Laboratory #11

Signal Generator and Waveform-Shaping Circuits

I. Objectives

1. Familiarize with the waveforms generation using a combination of multivibrators.
2. Familiarize with the square-waveform oscillator.

II. Components and Instruments

1. Components
   (1) CD4007 ×1
   (2) LM324 ×1
   (3) Resistor: 10kΩ ×1, 100kΩ ×4, 1MΩ ×2
   (4) Capacitor: 330pF ×2, 0.01μF ×1, 10μF ×1, 100μF ×1
   (5) Crystal: DT26×1
2. Instruments
   (1) DC power supply (Keysight E36311A)
   (2) Oscilloscope (Agilent MSOX 2014A)

III. Reading

1. Section 12-4, and 12-5 of "Microelectronics Circuits 6th edition, Sedra/Smith".
2. Experiment 29 of "Laboratory Explorations for Microelectronic Circuits 4th edition, Kenneth C. Smith".

IV. Preparation

1. Introduction

   The target of this experiment is to familiarize you with some quite general ideas concerning the generation of waveforms using a combination of fast-acting positive feedback and delayed negative feedback, ideas which are captured in the generic term, multivibrators. For reasons both of convenience and importance in practice, we will explore circuits which employ OPAMPs.

2. The Schmitt Trigger, a Bistable Multivibrator

   Fig. 11.1 shows the positive-feedback Schmitt-Trigger Bistable Multivibrator. It is operated typically with either of node A or D as input, while the other is connected to a reference voltage. Because of the positive feedback, the output voltage (C) is stable at one of two limiting values (a high one, L^+, and a low one, L^-) depending on the choice of power-supplies, V^+ and V^-, and the amplifier saturation characteristics.

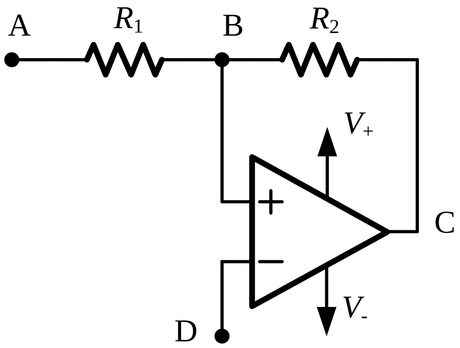


Fig. 11.1 Schmitt-trigger bistable multivibrator

Inverting Operation

Fig. 11.2 shows the bistable circuit with a voltage v_I applied to the inverting input.

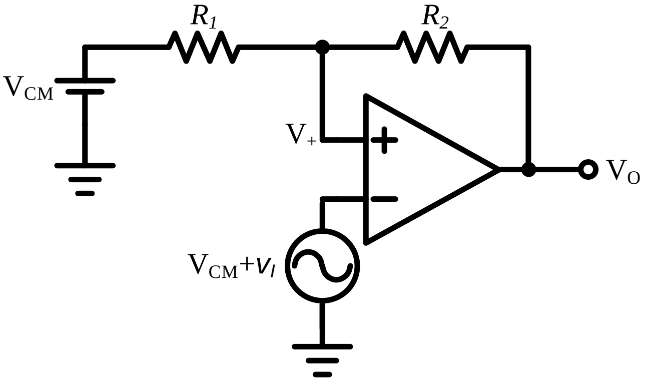


Fig. 11.2 The bistable circuit with a voltage v_I applied to the inverting input.

The transfer characteristics, v_o-v_I, of the circuit in Fig. 11.2 is shown in Fig. 11.3, where L_+ and L_- are the logic high and logic low saturation voltages of op amp.

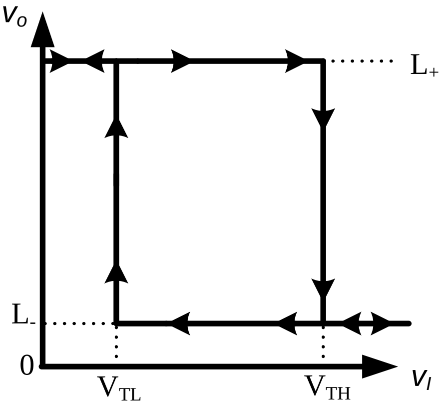


Fig. 11.3 The transfer characteristics of the circuit in Fig. 11.2

We can observe that the characteristic that of a comparator with threshold voltages denoted V_{TH} and V_{TL}, where $V_{TH} =(1-\beta)V_{CM}+\beta L_+$ and $V_{TL} =(1-\beta)V_{CM}+\beta L_-$. The circuit changes state at different values of v_I, depending on whether v_I is increasing or decreasing. Thus the circuit is said to exhibit *hysteresis*; the width of the hysteresis is the difference between the high threshold V_{TH} and the low threshold V_{TL}. Also note that the bistable circuit is in effect a comparator with hysteresis.

3. Square-Wave Oscillator, an Astable Multivibrator

In general, one approach to create an oscillator is to use a positive-feedback-based bistable element with delayed negative feedback. From a linear-circuits point of view, the idea is that of a negative feedback loop which is unstable because of the infinite loop gain which the positive-feedback element can provide. From a more digital point of view, the idea is to derive a signal from the output of the bistable which, fed back to the input, reverses the original state.

A square waveform can be generated by arranging for a bistable multivibrator to switch states periodically. This can be done by connecting the bistable multivibrator with an RC circuit in a feedback loop, as shown in Fig. 11.4. This circuit has no stable states and thus is appropriately named an astable multivibrator.

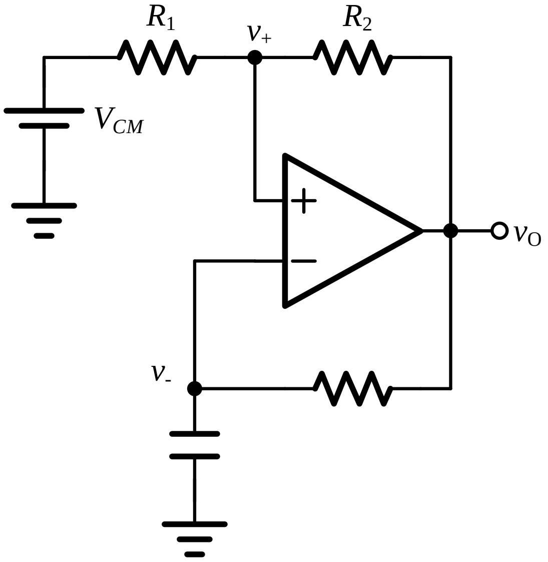


Fig. 11.4 A square-wave oscillator, or an astable multivibrator

The astable circuit oscillates and produces a square waveform at the output of the op amp. This waveform, and the waveforms at the two input terminals of the op amp, are depicted in Fig. 11.5.

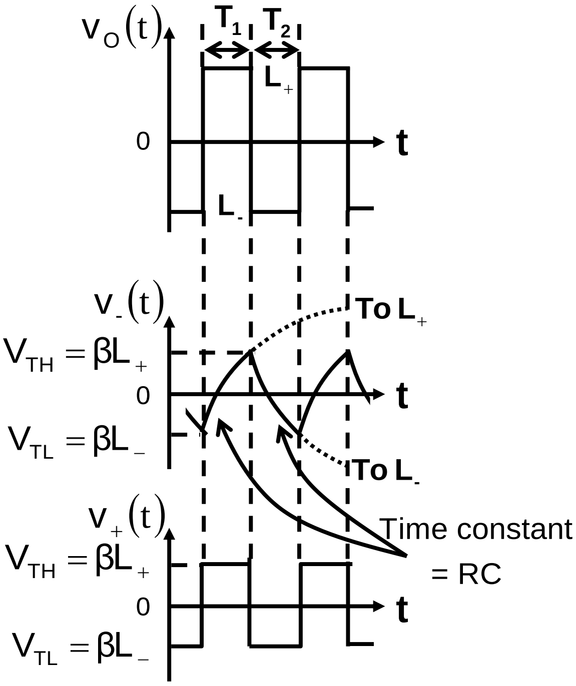


Fig. 11.5 Waveform at various nodes of the circuit in Fig. 11.4

The period T of the square wave can be found as follows:

During T1:

$$v_- = L_+ - \left(L_+ - \beta L_-\right)e^{-t/\tau} \text{ where} \tau = RC, \beta = \frac{R_1}{R_1 + R_2}$$

$$if\ v_- = \beta L_+ \text{ at } \mathrm{t} = \mathrm{T}_1 \Rightarrow \mathrm{T}_1 = \tau \ln \frac{1 - \beta\left(L_-/L_+\right)}{1 - \beta}$$

During T2:

$$v_- = L_- - \left(L_- - \beta L_+\right)e^{-t/\tau}$$

$$if\ v_- = \beta L_{--} \text{ at } \mathrm{t} = \mathrm{T}_2 \Rightarrow \mathrm{T}_2 = \tau \ln \frac{1 - \beta\left(L_+/L_-\right)}{1 - \beta}$$

$$\mathrm{T} = \mathrm{T}_1 + \mathrm{T}_2 = 2\tau \ln \frac{1 + \beta}{1 - \beta}$$

The other approach to realize square-wave oscillator is using inverters as shown in Fig. 11.6. The transient behavior and waveforms at nodes V_{o1}, V_{o2}, V_x, and V_c are depicted in Fig. 11.7.

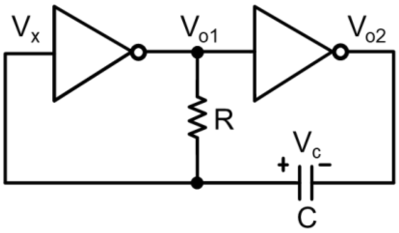


Fig. 11.6 Astable multivibrator implemented by inverters

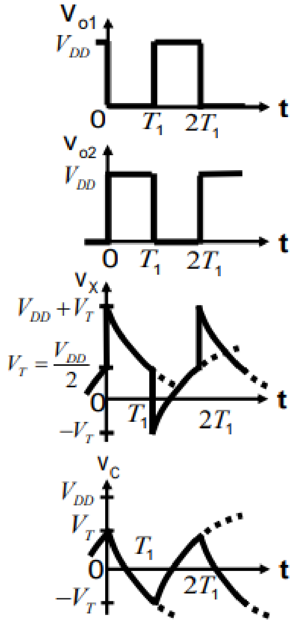


Fig. 11.7 Waveform at various nodes of the circuit in Fig. 11.6

The oscillation frequency f_o of the square wave can be found as follows:

During $0 < t < T_1$:

v_{o1}: $V_{DD} \rightarrow 0$ when t=0, v_{o2}: $0 \rightarrow V_{DD}$ when t=0

$$v_x = (V_{DD} + V_T)e^{-\frac{t}{RC}}$$

$$v_c = v_x - v_{o2} = -V_{DD} + (V_{DD} + V_T)e^{-\frac{t}{RC}}$$

During $T_1 < t < (T_1+T_2)$:

v_{o1}: $0 \rightarrow V_{DD}$ when t=T_1, v_{o2}: $V_{DD} \rightarrow 0$ when t=T_1

$$v_x = V_{DD} - (V_{DD} + V_T)e^{-\frac{(t-T_1)}{RC}}$$

$$v_c = v_x - v_{o2} = V_{DD} - (V_{DD} + V_T)e^{-\frac{(t-T_1)}{RC}}$$

Oscillation frequency:

$$v_x(T_1) = V_T \rightarrow T_1 = RC\ ln\frac{V_{DD}+V_T}{V_T}$$

If $V_T = \frac{V_{DD}}{2}$, then $T_1 = T_2 = RC\,ln\,3$

$$f_o = \frac{1}{2RC\,ln\,3} = \frac{0.455}{RC}$$

4. Crystal oscillator

An approach to implement oscillator is to utilize crystal, which features high quality factor with the equivalent model in Fig. 11.8. A crystal oscillator is an oscillator that uses the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with constant frequency, regardless aging and temperature ideally. Hence, application of crystal oscillator is to provide stable clock signal for digital circuits, such as microprocessor.

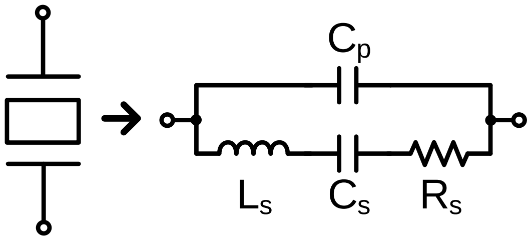


Fig. 11.8 Circuit model of crystal

After neglecting the resistance R_s, the corresponding crystal reactance can be plotted as shown in Fig. 11.9. Because the behavior of crystal is similar to an LC resonator ($\omega = 1/\sqrt{LC}$), there will be two oscillation frequency (ω_s and ω_p) due to the two capacitors in crystal (C_s and C_p). As a result, the oscillation frequency is between ω_s and ω_p labeled in Fig. 11.9.

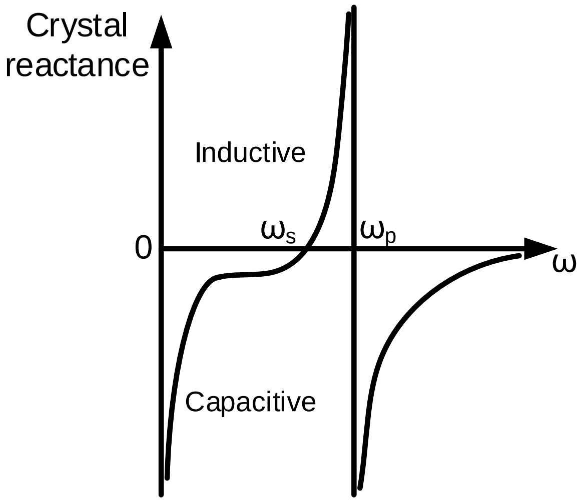
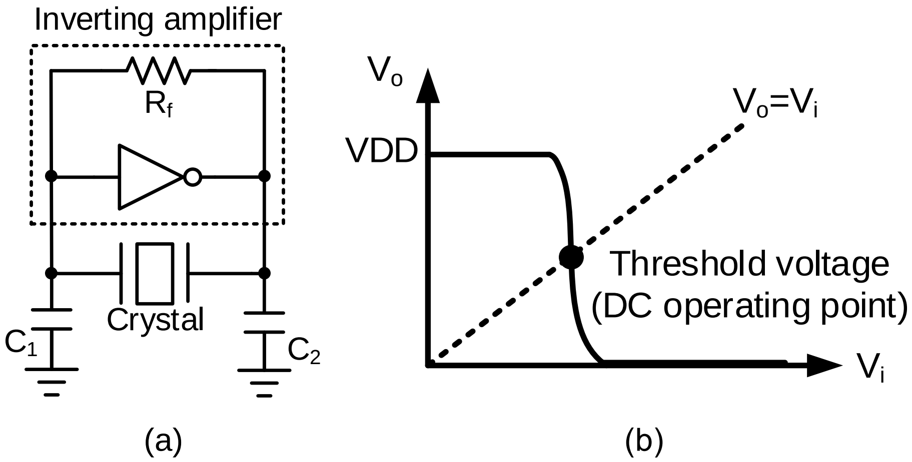


Fig. 11.9 Crystal reactance versus frequency

A popular configuration called Pierce crystal oscillator combines crystal, inverter and feedback resistor (R_f) as shown in Fig. 11.10 (a). Fig. 11.10 (b) illustrates the DC operation point of inverter that serves as an amplifier. The function of R_f is to ensure that the inverter is operated near the threshold voltage. The oscillation occurs due to the phase difference at the two terminals of the crystal.



(a) (b)

Fig. 11.10 (a) Pierce crystal oscillator (b) DC operation point of the inverter with feedback resistance

V. Exploration

1. Measure the characteristics of Schmitt trigger
   (1) Complete the wiring of inverting operation as the figure below.

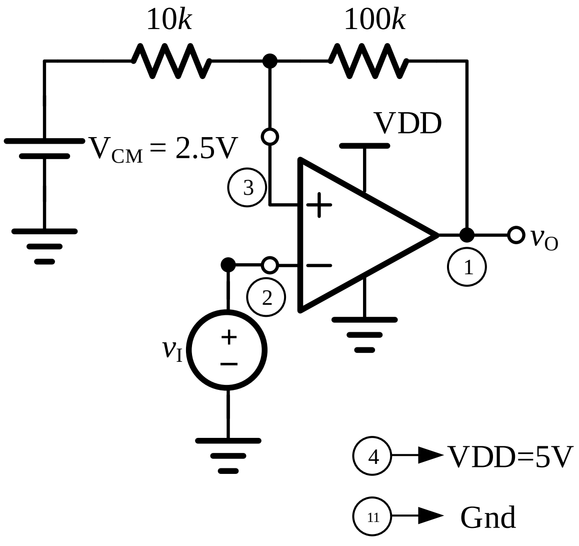


Fig. 11.11 Schmitt trigger with inverting operation

   (2) Apply a 5 Vpp sine wave with 1kHz at v_I.
   (3) Measure the waveform of v_O versus v_I by oscilloscope.

2. Measure the characteristics of square-wave oscillator
   (1) Complete the wiring of square-wave oscillator as the figure below.

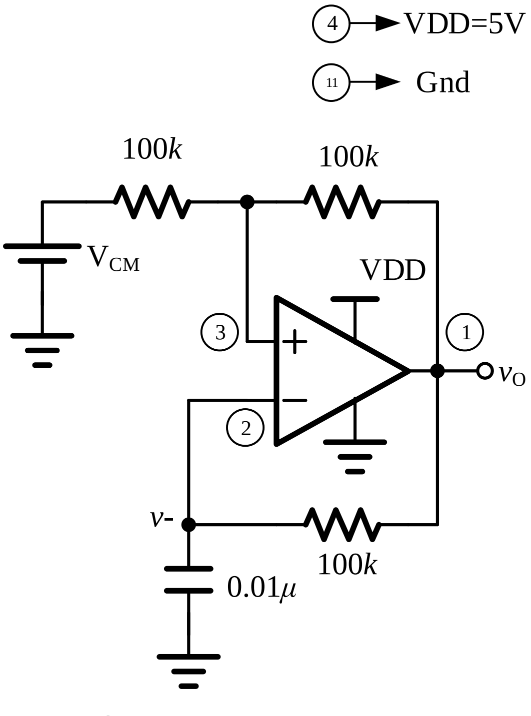


Fig. 11.12 Square-wave oscillator with opamp

(2) Measure the waveform of v_- versus v_O by oscilloscope.

(3) Complete the wiring of square-wave oscillator with R=10kΩ and C=0.01μF as the figure below. Then, measure the waveform of V_{o2} by oscilloscope.

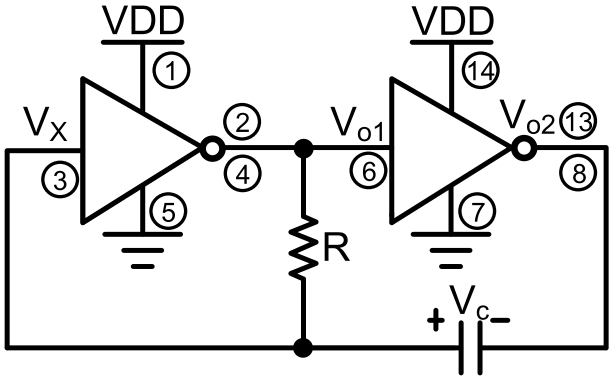


Fig. 11.13 Square-wave oscillator with inverters

(4) Change R into 100kΩ and observe the waveform. Please explain the difference of the results.

3. Measure the characteristics of Pierce crystal oscillator

(1) Complete the wiring of square-wave oscillator as the figure

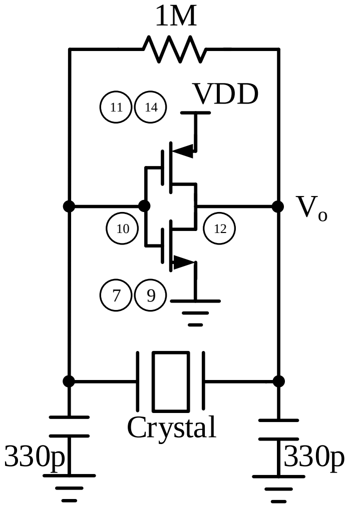


Fig. 11.14 Pierce crystal oscillator

(2) Measure the waveform of V_o

VI. Reference

1. “DT26” datasheet.

(https://datasheetspdf.com/pdf-file/958525/YIC/DT26/1)

Laboratory #11 Pre-lab

Class:

Name: Student ID:

1. Explore the characteristics of Schmitt trigger.
   (1) Use PSpice to do the transient analysis on the circuit below.
      a. Apply a 5 Vpp sine wave with 1kHz at terminal V_3.
      b. Show the waveforms of V_o versus V_i.

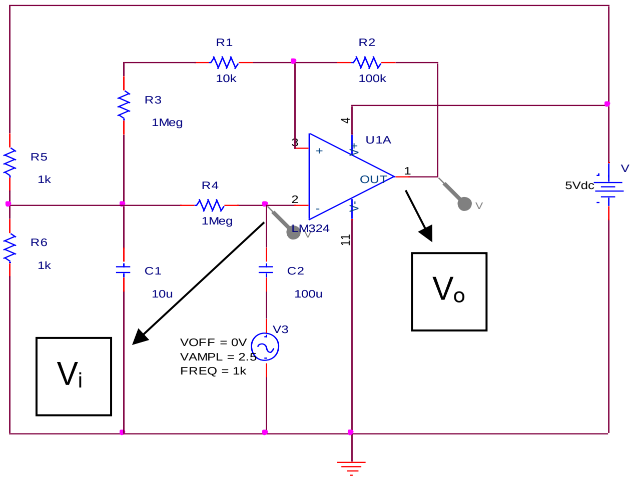


Fig. 11.15 Schematic of Schmitt trigger with inverting operation

2. Explore the characteristics of square-waveform oscillator
   (1) Use PSpice to do the transient analysis on the circuit below, and show the waveform of V_- versus V_o.

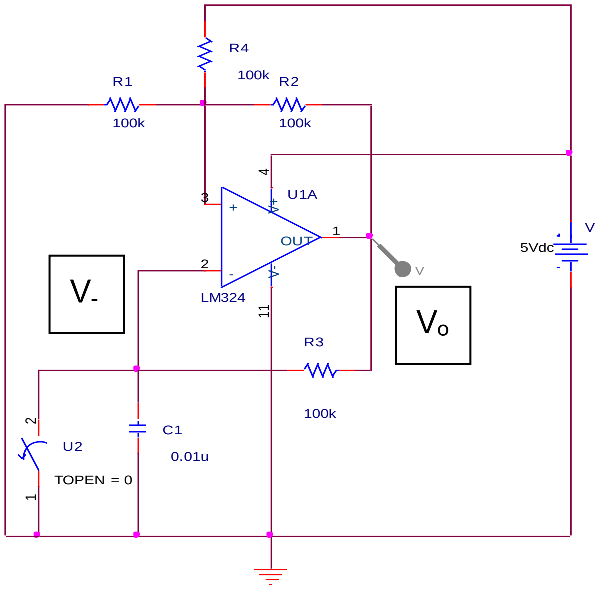


Fig. 11.16 Schematic of square-wave oscillator with opamp

(2) Remove the component U2, and do the transient analysis again. Please describe the difference between the output waveforms with and without U2.

(3) Use PSpice to do the transient analysis (transient time=10ms) on the circuit below, and show the waveform of V_{o2}

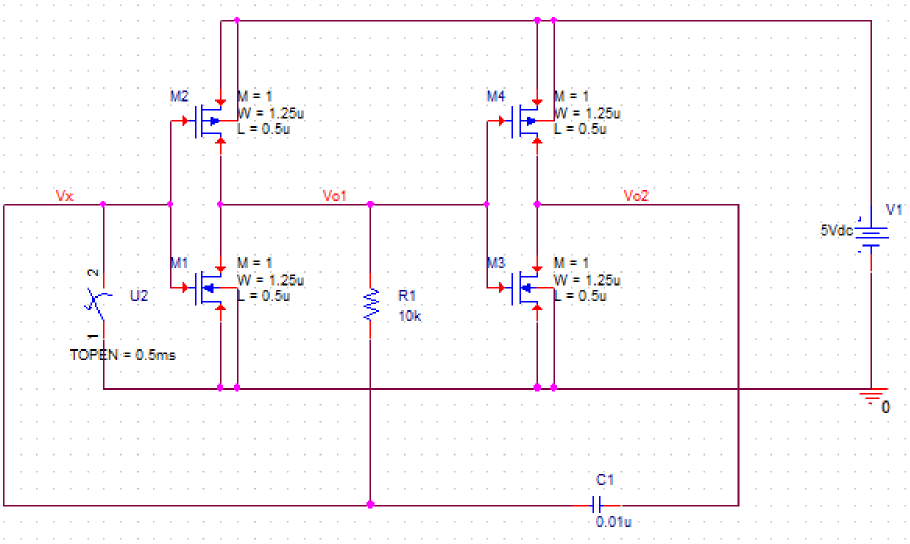


Fig. 11.17 Schematic of square-wave oscillator with inverter

(4) Change R1 from 10kΩ to 100kΩ and explain the difference of V_{o2} waveform.

3. Datasheet reading

Download the datasheet of DT26 (the website is listed in Ref [1]), then read and answer the following questions:

(1) List several specifications related to stability and explain reasons.

Laboratory #11 Report

Class:
Name: Student ID:

1. Exploration 1

   The waveform of V_i and V_o of inverting operation.

2. Exploration 2

   (1) The waveform of square-waveform oscillator.

   (2) The waveform of V_- and V_o (R=10kΩ)

   (3) The waveform of V_- and V_o (R=100kΩ)

3. Exploration3

   The waveform of Pierce crystal oscillator

4. Problem 1

   How to decrease the frequency of square-wave oscillator?

5. Problem 2

   Describe the main function of the feedback resistor in Pierce crystal oscillator

6. Conclusion