET) configured with passive loads as inverters was used to achieve a very low operating voltage. Thus, the use of these three devices namely ALD110900, ALD114904 and ALD110804 can potentially result in substantial power savings in the front-end circuitry, and in turn lead to battery life extension in portable devices.

II. OSCILLATOR CONFIGURATIONS

LC Feedback Oscillator

The LC feedback oscillator (Figure 1) is a parallel resonant tuned circuit. Capacitors CL_1 and CL_2 are used to form a capacitive voltage that couples some of the energy from the transistor inverter in order to provide a phase lag of 180°, and to determine the frequency of oscillation in conjunction with the inductor L_1. This oscillation frequency can be represented by the following formula:

$$f_{OSC} = \frac{1}{2\pi \sqrt{L_1 \times [(CL_1 x CL_2)/(CL_1+CL_2)]}}$$

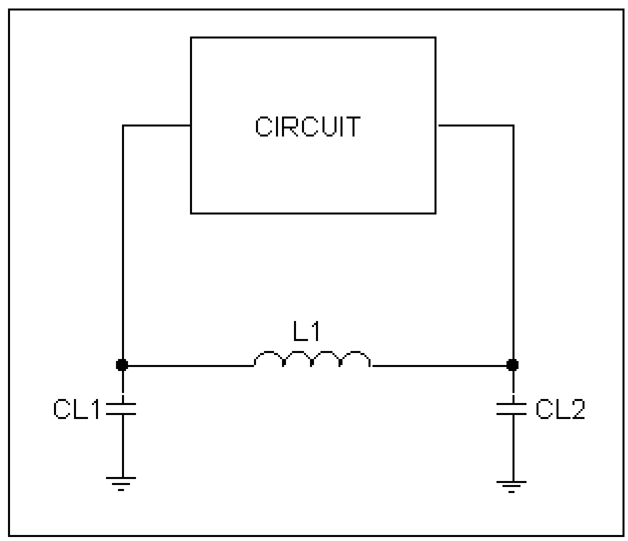

FIGURE 1: LC Feedback Oscillator Network.

Like in the crystal oscillator circuit network, transistor biasing resistors can increase the effective resistance of the tuned circuit LC thus reducing its quality factor Q and decreasing the loop gain.

Crystal Oscillator

Unlike the Colpitts oscillator, crystal oscillator has very desirable characteristics as oscillator tuned circuit mainly because of the natural oscillation frequency is very stable with changes in temperature, power supply voltage, or mechanical vibrations. The oscillation frequency of a crystal oscillator can be calculated by the following equation:

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

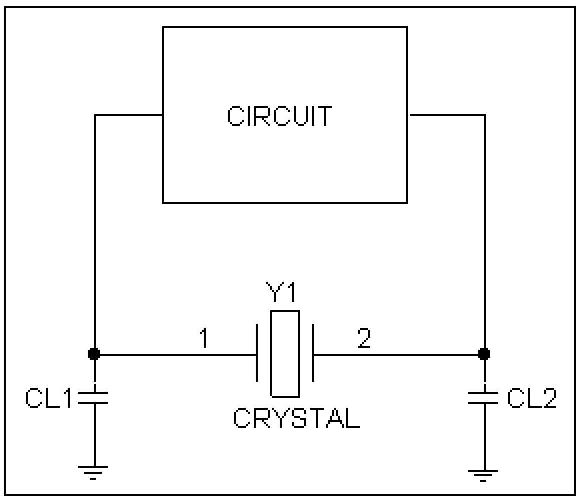

FIGURE 2: Crystal Oscillator Network.

The equivalent circuit for a crystal is shown in Figure 3. This equivalent circuit is an electrical representation of the crystal's electrical and mechanical behaviors. It does not represent actual circuit components.

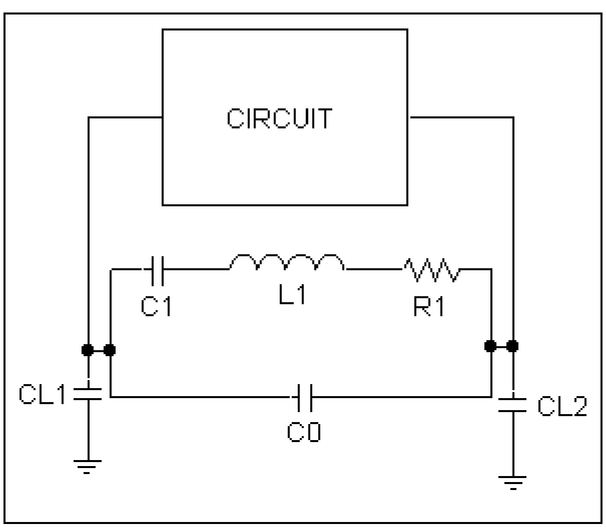

FIGURE 3: Crystal Equivalent Circuit Network.

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

RC Oscillator

The RC oscillator (Figure 4) consists of a feedback network of a capacitor C_L and resistors R_1 and R_2 used to form a capacitive voltage that couples some of the energy from the transistor inverter in order to provide a phase lag of 180^{o}. The oscillation frequency can be for this oscillator technique represented by the following formula:

$$f_{OSC} = \frac{1}{2\pi \times R_1 \times C_L}$$

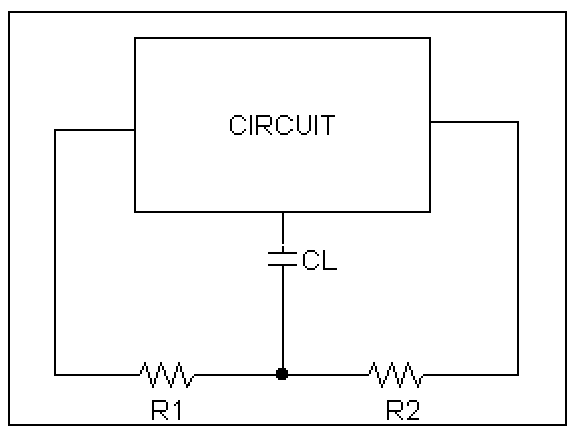

FIGURE 4: RC Feedback Circuit Network.

III. CRYSTAL OSCILLATOR EXPERIMENT

The main objective of the design is to create a low power oscillator circuit. It is becoming more common to configure the oscillation circuit using an inverter gate.

For this purpose, ALD110900 n-channel enhancement MOSFET was selected as the inverter component. In order to create a passive load inverter from the MOSFET device, a 10KΩ resistor acting as passive load was used. Another approach to minimize power of the oscillation circuit was to replace the 10KΩ passive load resistor with an active load component ALD114904 with gate connected to source to create an active load inverter.

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

The 6Ω damping resistance R_L was then added to the circuit. It makes the coupling between the inverter and the feedback circuit loose. Thereby, decreasing the load on the output side of the inverter. In addition, the phase of the feedback circuit is stabilized by means of reducing the gain at higher frequencies, thus preventing the possibility of spurious oscillation.

The load capacitances CL_1 and CL_2 were also utilized to provide a phase lag of 180°. If the CL_1 and CL_2 are low, the loop gain at high frequency is increased, which in turn increases the probability of spurious oscillation. Therefore, a 10pF CL_1 and a 22pF CL_2 were selected in the test circuit.

Another inverter using ALD114904 with 2.4KΩ R_{out} was then used as a waveform shaper and also acts as a buffer for the output of the oscillation inverter. This whole schematic of the test circuit is shown in Figure 4.

In order to maintain the power dissipation as low as possible, the voltages V_R and V_L to power both the main and the buffer inverters were decreased until the oscillation stops.

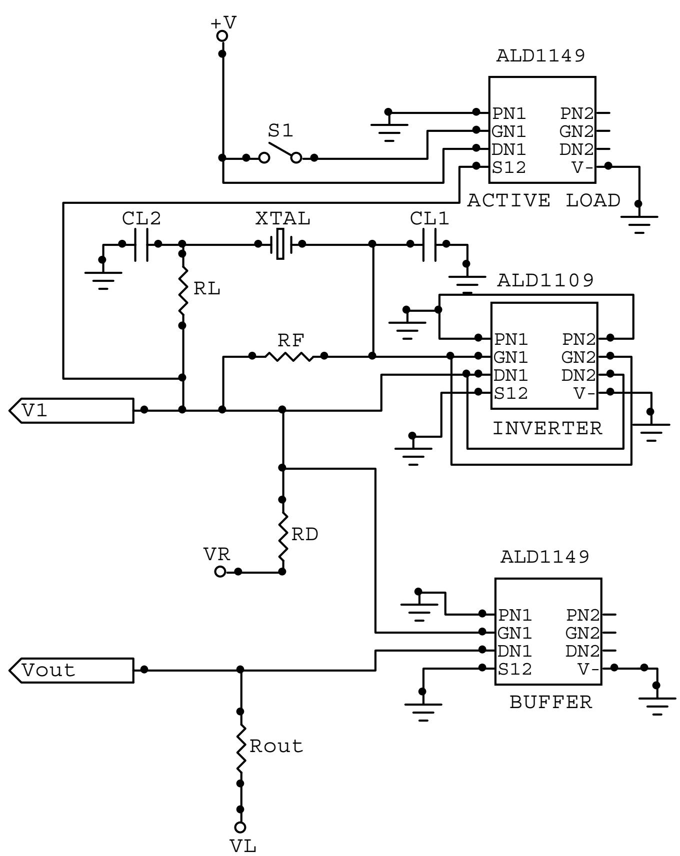

FIGURE 5: Crystal Oscillator Test Circuit

The test circuit in Figure 5 is configured for both passive load R_D and active load ALD114904 inverter. The circuit was tested at oscillation frequencies from 1MHz to 16MHz using various crystal manufacturers.

Using the passive load configuration, the test circuit was successfully oscillating from 1MHz to 16MHz with excellent output swings of 10mV to 3.4V with V_R and V_L ranging from 0.3V to 5V and 0.1V to 5V, respectively. The minimum power dissipation occurred at optimum oscillating frequency 4MHz of 7µW at V_R=0.3V and V_L=0.1V with 10mV output swing.

However, the active load optimum configuration was successfully achieved by using ALD114904 oscillating at frequency range of 1MHz to 8MHz with output swings of 5mV to 0.73V with V_R and V_L ranging from 0.3V to 5V and 0.1V to 5V, respectively. The minimum power dissipation occurred at optimum operating frequency 4MHz of 7µW at V_R=0.3V and V_L=0.1V with 5mV output swing.

IV. LC FEEDBACK OSCILLATOR EXPERIMENT

In order to further minimize power of the oscillation circuit, a LC Feedback oscillator design was implemented which turned out also minimizing the component costs as well. In this design, the crystal component was replaced by an inductor L_1, which was more cost efficient compared to the crystal itself.

In this circuit configuration, ALD110900 n-channel enhancement MOSFET with a 20KΩ resistor acting as passive load inverter was selected. Another effort to minimize power was also performed as experimental result comparison by replacing the 20KΩ passive load resistor with an active load component ALD114904 with gate connected to source for the active load inverter.

The 5.6MΩ-feedback resistance R_F provides negative feedback around the inverter so that the oscillation will start when power is applied.

The 6Ω damping resistance R_L was kept in the circuit to prevent the possibility of spurious oscillation.

The load capacitances CL_1 and CL_2 combinations of 10pF and 39pF, respectively, were also utilized to provide a phase lag of 180°.

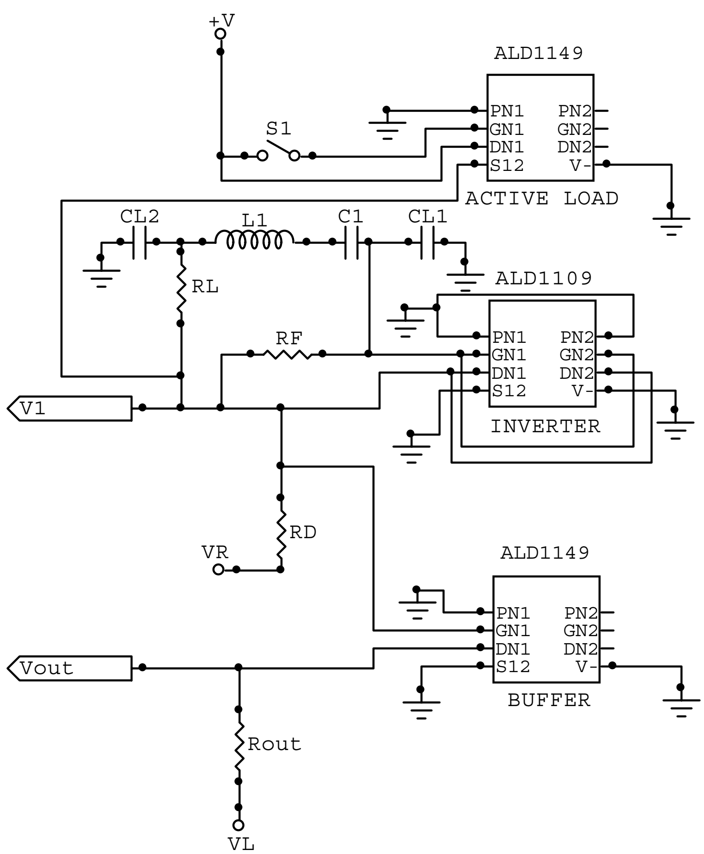

FIGURE 6: LC Feedback Oscillator Test Circuit

The buffer inverter using ALD114904 with 2.4KΩ R_{out} to was also kept. This whole schematic of the test circuit is shown in Figure 6.

In order to maintain the power dissipation as low as possible, the voltages V_R and V_L to power both the main and the buffer inverters were decreased until the oscillation stops.

The test circuit in Figure 5 is configured for both passive load R_D and active load ALD114904 inverter. The circuit was tested at oscillation frequencies at 1MHz and 4MHz using various values of inductor L_1 and capacitors CL_1 and CL_2.

In the passive load configuration, the test circuit was successfully oscillating at 1MHz with L_1=1mH, CL_1=10pF and CL_2=39pF producing output swings of 10mV to 2.3V with V_R and V_L ranging from 0.17V to 5V and 0.1V to 5V, respectively. The minimum power dissipation occurred at optimum oscillating frequency 1MHz of 0.8µW at V_R=0.17V and V_L=0.1V with 10mV output swing.

In the active load configuration, the test circuit was successfully oscillating at 1MHz with L_1=1mH, CL_1=10pF and CL_2=39pF producing output swings of 10mV to 0.6V with V_R and V_L ranging from 0.2V to 5V and 0.1V to 5V, respectively. The minimum power dissipation occurred at optimum oscillating frequency 1MHz of 3µW at V_R=0.2V and V_L=0.1V with 10mV output swing.

Adding another stage of ALD110900 inverter in parallel with the existing one in the circuit produced broader oscillation frequency range from 1MHz to 10MHz in the passive load configuration, and from 1MHz to 4MHz in the active load configuration.

In the passive load configuration with this additional ALD1109 inverter and L_1 of 10µH with CL_1=CL_2=39pF produced output swing of 10mV-0.7V with V_R=0.9V-5V and V_L=0.1V-5V oscillating at 10MHz.

Changing L_1=100µH with the same values of CL_1 and CL_2, the experiment showed the range of output swing produced was from 10mV to 2V with V_R=0.32V-5V and V_L=0.1V-5V oscillating at 4MHz.

Oscillation at 1MHz still happened by changing L_1=1mH with the same values of CL_1 and CL_2. The range of output swing produced by this setup was from 10mV to 3.5V with V_R=0.26V-5V and V_L=0.1V-5V.The power dissipation produced was 2.2µW at V_R=0.26V and V_L=0.1V with output swing of 10mV.

In the active load configuration with this additional ALD110900 inverter and setting L_1 to 100µH with CL_1=39pF and CL_2=47pF produced the range of output swing of 10mV-0.7V with V_R=0.28V-5V and V_L=0.1V-5V oscillating at 4MHz.

Changing L_1=1mH with the same values of CL_1 and CL_2, the experiment showed the range of output swing produced was from 10mV to 1.3V with V_R=0.22V-5V and V_L=0.1V-5V oscillating at 1MHz. The power dissipation produced was 4µW at V_R=0.22V and V_L=0.1V with output swing of 10mV.

V. SIMULATIONS

The simulation was performed based on the optimum experimental results of both crystal and LC oscillator circuits of Figure 5 and Figure 6, respectively.

The experiment of Figure 5 was simulated by replacing the crystal with the equivalent circuit as shown in Figure 3. The equivalent crystal parameters to produce the oscillating frequency of 4MHz are L_1=28mH, C_1=0.054pF, R_1=22.1Ω, and C_0=2.39pF. The other device and component parameters were selected according the values used in the experiment, i.e. CL_1=10pF, CL_2=22pF, ALD110900 with threshold voltage of 0.00V, ALD114904 with threshold voltage of –0.40V, R_D=10KΩ, R_{out}=2.4KΩ, R_F=5.6MΩ, and R_L=6Ω as shown in Figure 7.

Figure 8 and 9 shows that the circuit is oscillating at 4MHz with VR and VL ranging from 0.3V to 5V and 0.1V to 5V, respectively. The simulation result indicated a match to the experimental result.

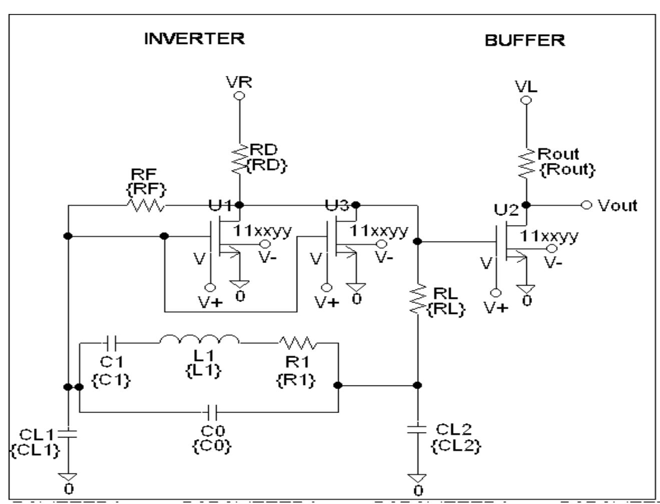

FIGURE 7: Crystal Oscillator Simulation Circuit with Passive Load Inverters.

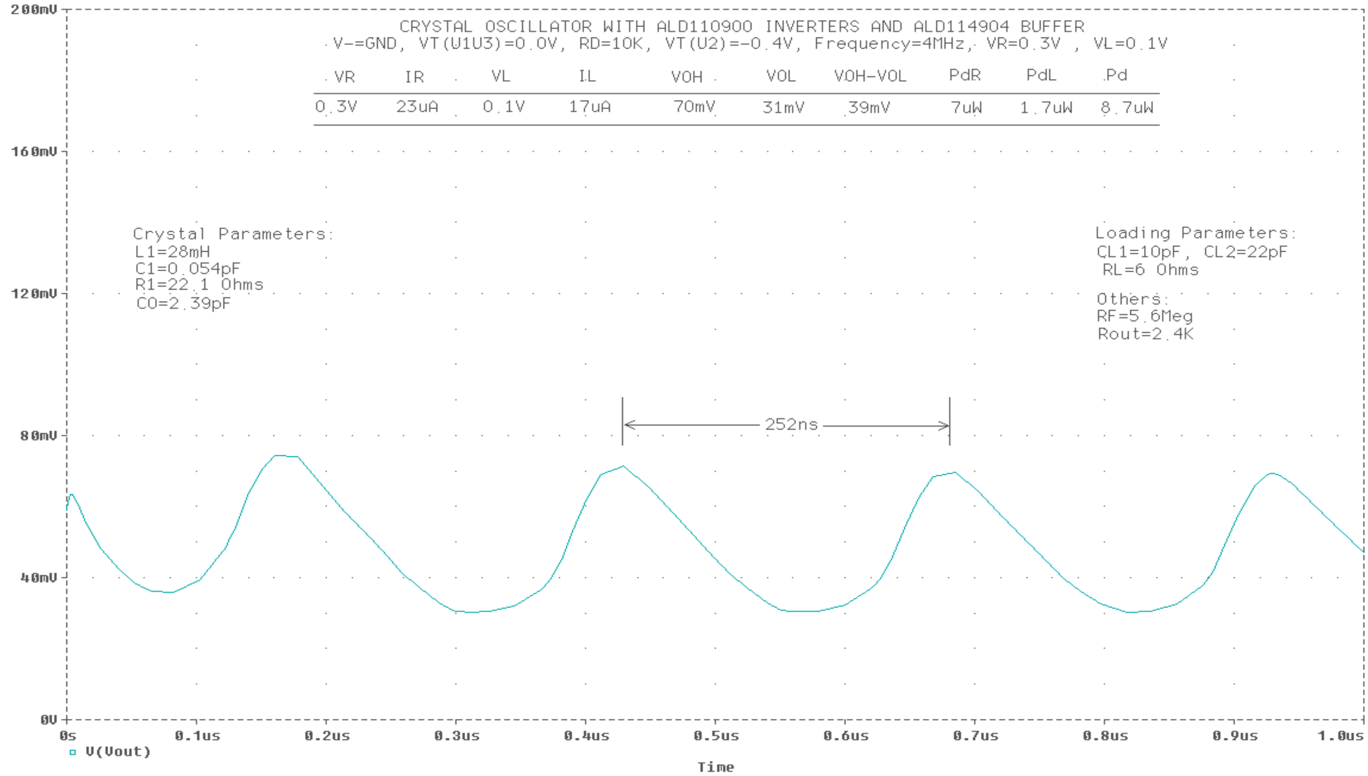

FIGURE 8: Crystal Oscillator with Passive Load Inverter Simulation Result at V_R=0.3V and V_L=0.1V

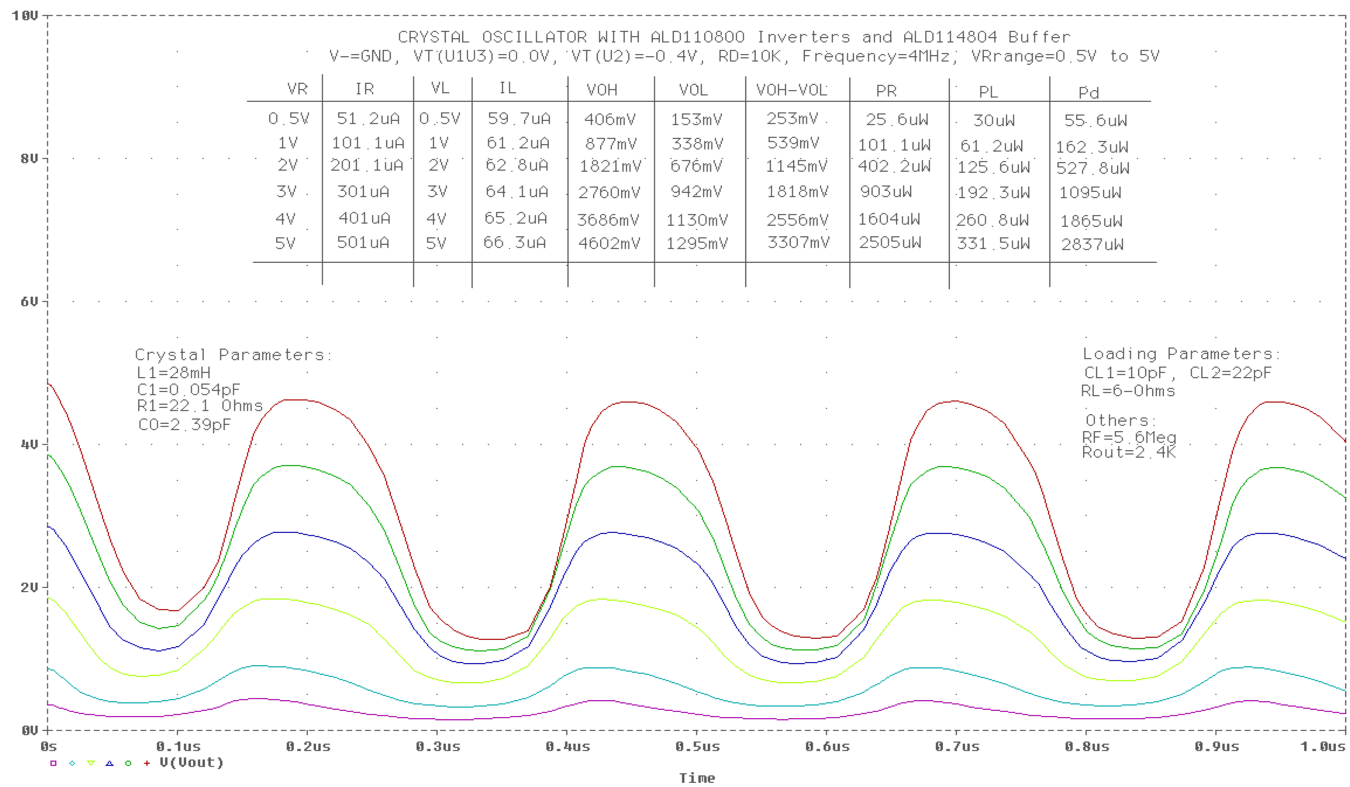

FIGURE 9: Crystal Oscillator with Passive Load Simulation Result at various V_R and V_L.

In the active load inverter configuration as shown in Figure 10, the resistor R_D was replace with ALD114904 with threshold voltage of –0.4V and the gate was connected to the source of the ALD114904 active load, while the remaining device and component parameters were kept the same. The optimum oscillation frequency in this simulation was also running at 4MHz.

Figure 11 and 12 shows that the circuit is oscillating at 4MHz with V_R and V_L ranging from 0.3V to 5V and 0.1V to 5V, respectively. The simulation result indicated a match to the experimental result.

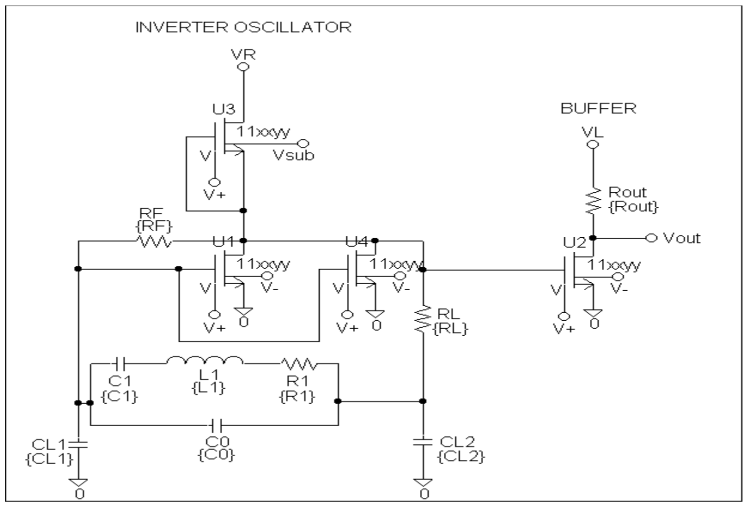

FIGURE 10: Crystal Oscillator Simulation Circuit with Active Load Inverters.

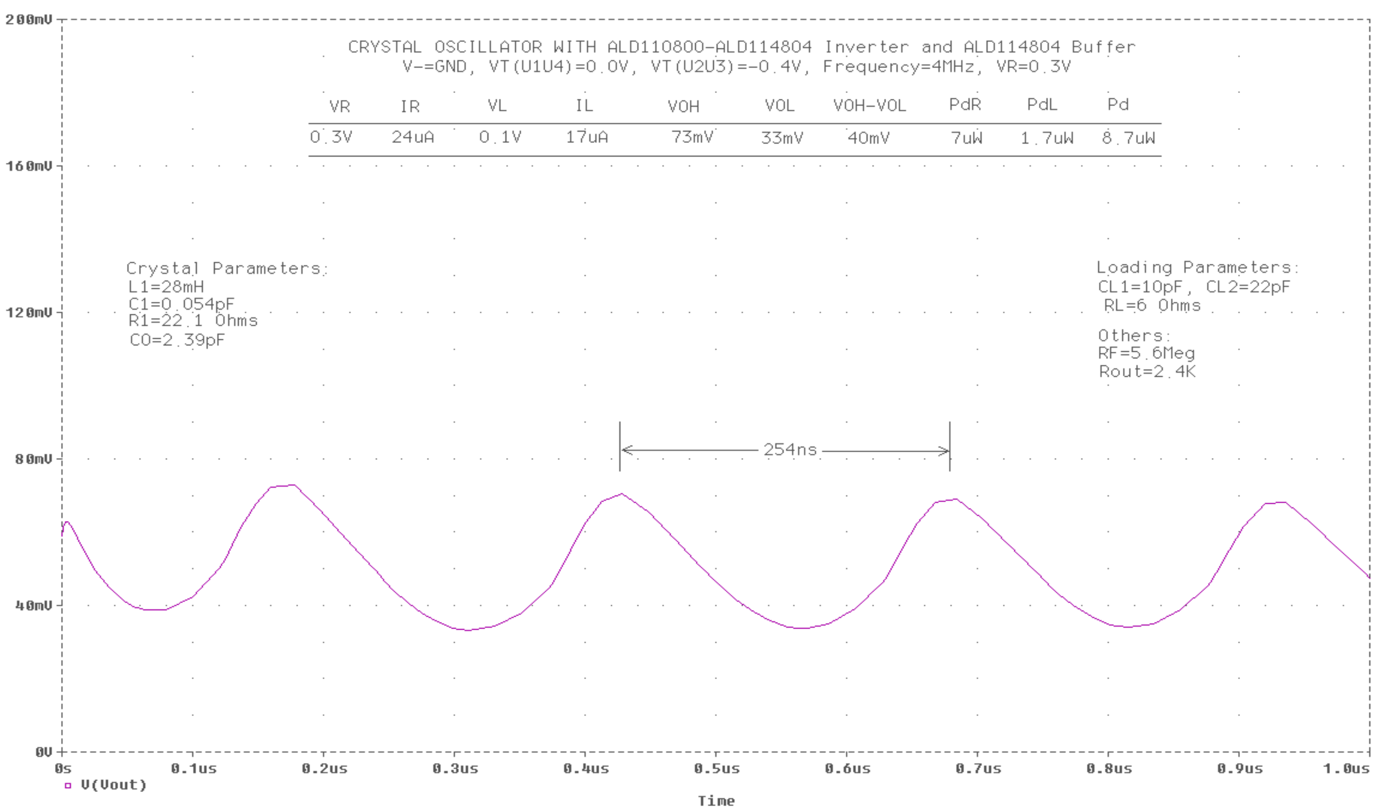

FIGURE 11: Crystal Oscillator with Active Load Simulation Result V_R=0.3V, V_L=0.1V.

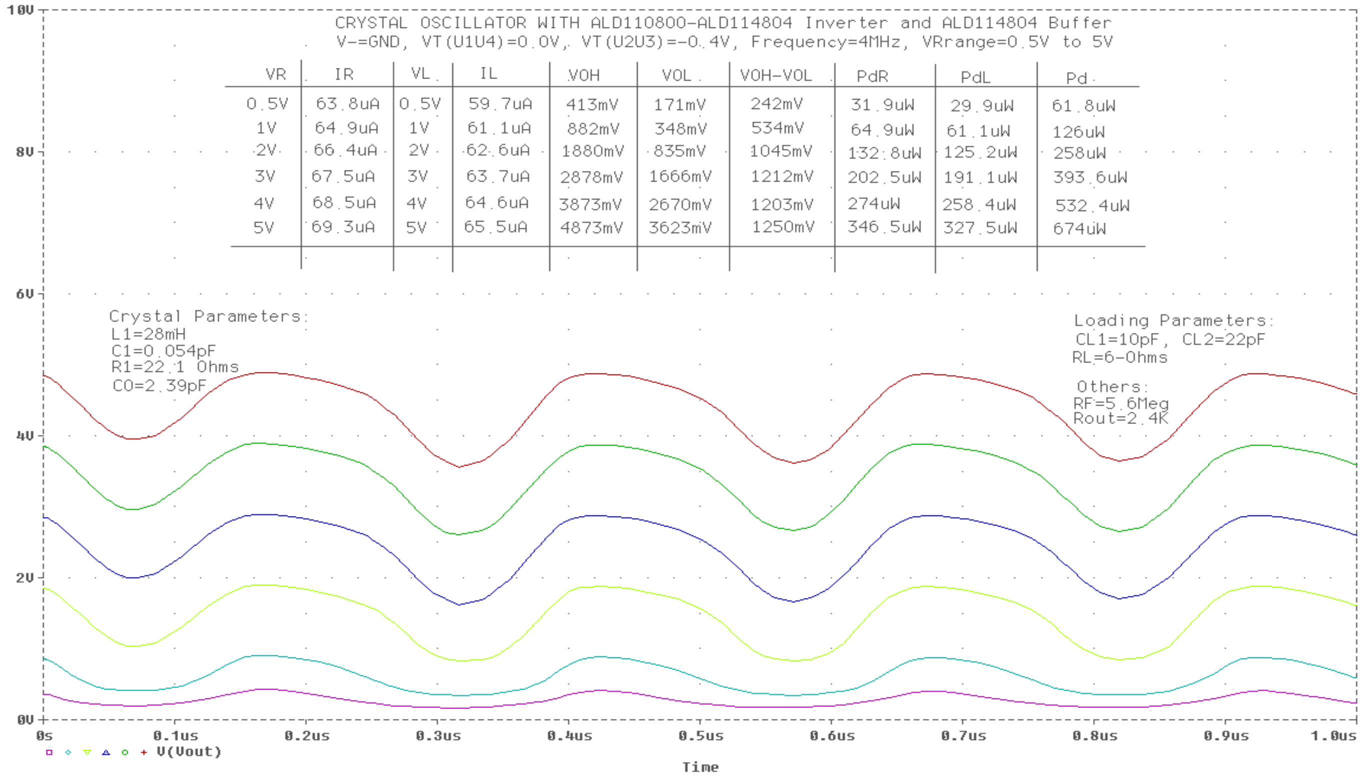

FIGURE 12:Crystal Oscillator with Active Load Simulation Result at various V_R and V_L.

By replacing crystal components shown in Figure 7 and 10 with an inductor L_1, a LC Feedback oscillator circuit in Figure 13 was created and simulated for minimum power dissipation configurations.

The oscillation component parameters to produce the oscillating frequency of 1MHz are L_1=1mH, CL_1=10pF and CL_2=39pF. The other component that needed to be replaced was the passive load resistor R_D=20kΩ.

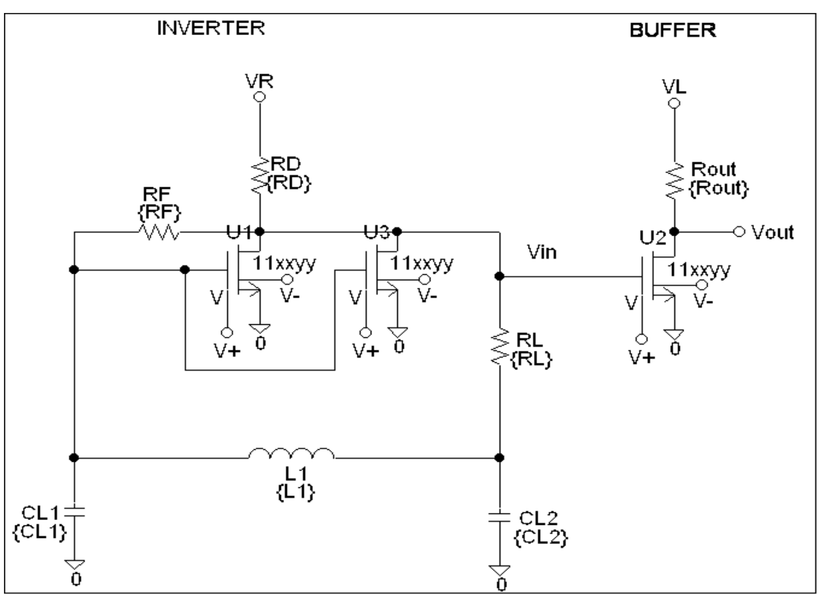

FIGURE 13: LC Feedback Oscillator Simulation Circuit with Passive Load Inverters.

Figure 14 and 15 shows that the circuit is oscillating at 1MHz with V_R and V_L ranging from 0.17V to 5V and 0.1V to 5V, respectively. The simulation result indicated a match to the experimental result.

Another oscillator technique to further minimize power dissipation by implementing RC combinations was also simulated with successful results. Both ALD110802 (quad 0.2V threshold) and ALD110804 (quad 0.4V threshold) were used in the simulations. The RC

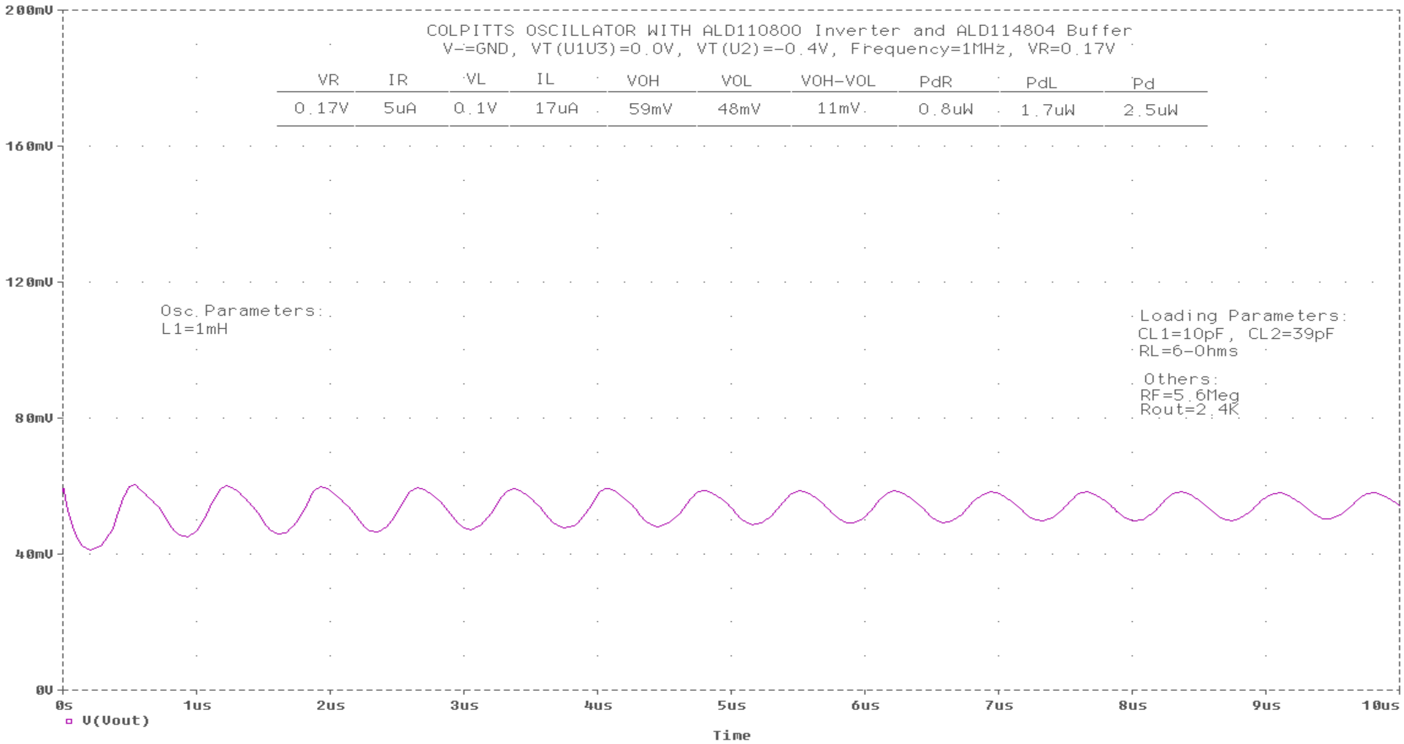

FIGURE 14: LC Feedback Oscillator with Passive Load Simulation Result V_R=0.17V, V_L=0.1V.

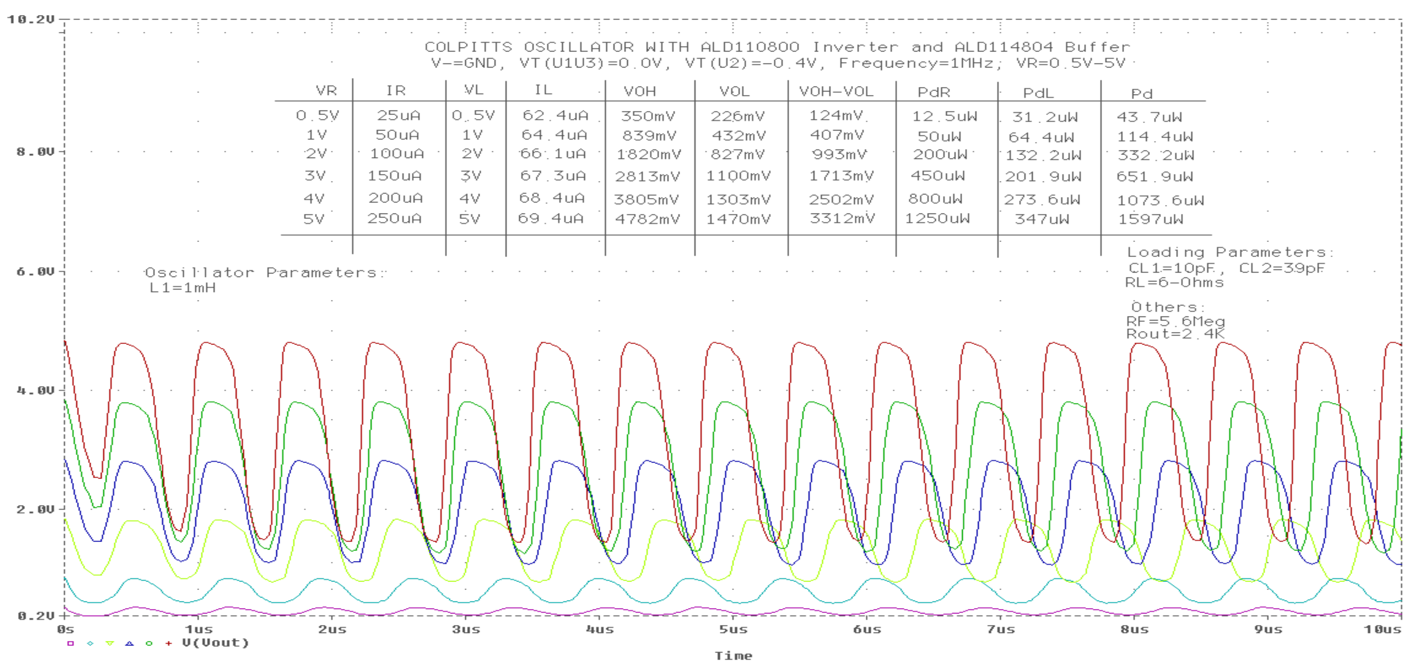

FIGURE 15:LC Feedback Oscillator with Passive Load Simulation Result at various V_R and V_L.

oscillator circuit is shown in Figure 16. The oscillation frequency is determined by the inverse of the R_5C_L product. In this figure ALD110802 with R_5=1.76MΩ and C_L=10nF produced 10Hz oscillating frequency at V^+=0.16V with total power of 36nW.

The oscillator portion dissipated power of 33nW, while the inverter itself dissipated power of 3nW. This result is illustrated in Figure 17.

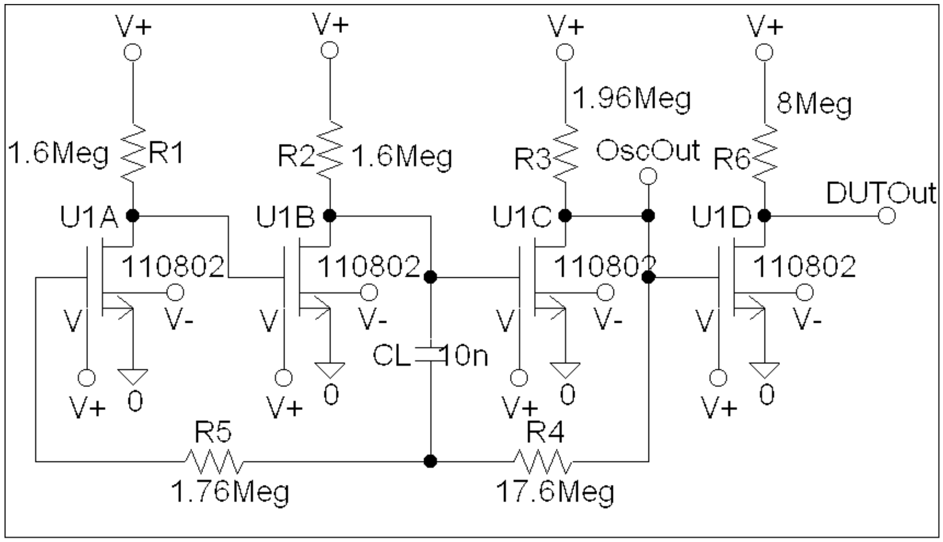

FIGURE 16: RC Oscillator Simulation Circuit using ALD110802 with Passive Loads.

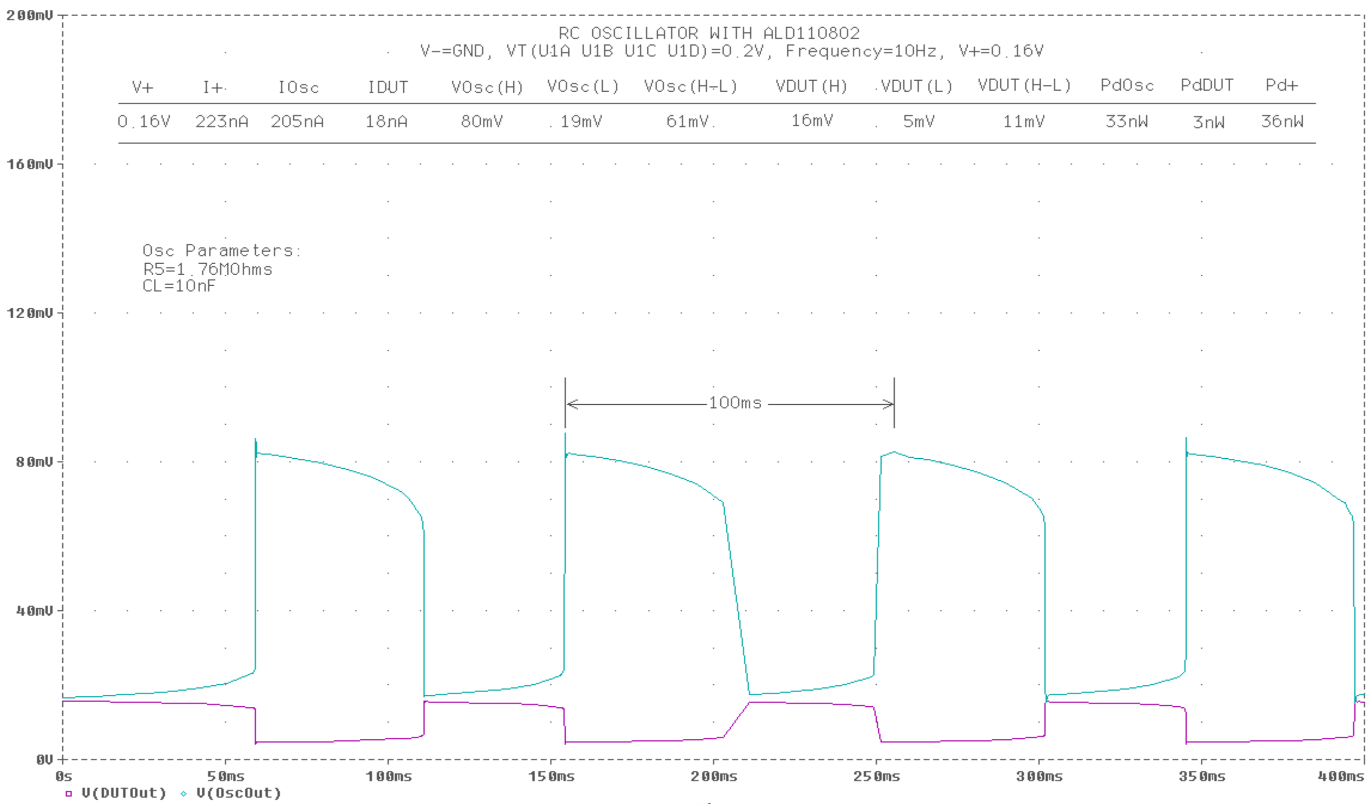

FIGURE 17: RC Oscillator using ALD110802 with Passive Loads Simulation Result V^+=0.16V.

Further attempt was carried out to further minimize power by replacing ALD110802 (U1A, U1B, U1C, and U1D) with ALD110804 and changing the value of R_5 to 4MΩ and C_L to 0.1nF shown in Figure 18.

The circuit produced 40Hz oscillating frequency at V^+=0.14V with total power of 1.2nW. The oscillator portion dissipated power of 1nW, while the inverter itself dissipated power of 0.24nW. This result is illustrated in Figure 19.

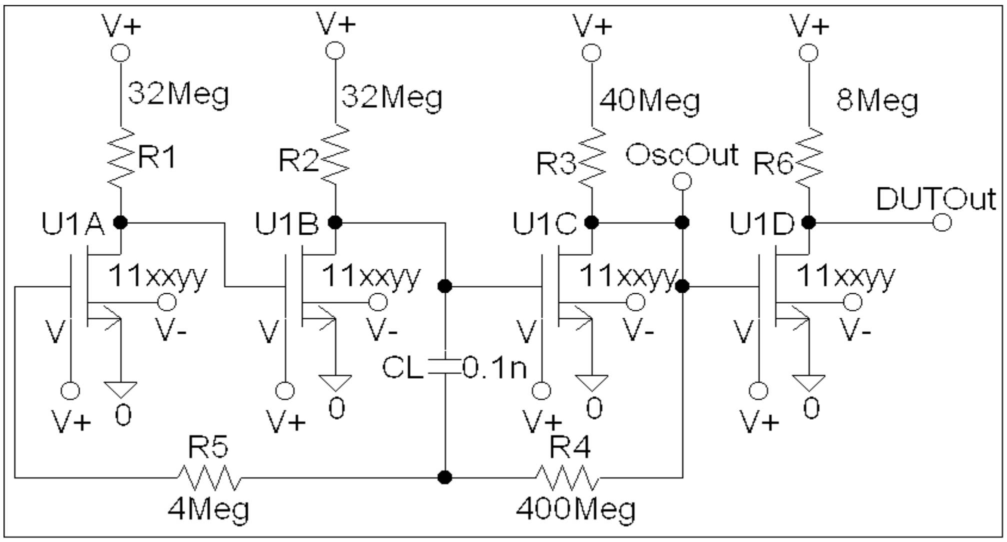

FIGURE 18: RC Oscillator Simulation Circuit using ALD110804 with Passive Loads.

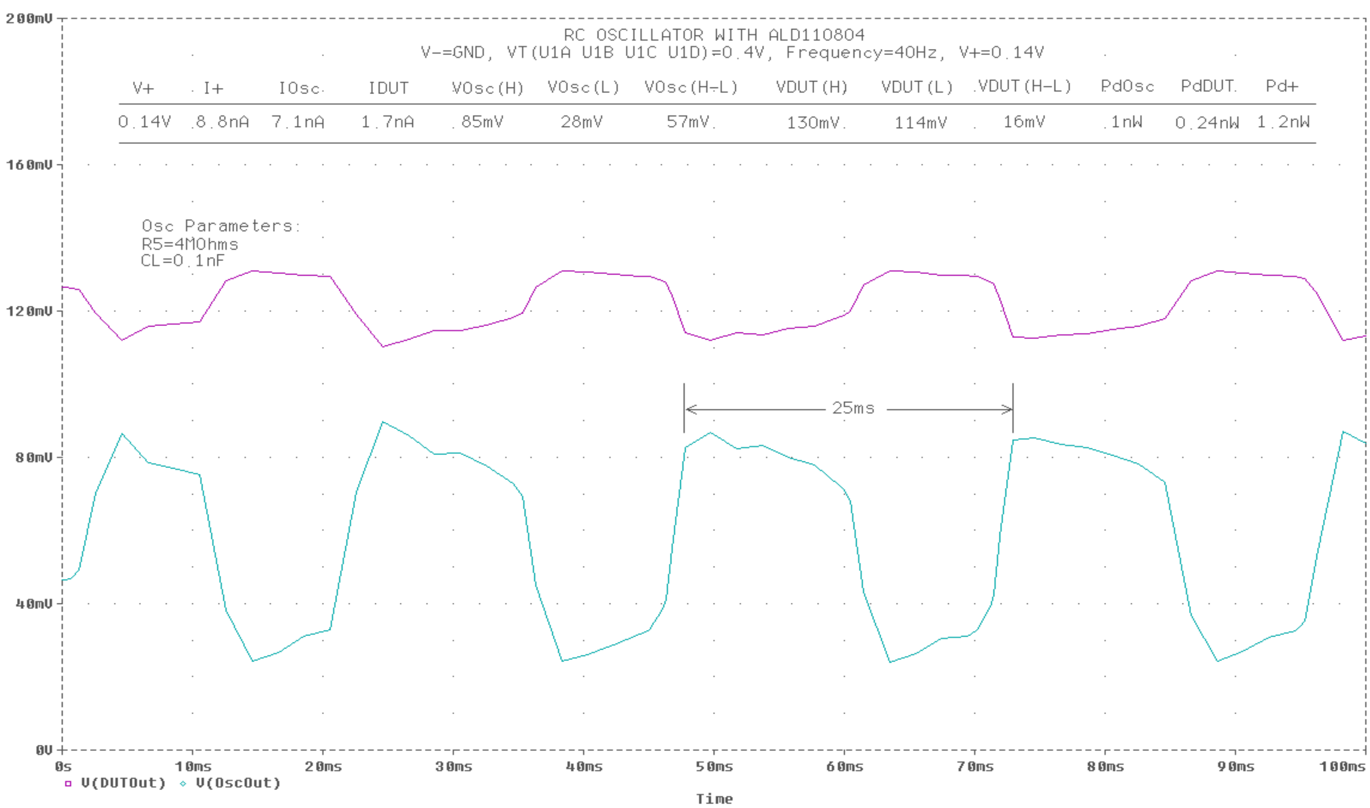

FIGURE 19: RC Oscillator using ALD110804 with Passive Loads Simulation Result V^+=0.14V.

VI. CONCLUSIONS

A proof of concept design for an ultra low power crystal and LC Feedback oscillator networks in parallel resonant mode was simulated and tested with results showing the feasibility of obtaining substantial low power dissipation.

Both experiment and simulation demonstrated that the use of LC Feedback technique produced better result in term of minimum power dissipation compared to the use of Crystal component for oscillation circuit.

However, the use of crystal component showed a broader range of oscillating frequency could be achieved.

The use of passive loads indicated that lower power dissipation was achieved compare to the use of active load inverter configuration.

RC oscillator was also proven by simulation results to produce nano-watts power dissipation at slower oscillating frequencies.

The minimum power was achieved at optimum frequencies of 1MHz and 4MHz at 0.17V and 0.3V operating voltages with power dissipation of 7μW and 0.8μW for LC and Crystal oscillator, respectively.

The lowest power at optimum frequency 40Hz was in the order of 1nW at 0.14V operating voltage achieved by the RC oscillator network.

Further work is needed to investigate noise figure and phase noise performance.

GLOSSARY

Frequency –The rate at which a periodic phenomenon occurs over time.

Quality Factor (Q) –The ratio of energy stored in a reactive component (such as a capacitor or inductor) to the energy dissipated. Equal to the reactance divided by the resistance.

Stability –Statistical estimate of the [frequency] fluctuations of a signal over a given time interval.