OSCILLATORS

By Edgar Sánchez-Sinencio

- Oscillator is a system that is able to produce independently bounded and permanent oscillations of at least one of the variables that describe it.

- Types of Oscillators:

- Periodic. This oscillator has an spectrum consisting of a fundamental frequency plus and infinite number of harmonics.
- Pseudo-periodic. The spectrum consists of more than one frequencies not related to each other.
- Chaotic. The spectrum of the response is flat. That is, it contains frequency components of all frequencies.

For sinusoidal oscillators a figure of merit is the distortion which is characterized by the Total Harmonic Distortion (THD)

- Oscillator Implementations
  - Ring Oscillators
  - LC Tuned
  - Crystal
  - Relaxation
  - Bandpass Filter- based
  - Quadrature
  - YIG Oscillators
  - Dielectric Resonance Oscillators

- An oscillator consists of three main components:

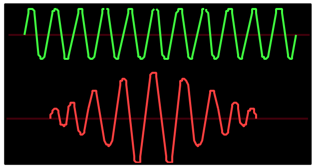
  An active device that acts as an amplifier and

  a feedback network to provide positive feedback in the system, and

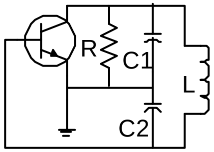
  a non-linear control mechanism to stabilize the amplitude

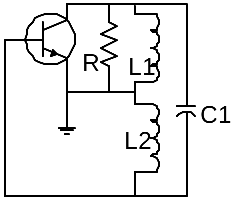
- Design Specs
  - Low Noise
  - High Efficiency
  - Temperature Stability
  - Bandwidth
  - Linear and Wideband Tunability
  - Low Cost
  - Reliability

SINUSOIDAL OSCILLATORS



There are a number of circuit implementations of sinusoidal oscillators. In traditional communication circuits oscillators use one transistor, R's, C's and sometimes inductors. These filters were often used in RF circuits. Current RF oscillators used either ring oscillators or LC tuned oscillators. The last one consists of differential pairs and inductor(s) and capacitor(s)





In these notes we will first focus more on oscillators based on *state-variable structures* (SVS). We will discuss several implementations and the design procedures.

SINUSOIDAL OSCILLATORS

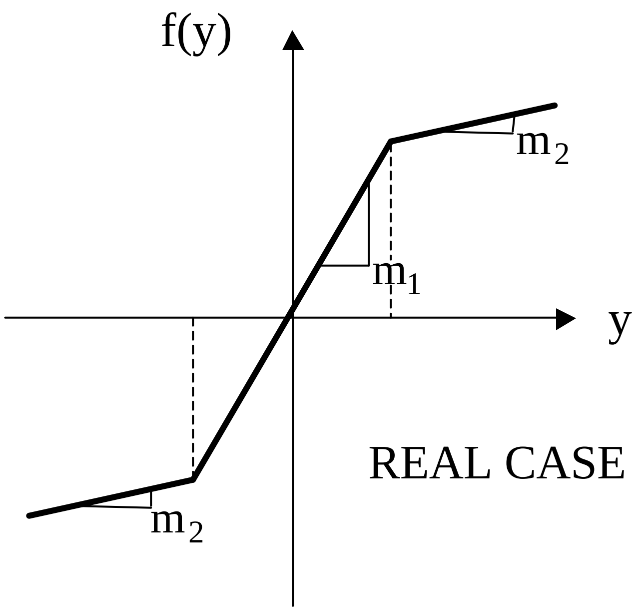
A sinusoidal oscillator is composed of:

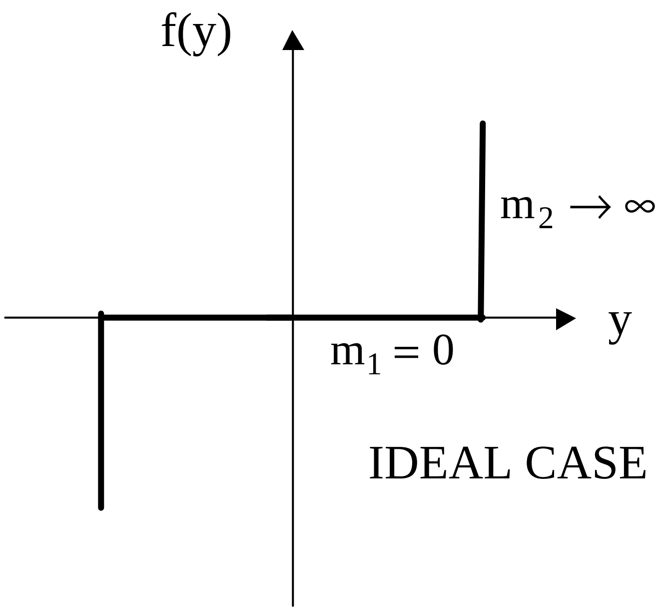
1. A linear circuit that sets the oscillation frequency.
2. An active element that gains power at the frequency of oscillation.
3. A nonlinear mechanism to stabilize the amplitude.

Nonlinear Mechanism

- Static, when its input-output characteristic is fixed in time, as in a hard limiting device or an amplifier nonlinear gain.
- Dynamic, when its characteristic changes in time as in an AGC.

Examples of Nonlinear (static) Characteristics





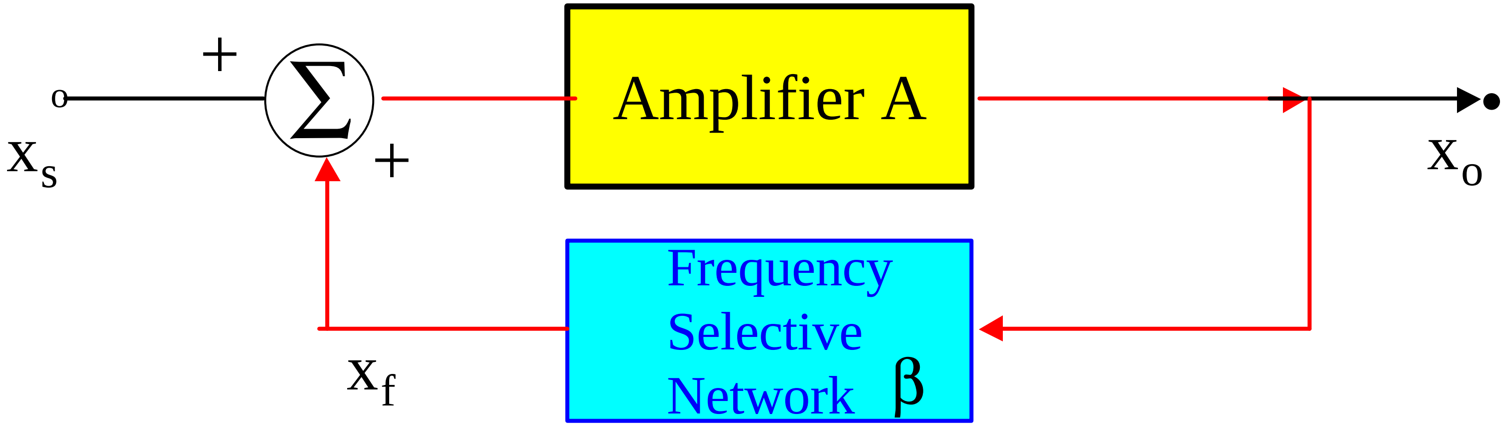
There are a number of topologies yielding sinusoidal oscillators. In our discussion we will first present two popular types in frequency ranges below hundreds of MHz:

i) **Quadrature Oscillator**

ii) **Bandpass - based**

OSCILLATORS

Fundamentals. Linear Aspects: Oscillation conditions.



$$A_f = \frac{x_o}{x_s} = \frac{A}{1-\beta A} = \frac{A(s)}{1-\beta(s)\,A(s)}$$

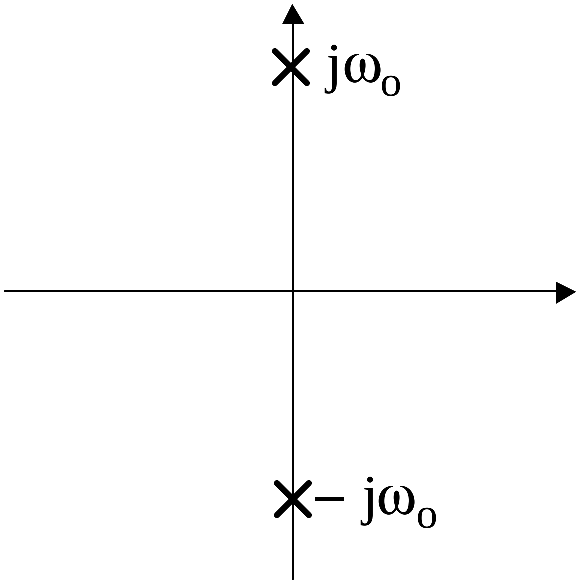
$$D(s) = 1-\beta(s)\,A(s) = 1 - L(s)$$

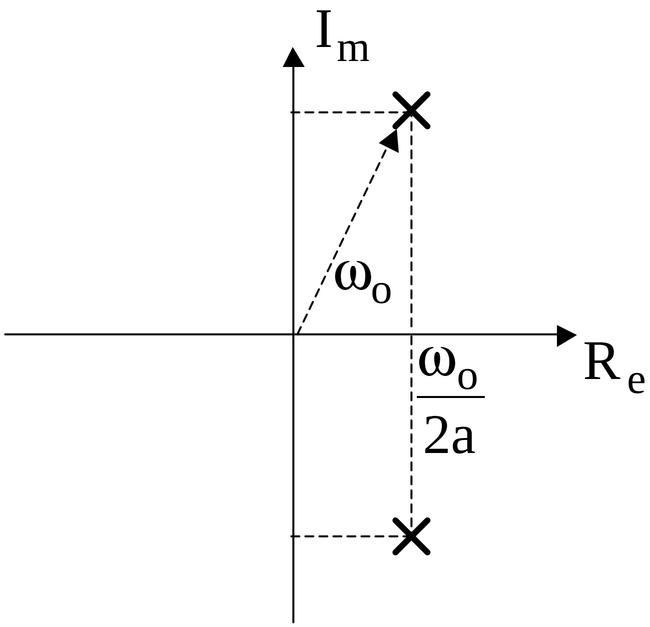
$$L(j\omega_o) \triangleq A(j\omega_o)\,\beta(j\omega_o) = 1$$ **Barkhausen Criteria**

Note that for the circuit to oscillate at one frequency the oscillation criterion should be satisfied at one frequency only; otherwise the resulting waveform will not be a simple sinusoid.

Need of Nonlinear Amplitude Control

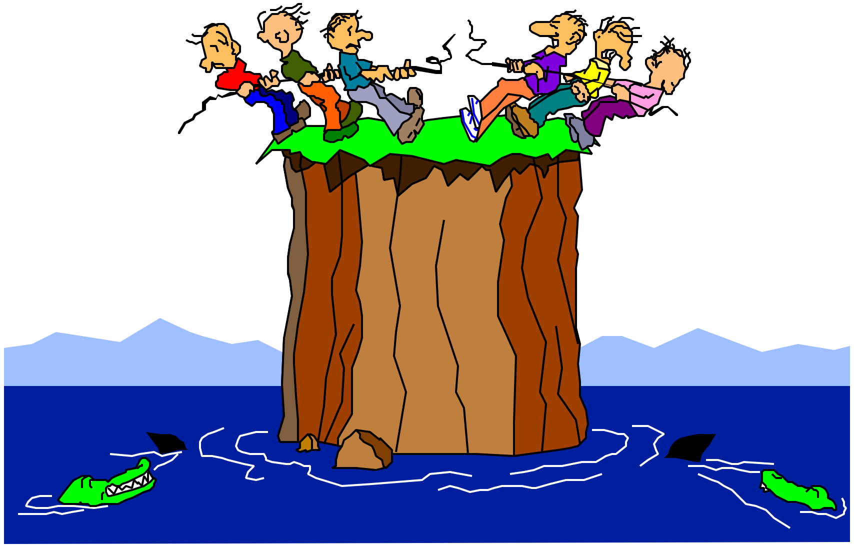
Location of poles





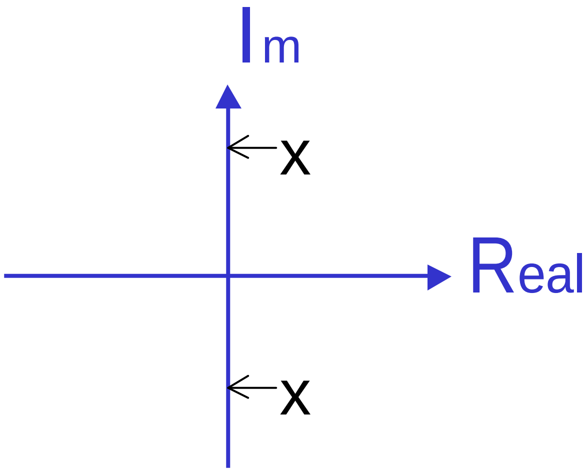
Not practical
why?

Practical.
How do you push
the poles into the
$j\omega$ axis?



In the ideal case this is easy to design, but in the real case there a lot of system parameters that can change the poles due to their physical characteristics.

Therefore, the poles should not lie on the imaginary axis. One should design the poles so that they lie in the right half of the s-plane. This creates positive feedback and guarantees that the circuit will oscillate. How far should we place the poles ?



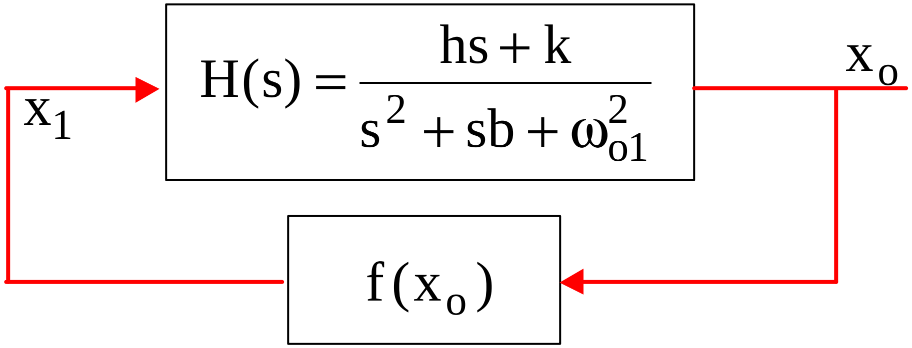
Oscillation Criterion

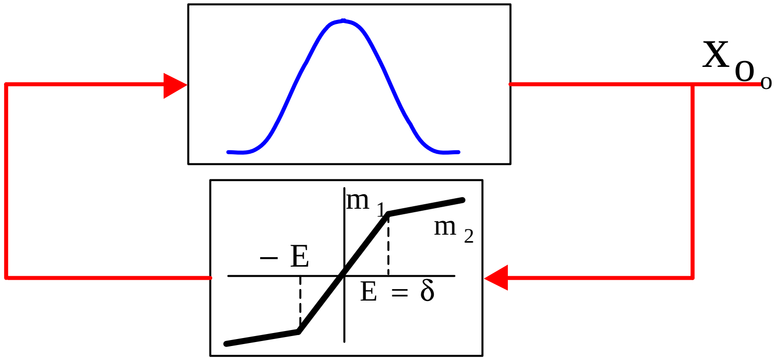
$$L(j\omega_o) \triangleq A(j\omega_o)\,\beta(j\omega_o) = 1$$

At ω_o the phase of $L(j\omega_o)$ should be zero. This is known as the Barkhausen Criterion

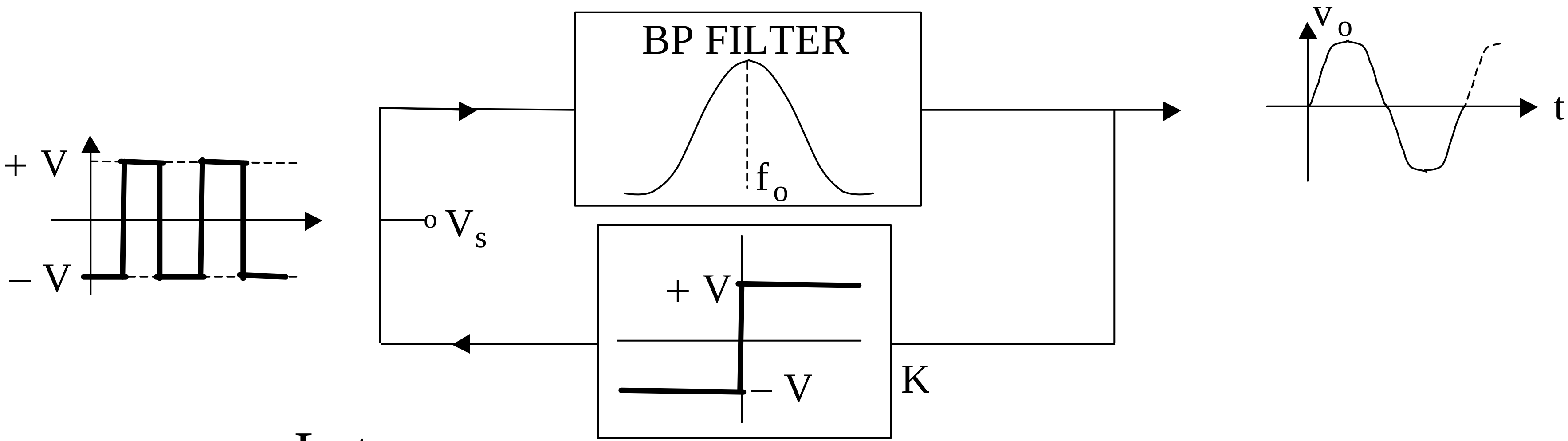
.

Next we describe the <u>BP - based oscillator</u>:





BP Based Oscillator



Let

$$H_{BP}(s) = \frac{K_1 s}{s^2 + \frac{\omega_o}{Q}s + \omega_o^2}$$

$$D(s) = 1 - KH_{BP}(s)$$

$$\left(s^2 + \frac{\omega_o}{Q}s + \omega_o^2\right)D(s) = s^2 + \frac{\omega_o}{Q}s + \omega_o^2 - KK_1S$$

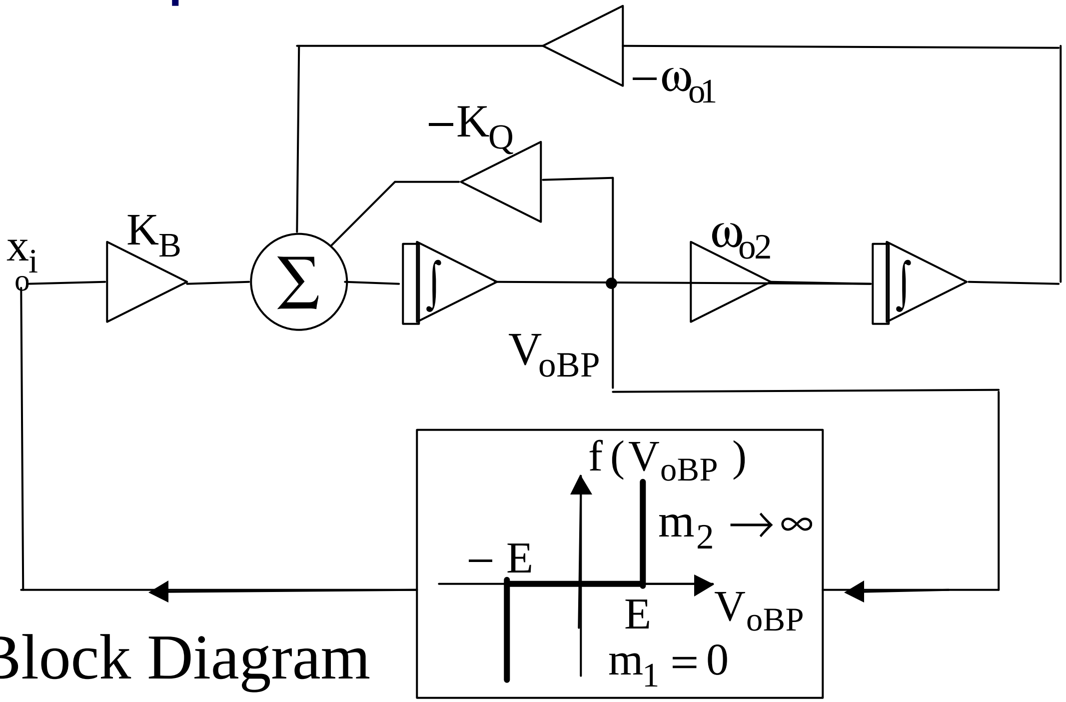
Characteristic Equation

$$s^2 - s\left(KK_1 - \frac{\omega_o}{Q}\right) + \omega_o^2$$

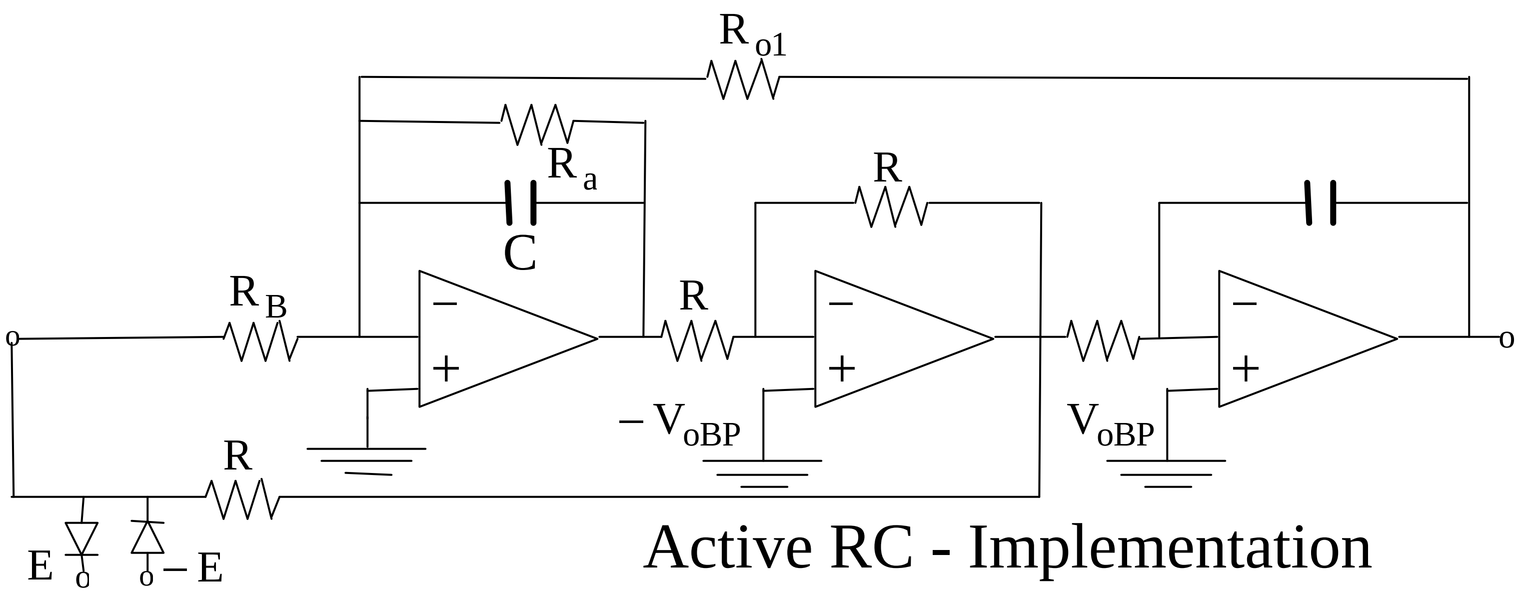
$$KK_1 > \frac{\omega_o}{Q}$$

i.e. positive feedback

A bandpass based Sinusoidal Oscillator

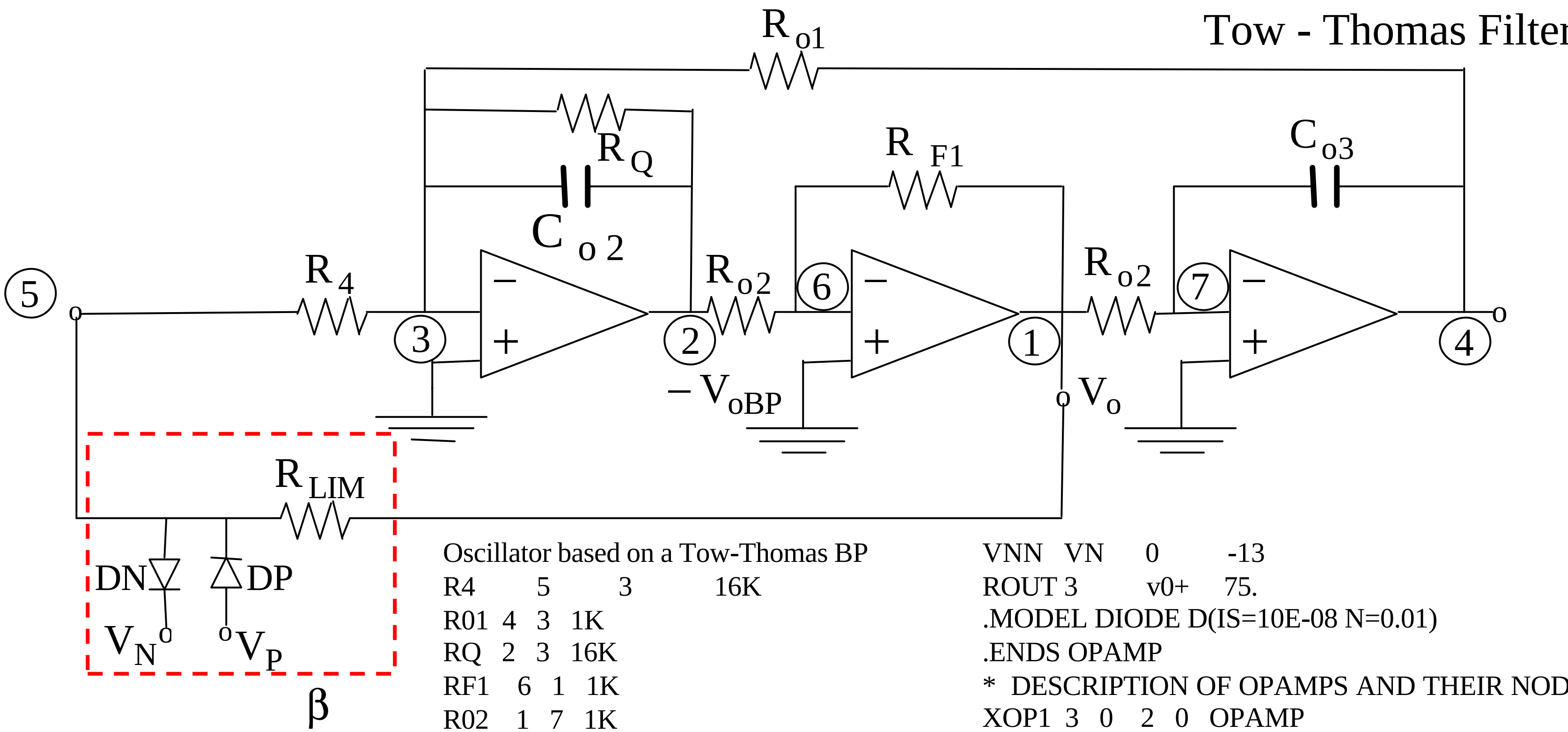


Block Diagram



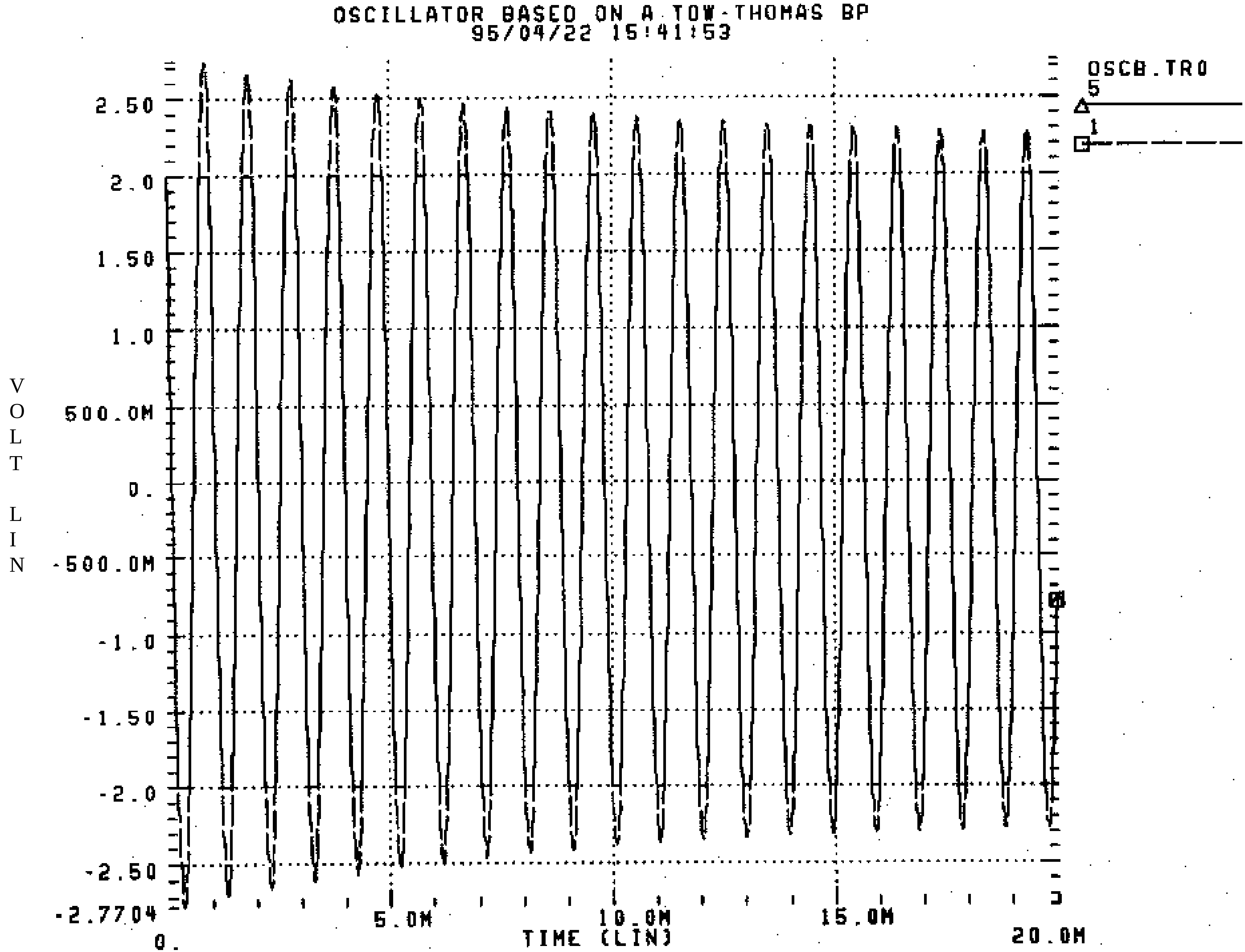
Active RC - Implementation

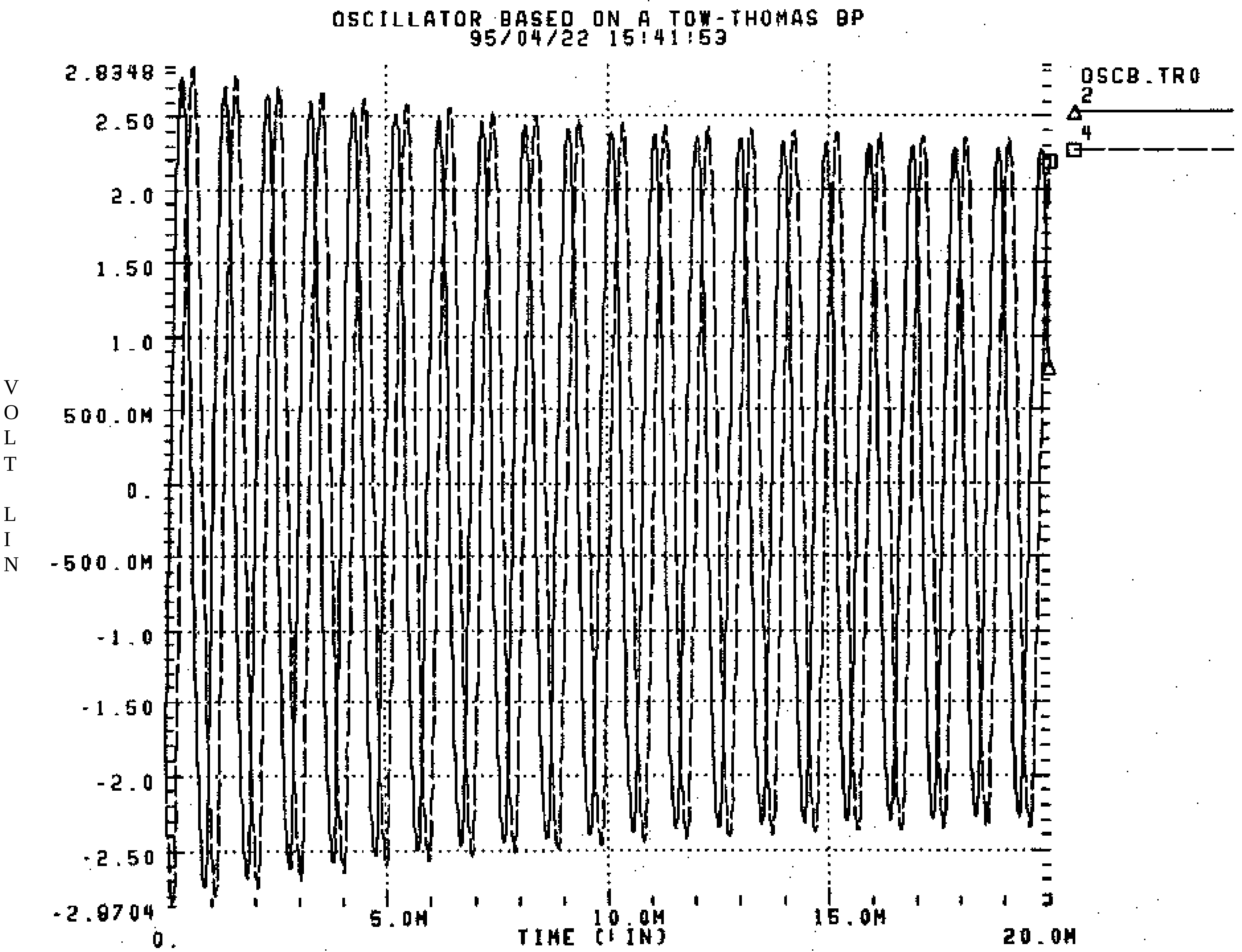
BP Oscillator




```
Oscillator based on a Tow-Thomas BP
R4        5         3          16K
R01  4   3   1K
RQ   2   3   16K
RF1    6   1   1K
R02    1   7   1K
C02    3   2           0.1591549U
R03        2       6             1K
C03    7   4    0.1501549U
.SUBCKT OPAMP vi-   vi+   v0+   v0-
*
*
RIN      vi-      vi+      10E6
EIN      1        0        vi+      vi-      2E05
R3DB  1        2        1K
C3DB  2        0        0.159E-04
EOUT  3        VO-      2        0        1
DP       2        VP       DIODE
DN       VN       2        DIODE
VPP    VP       0        13
```

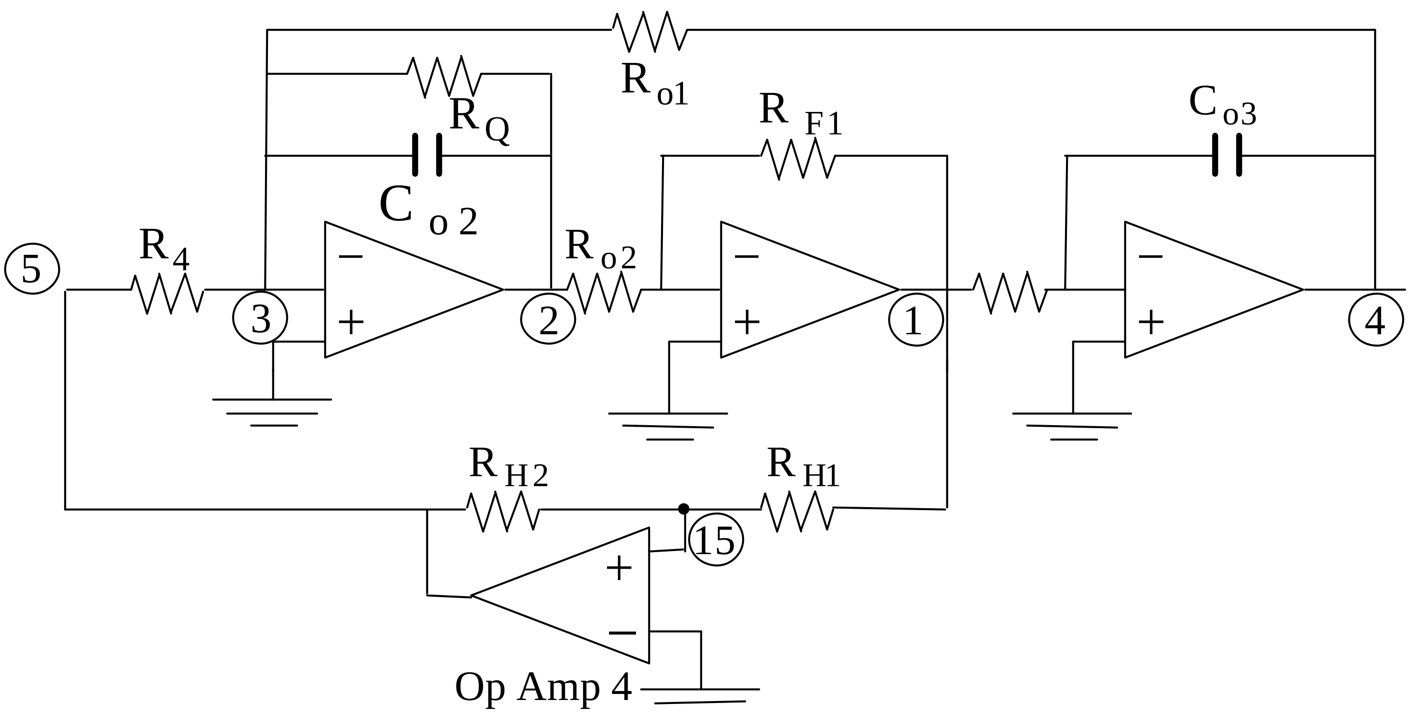
```
VNN   VN      0         -13
ROUT 3         v0+     75.
.MODEL DIODE D(IS=10E-08 N=0.01)
.ENDS OPAMP
*  DESCRIPTION OF OPAMPS AND THEIR NODES
XOP1  3   0    2   0   OPAMP
XOP2     6    0     1     0       OPAMP
XOP3     7    0     4     0       OPAMP
*LIMITER CIRCUIT DESCRIPTION
RLIM        1              5              200
DP            5              VP            DL
DN           VN            5              DL
.MODEL   DL           D (IS=10E-09 N=0.0001)
VNL          VN           0                -2
VPL           VP           0                2
.TRAN       5U           20m           UIC
.FOURIER                  57              V(1)        V(2)        V(4)
.IC  V(1)=2  V(2)=-2  V(4)=-2  V(5)=2
.OPTIONS POST
.END
```

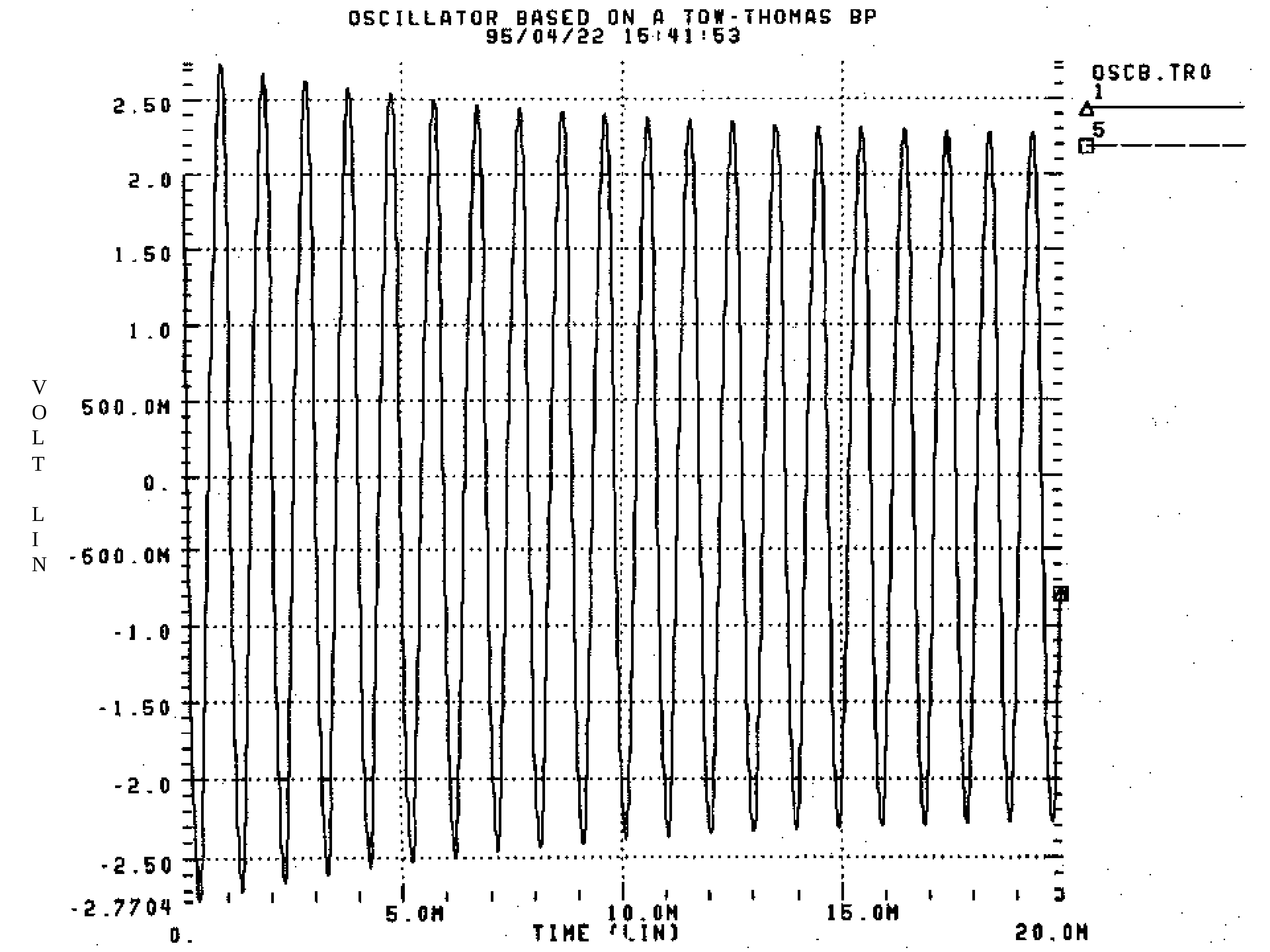

OSCILLATOR BASED ON A TOW-THOMAS BP
95/04/22 15:41:53
OSCB.TR0
5
1
2.50
2.0
1.50
1.0
500.0M
0.
-500.0M
-1.0
-1.50
-2.0
-2.50
-2.7704
VOLT LIN
0.
5.0M
10.0M
15.0M
20.0M
TIME (LIN)

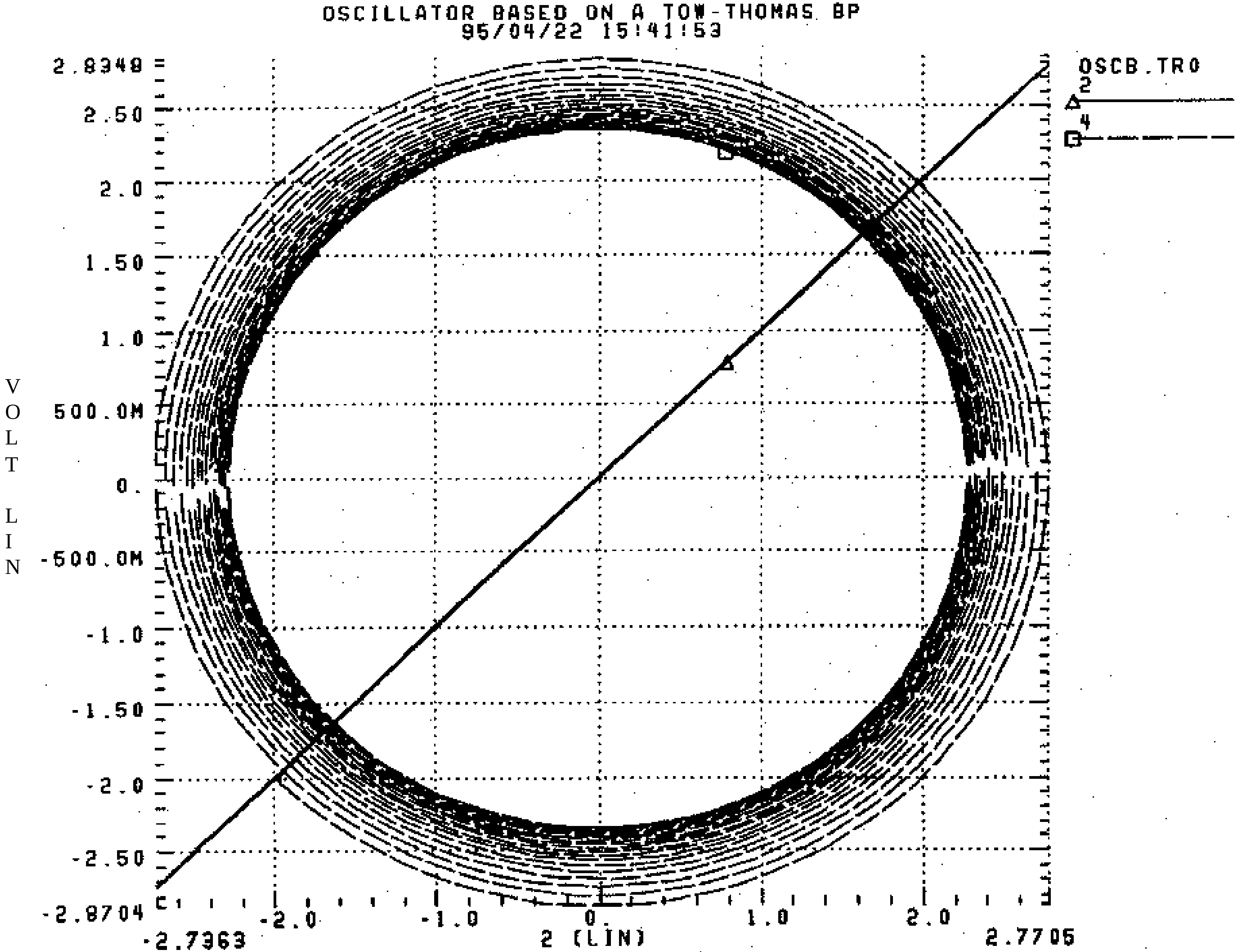


OSCILLATOR BASED ON A TOW-THOMAS BP
95/04/22 15:41:53
OSCB.TR0
2
4
VOLT LIN
2.8348
2.50
2.0
1.50
1.0
500.0M
0.
-500.0M
-1.0
-1.50
-2.0
-2.50
-2.9704
0.
5.0M
10.0M
15.0M
20.0M
TIME (LIN)

```
Oscillator based on a Tow-Thomas BP
R4      5     3     16K
R01  4   3   1K
RQ   2   3   16K
R      6   1   1K
R      1   7   1K
C02    3   2      0.1591549U
R03       2      6          1K
C03    7   4   0.1501549U
.SUBCKT OPAMP  vi-    vi+    v0+    v0-
*
*
RIN       vi-    vi+    10E6
EIN       1      0      vi+    vi-    2E05
R3DB    1      2      1K
C3DB    2      0      0.159E-04
EOUT   3      V0-    2      0      1
DP       2      VP     DIODE
DN       VN     2      DIODE
VPP     VP     0      13
VNN     VN     0      -13
ROUT   3      v0+    75.
.MODEL DIODE D(IS=10E-08 N=0.01)
.ENDS OPAMP
*  DESCRIPTION OF OPAMPS AND THEIR NODES
XOP1   3   0    2   0   OPAMP
XOP2     6    0    1    0       OPAMP
XOP3     7    0    4    0       OPAMP
*LIMITER Hysteresis CIRCUIT DESCRIPTION
RH1        1         15        2K
RH2        15        5         13K
XOP4      0         15        5         0         OPAMP
*  DESIRED ANALYSIS RESPONSE
.TRAN      5U         20m        UIC
.FOURIER             57           V(1)    V(2)    V(4)
.IC  V(1)=2  V(2)=-2  V(4)=-2  V(5)=2
.OPTIONS POST
.END
```



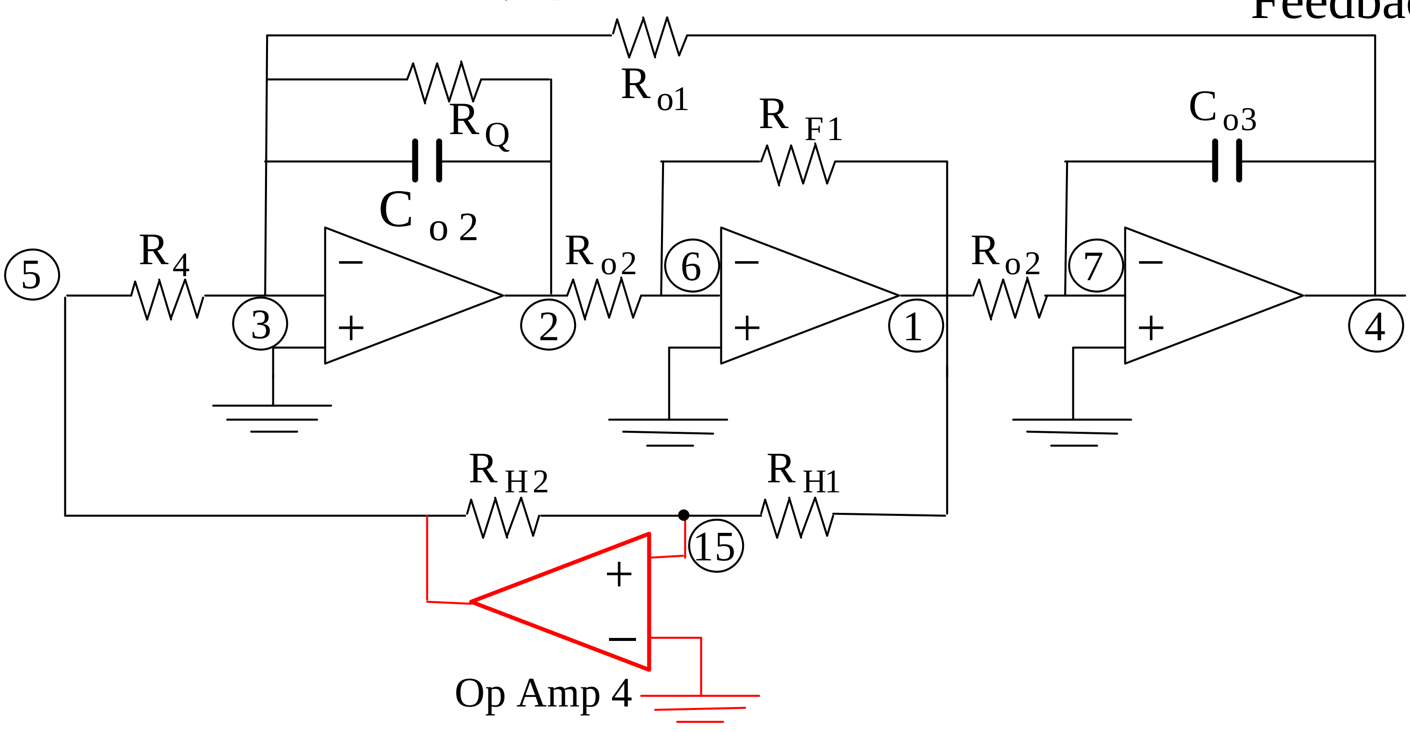

OSCILLATOR BASED ON A TOW-THOMAS BP
95/04/22 15:41:53
OSCB.TR0
1
5
2.50
2.0
1.50
1.0
500.0M
0.
-500.0M
-1.0
-1.50
-2.0
-2.50
-2.7704
VOLT LIN
0.
5.0M
10.0M
15.0M
20.0M
TIME (LIN)

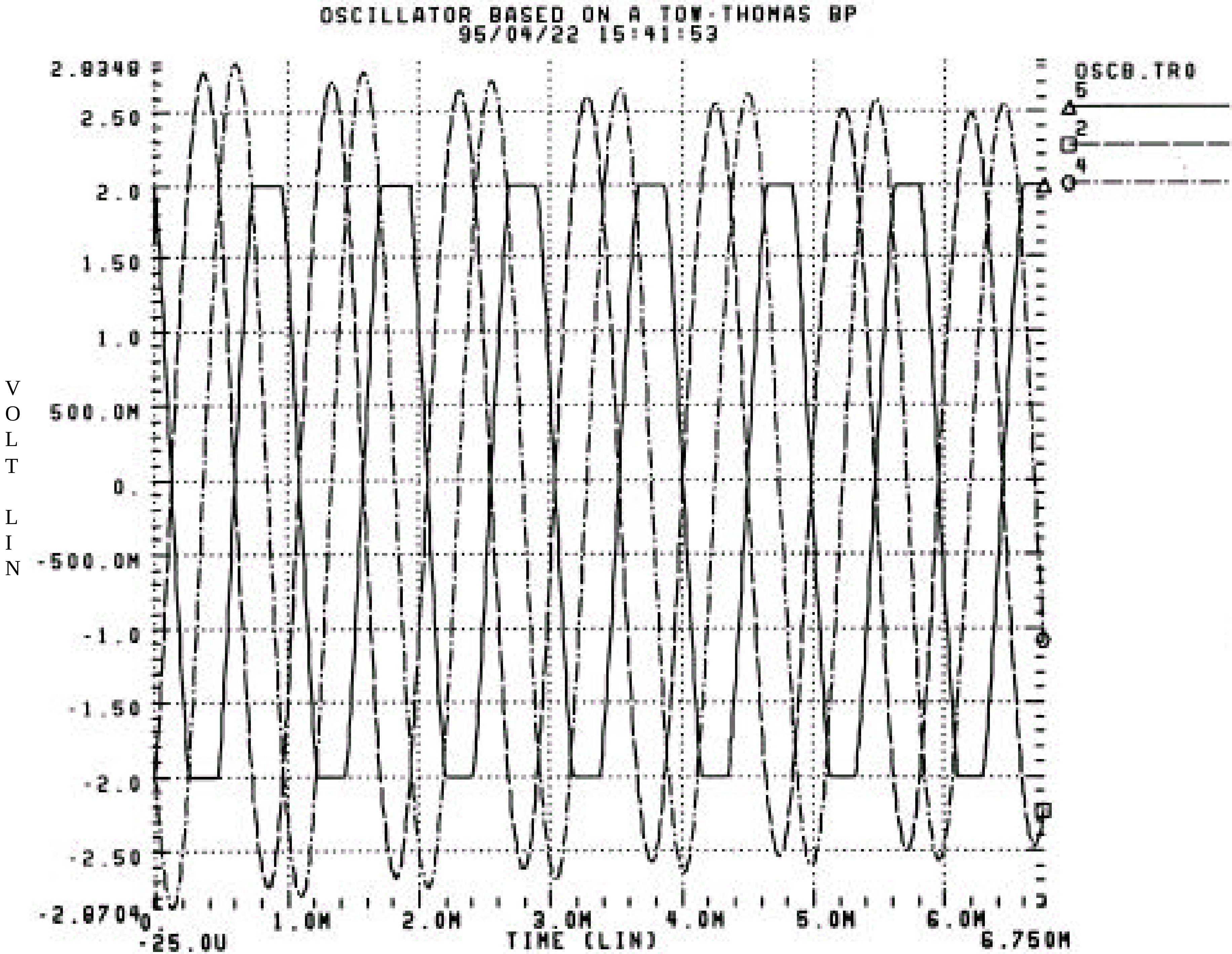


OSCILLATOR BASED ON A TOW-THOMAS BP
95/04/22 15:41:53
OSCB.TR0
2
4
2.8348
2.50
2.0
1.50
1.0
500.0M
0.
-500.0M
-1.0
-1.50
-2.0
-2.50
-2.8704
VOLT LIN
-2.7363
-2.0
-1.0
0.
1.0
2.0
2.7705
2 (LIN)

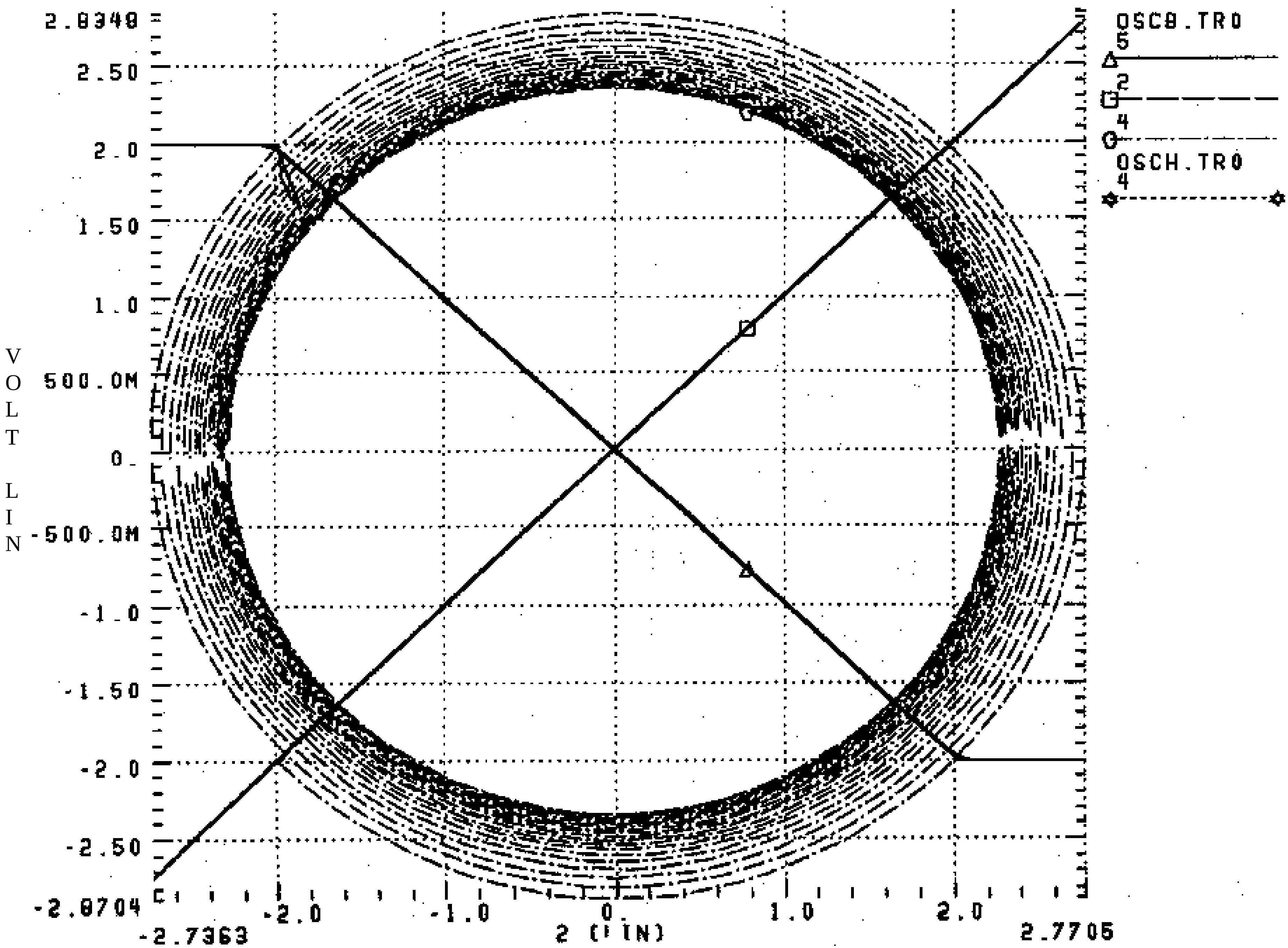
```
Oscillator based on a Tow-Thomas BP
R4       5        3        35K
R01  4   3   1.4K
RQ   1   3   9.6K
R       6   1   1K
R       1   7   1K
C02    3   2      0.1591549U
R03       2       6          1K
C03    7   4   0.1501549U
.SUBCKT OPAMP  vi-    vi+    v0+    v0-
*
*
RIN       vi-     vi+     10E6
EIN       1       0       vi+      vi-      2E05
R3DB    1       2       1K
C3DB    2       0       0.159E-04
EOUT   3       V0-      2        0        1
DP       2        VP     DIODE
DN       VN      2       DIODE
VPP     VP     0       13
VNN     VN     0       -13
ROUT   3       v0+    75.
.MODEL DIODE D(IS=10E-08 N=0.01)
.ENDS OPAMP
*  DESCRIPTION OF OPAMPS AND THEIR NODES
XOP1   3   0    2   0   OPAMP
XOP2     6     0    1    0       OPAMP
XOP3     7     0    4    0       OPAMP
*LIMITER Hysteresis CIRCUIT DESCRIPTION
RH1         1           15          2K
RH2         15          5           13K
XOP4       0            15          5            0          OPAMP
*  DESIRED ANALYSIS RESPONSE
.TRAN       5U          20m          UIC
.FOURIER                 57              V(1)    V(2)    V(4)
.IC  V(1)=2  V(2)=-2  V(4)=-2  V(5)=2
.OPTIONS POST
.END
```

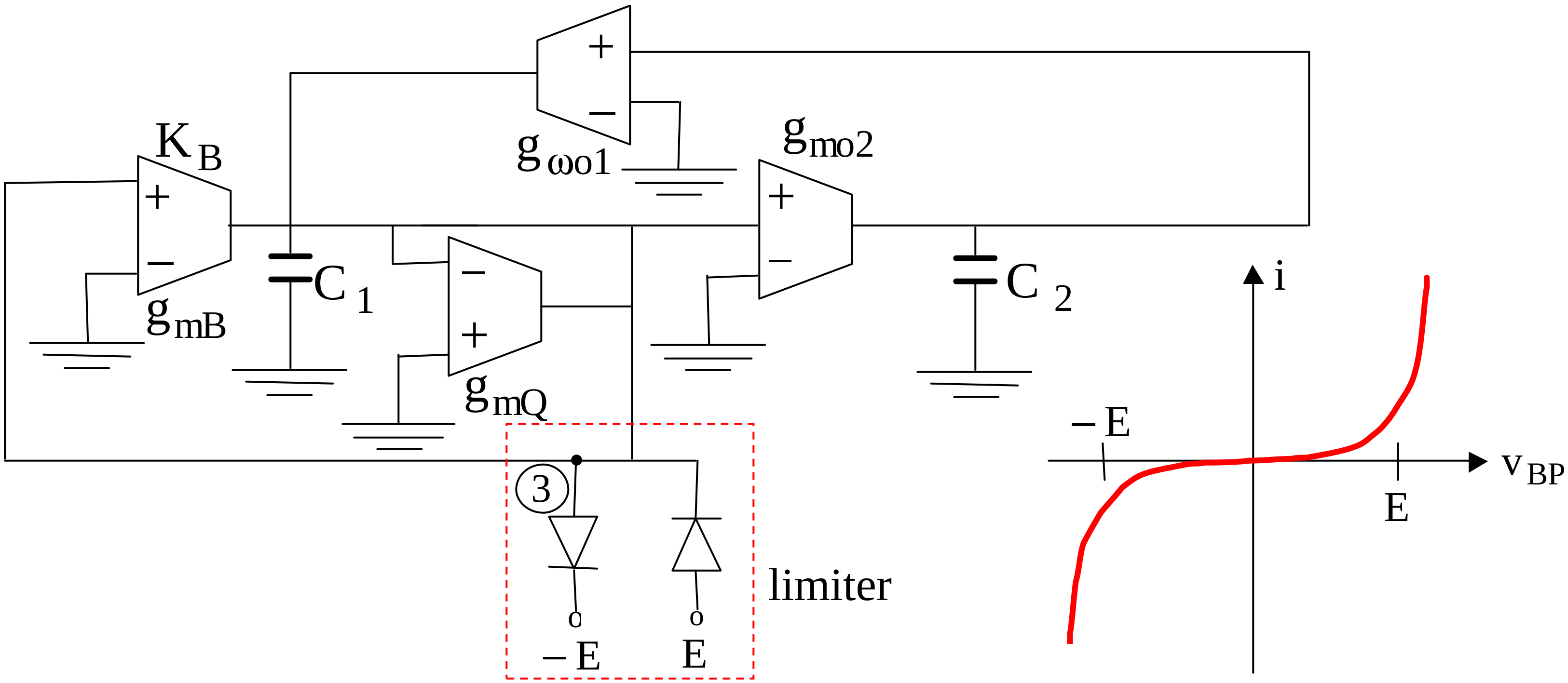
Double Positive Feedback




OSCILLATOR BASED ON A TOW-THOMAS BP
95/04/22 15:41:53
OSC8.TR0
5
2
4
2.8348
2.50
2.0
1.50
1.0
500.0M
0.
-500.0M
-1.0
-1.50
-2.0
-2.50
-2.8704
VOLT LIN
0
-25.0U
1.0M
2.0M
3.0M
4.0M
5.0M
6.0M
6.750M
TIME (LIN)

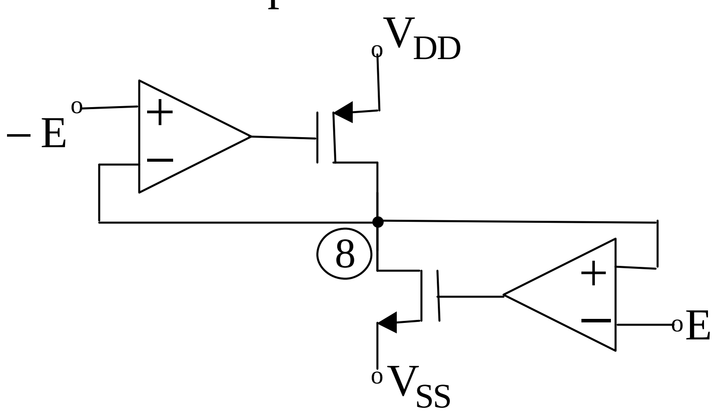
OSCILLATOR BASED ON A TOW-THOMAS BP
95/04/22 15:41:53

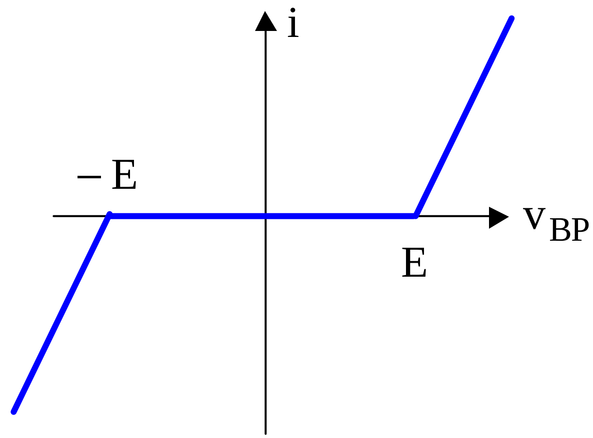




OTA - C Bandpass Based Oscillator

Another possible limiter can be:



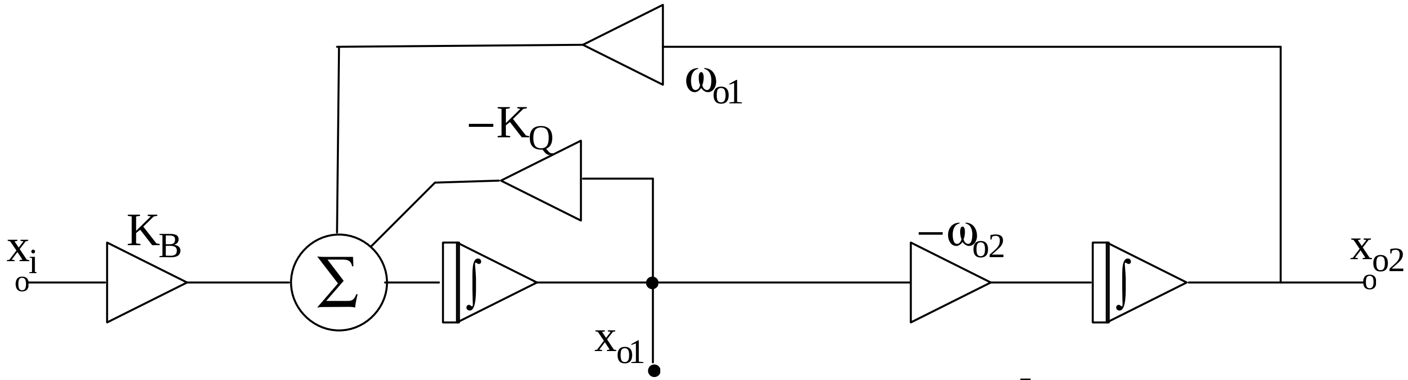


Simulations
Active-Filter Tuned Oscillator

Hints

- First design a band pass filter
  - High Q
  - Gain
- Next decide on type of limiter
- Finally be sure the path from the band pass output through the limiter to the input is positive feedback.

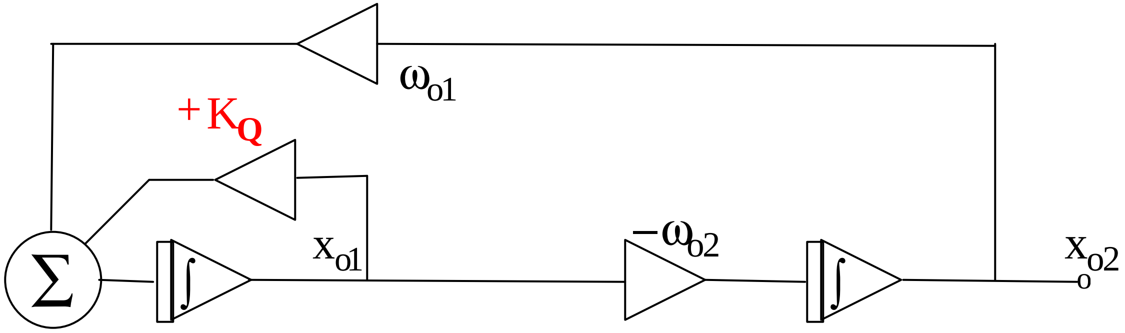
Quadrature Oscillator



Two Integrator Loop Filter

$$H_1(s) = \frac{x_{o1}(s)}{x_i(s)} = \frac{\dfrac{K_B}{s}}{1 + \dfrac{K_Q}{s} + \dfrac{\omega_{o1} \cdot \omega_{o2}}{s^2}} = \frac{K_B s}{s^2 + K_Q s + \omega_{o1}\omega_{o2}}$$

$H_1(s)$ is a second-order bandpass. The topology of this integrator loop can be modified to yield a *quadrature oscillator*.



Quadrature Oscillator Architecture

Observe that the characteristic equation yields:

$$1-\frac{K_Q}{s}+\frac{\omega_{o1}\omega_{o2}}{s^2}=0$$

or

$$s^2-K_Q s+\omega_{o1}\omega_{o2}=0$$

The roots are placed at

$$s_{1,2}=\frac{K_Q \pm \sqrt{K_Q^2-4\omega_{o1}\omega_{o2}}}{2}$$

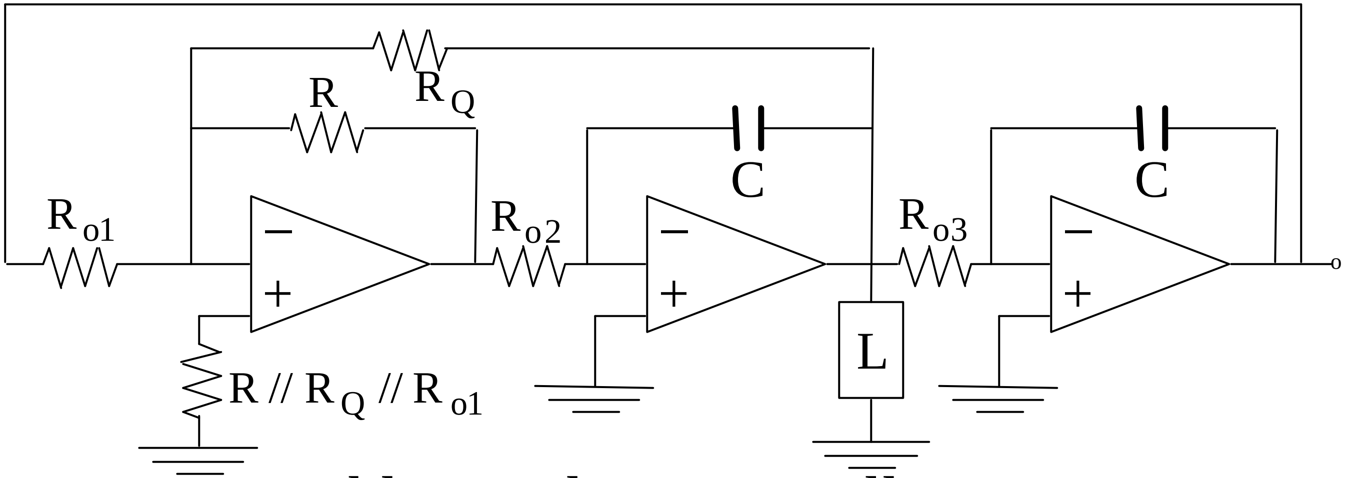
$$=\frac{K_Q}{2}\pm\frac{j}{2}\sqrt{4\omega_{o1}\omega_{o2}-K_Q^2}$$

$$K_Q^2<4\omega_{o1}\omega_{o2}$$

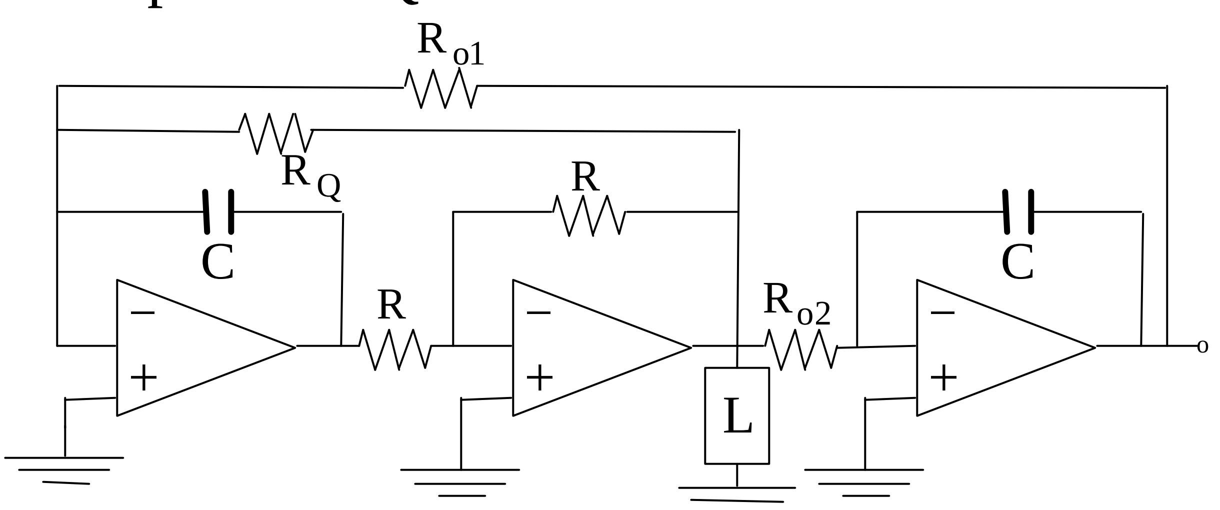
To provide sustained oscillations we need to locate the poles on the $j\omega$ axis, this requires:

i) $K_Q = E$ small positive value

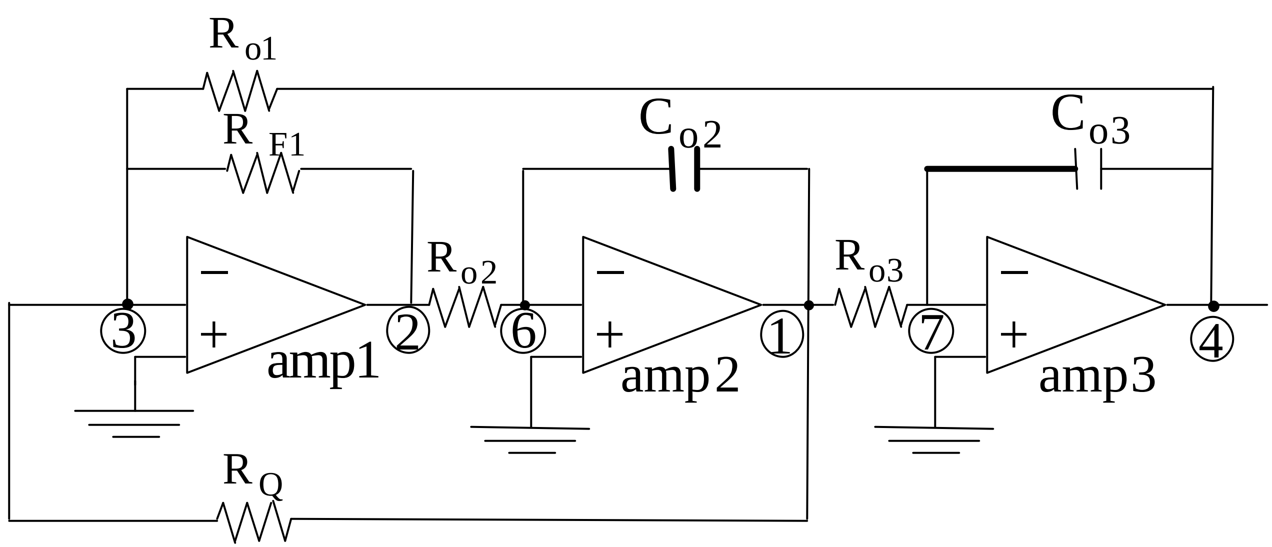
ii) To limit the output by means of a nonlinear gain control.



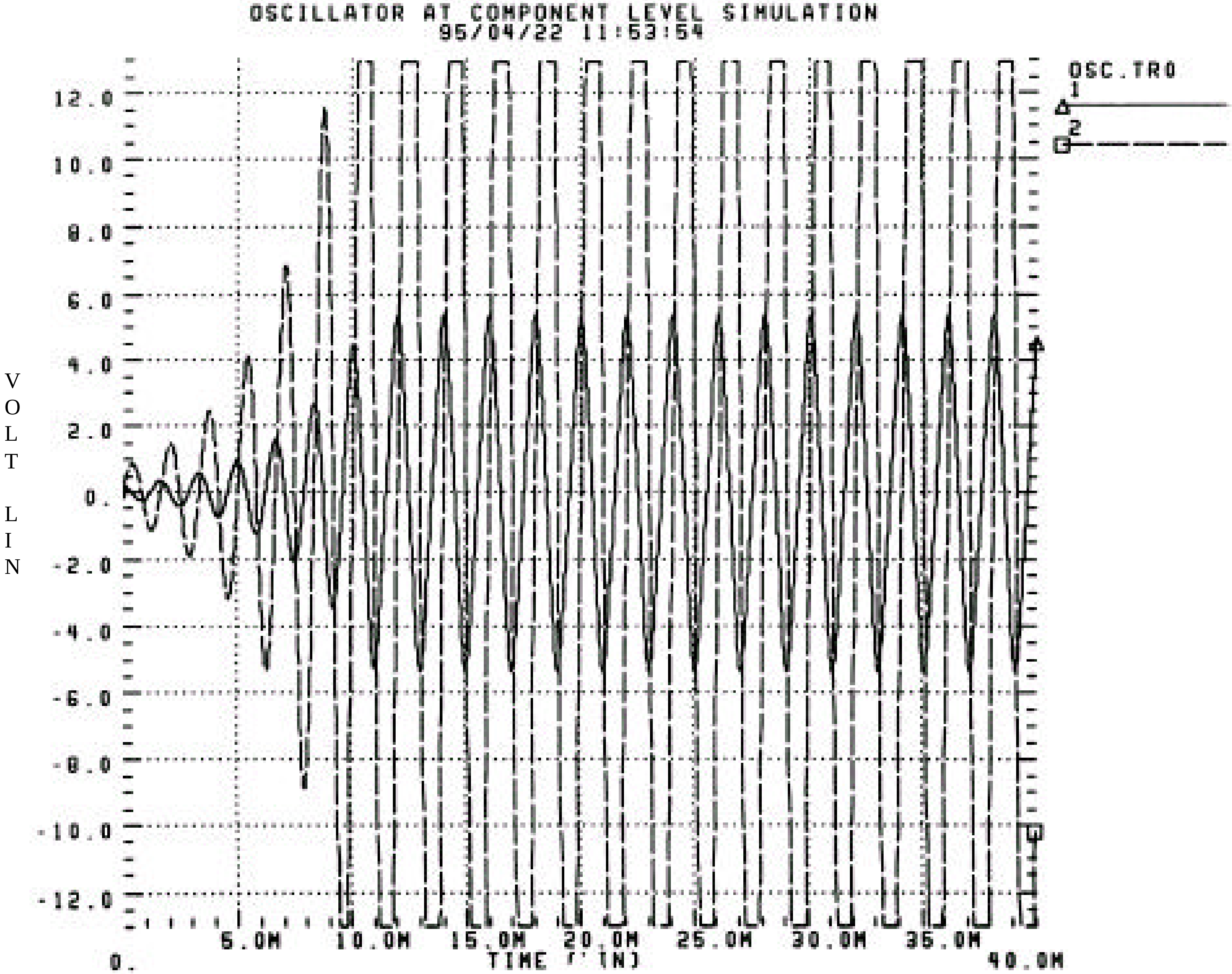
One possible Quadrature Oscillator Structure



```
Oscillator at component level simulation
RO1    4    3    220K
RQ      1    3    510K
RF1     3    2    310K
RO2    2    6    100K
CO2    6    1    0.01U
RO3    1    7    100K
CO3    7    4    0.001U
.SUBCKT OPAMP    vi-     vi+     v0+     v0-
*
*
RIN      vi-    vi+    10E6
BIN     1       0       vi+       vi-       2E05
R3DB   1       2        1K
C3DB   2       0        0.159E-04
BOUT  3    V0-     2        0       1
DP       2    VP     DIODE
DN       VN      2     DIODE
VPP      VP      0      13
VNN    VN      0      -13
ROOT    3       v0+   75.
.MODEL DIODE D (IS=10E-0S N=0.001)
.ENDS OPAMP
*    DESCRIPTION OF OPAMPS AND THEIR NOOES
XOP1          3      0      2      0      OPAMP
XOP2              6      0      1      0      OPAMP
XOP3              7      0      4      0      OPAMP
.TRAN            10U   40m   UIC
.FOURIER       57     V(1)    V(2)     V(4)
.IC                 V(1)=.2     V(2)=-.2    V(4)=-.2
.OPTIONS POST
.OP .08
.END
```

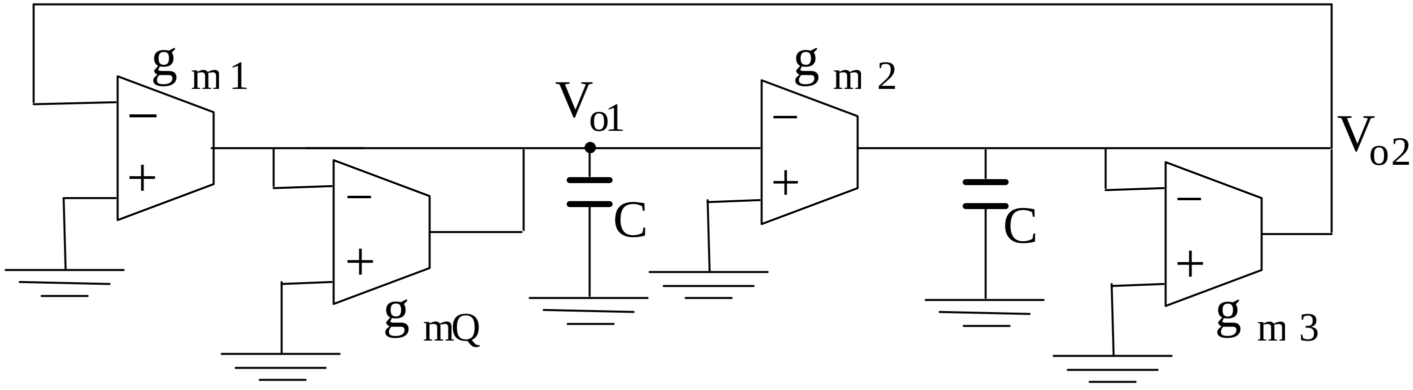


QUADRATURE OSCILLATOR
(NO EXTERNAL LIMITER)



OSCILLATOR AT COMPONENT LEVEL SIMULATION
95/04/22 11:53:54
OSC.TR0
1
2
12.0
10.0
8.0
6.0
4.0
2.0
0.
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
VOLT LIN
0.
5.0M
10.0M
15.0M
20.0M
25.0M
30.0M
35.0M
40.0M
TIME (LIN)

OTA-C QUADRATURE OSCILLATOR



Structure 1. Note the positive feedback in the main loop

$$V_{o1} = \frac{g_{m1} V_{o2}}{g_{mQ} + sC} \qquad (1)$$

$$V_{o2} = \frac{g_{m2} V_{o1}}{g_{m3} + sC} \qquad (2)$$

C.E

$$1-\frac{g_{m1}}{g_{mQ}+sC}\frac{g_{m2}}{g_{m3}+sC}=0$$

or

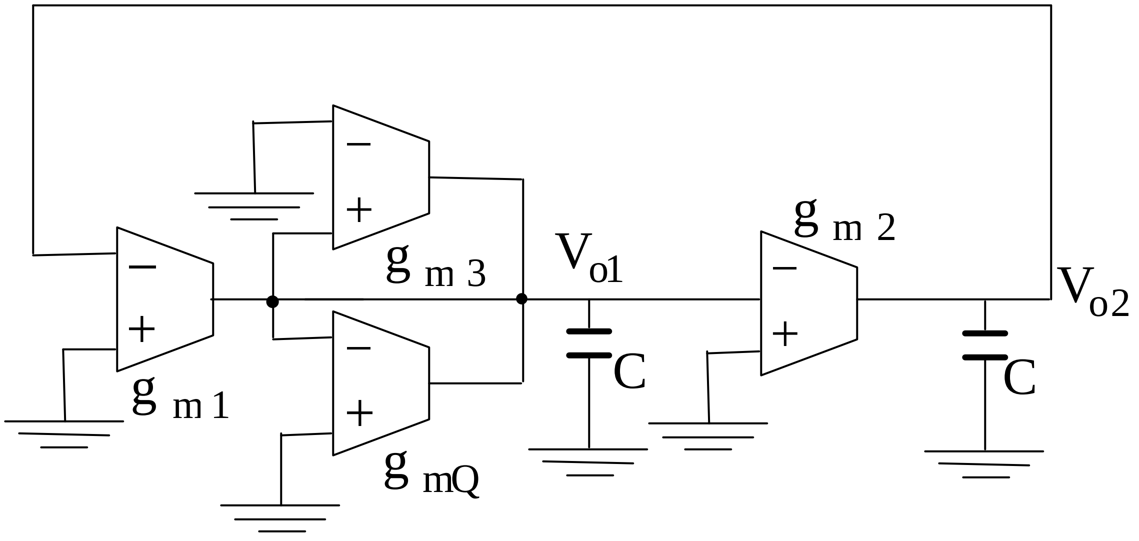
$$s^2-K_Q s+\omega_{o1}\omega_{o2}=0$$

Where

$$K_Q=\frac{g_{mQ}-g_{m3}}{C}$$

$$w_o^2=\frac{g_{m1}g_{m2}-g_{mQ}g_{m3}}{C^2}$$

An alternative structure is considered next

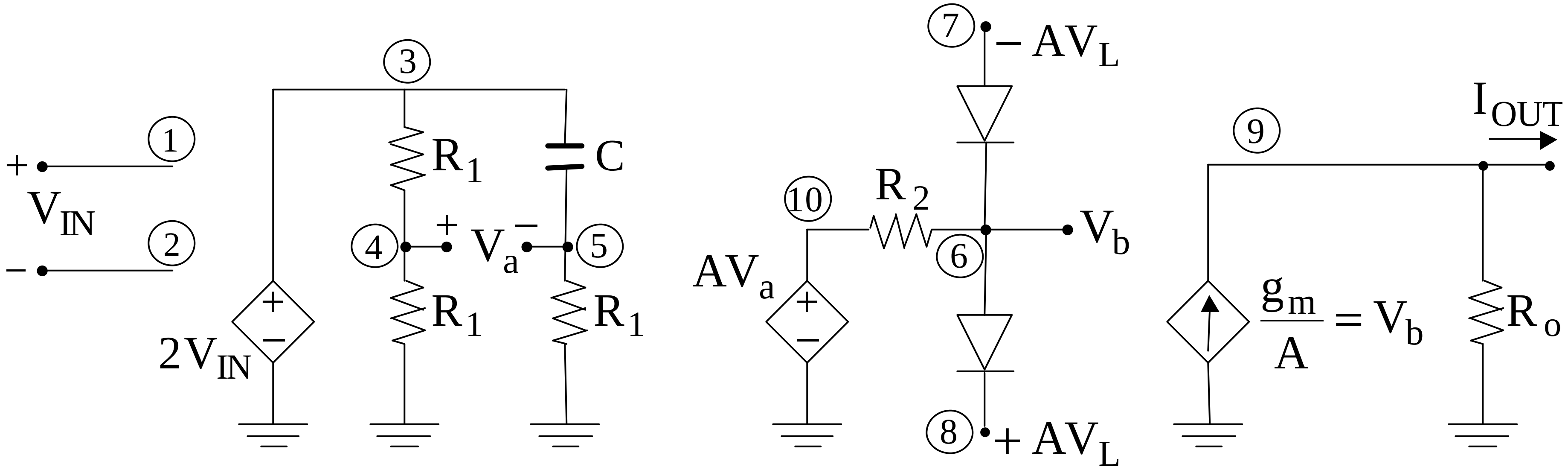


Structure 2. Observe the positive and negative resistance associated with integrator 1.

Where $\omega_o^2 = \dfrac{g_{m1} g_{m2}}{C^2}$

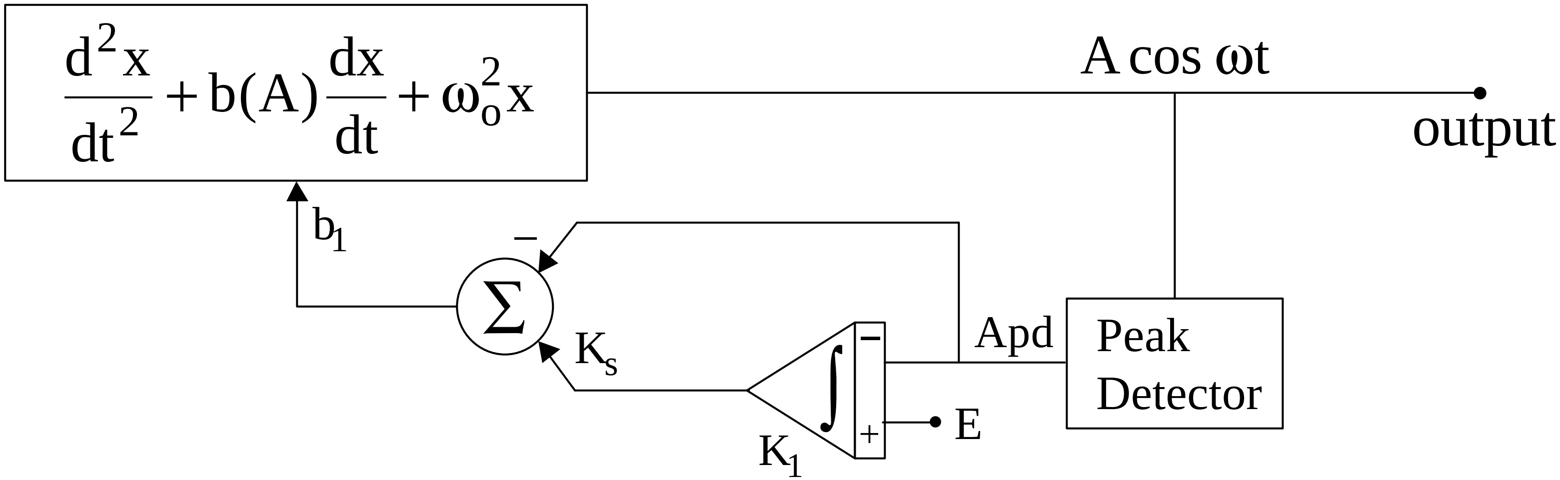
$$K_Q = \frac{g_{mQ} - g_{m3}}{C}$$

This structure is easier to tune. For a realistic design the OTA non-idealities have to be considered.

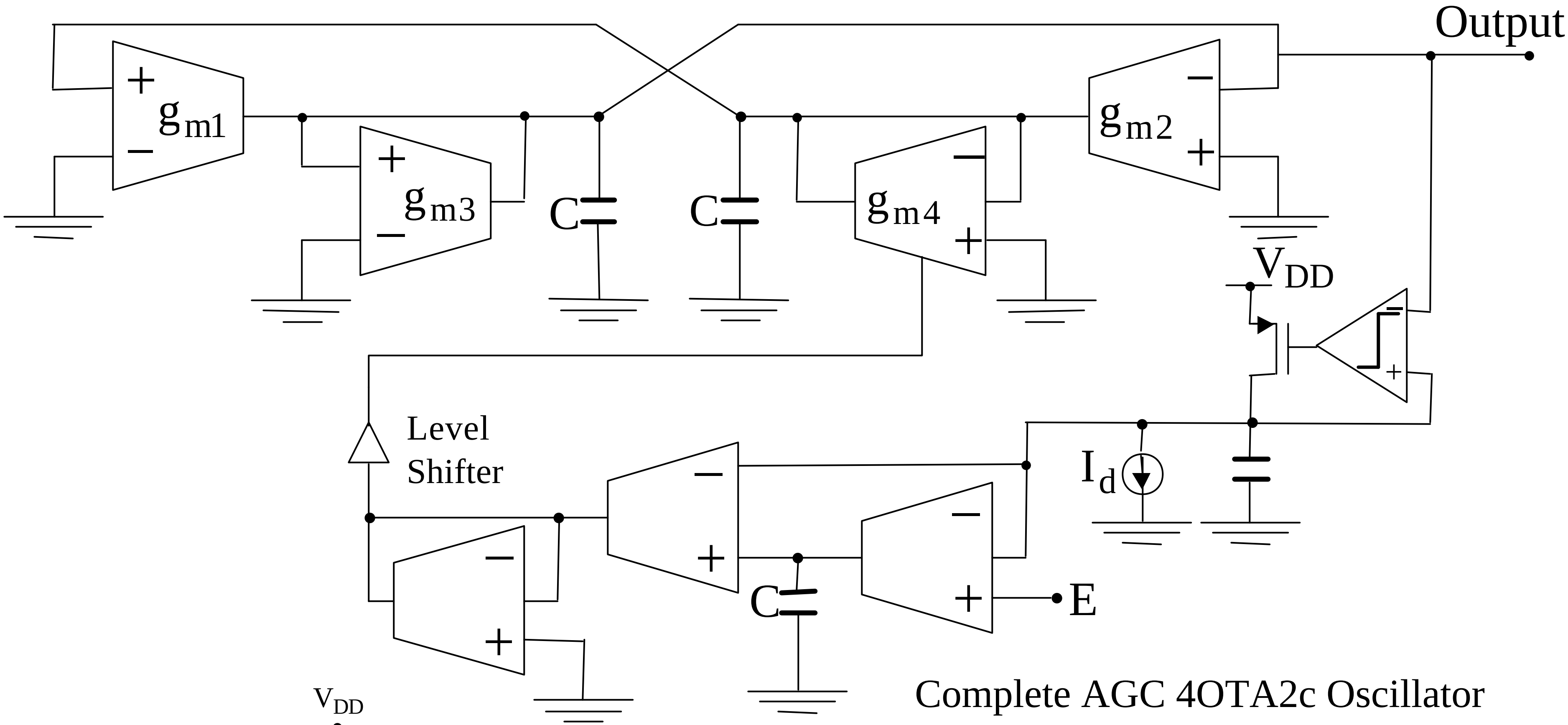


Furthermore amplitude control by external limiters. That is connect the limiters discussed before* at the output of any of the integrators.

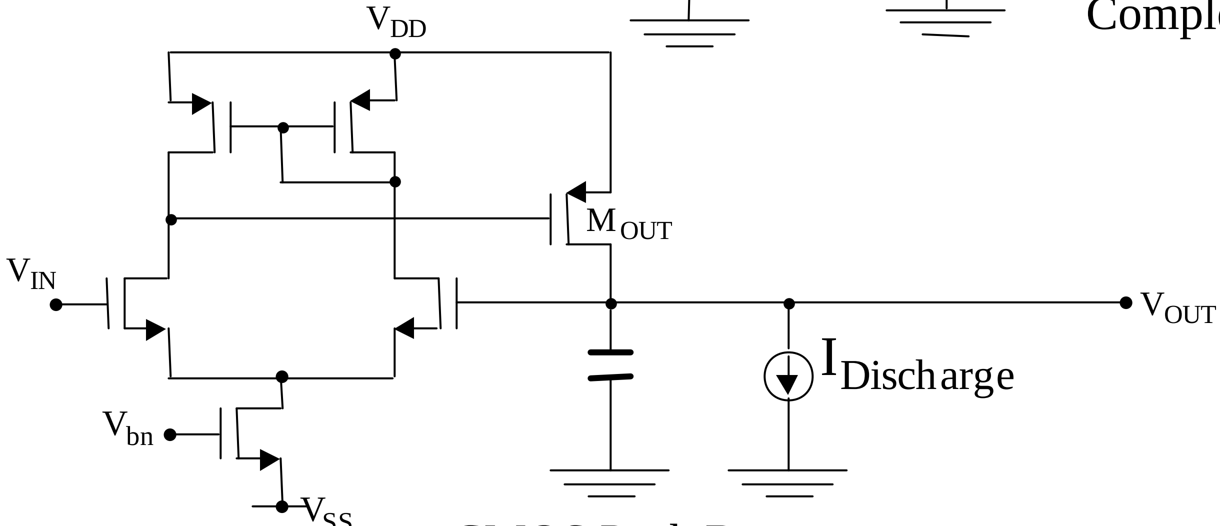
Instead of using limiters, another strategy is using an automatic gain control i.e.,



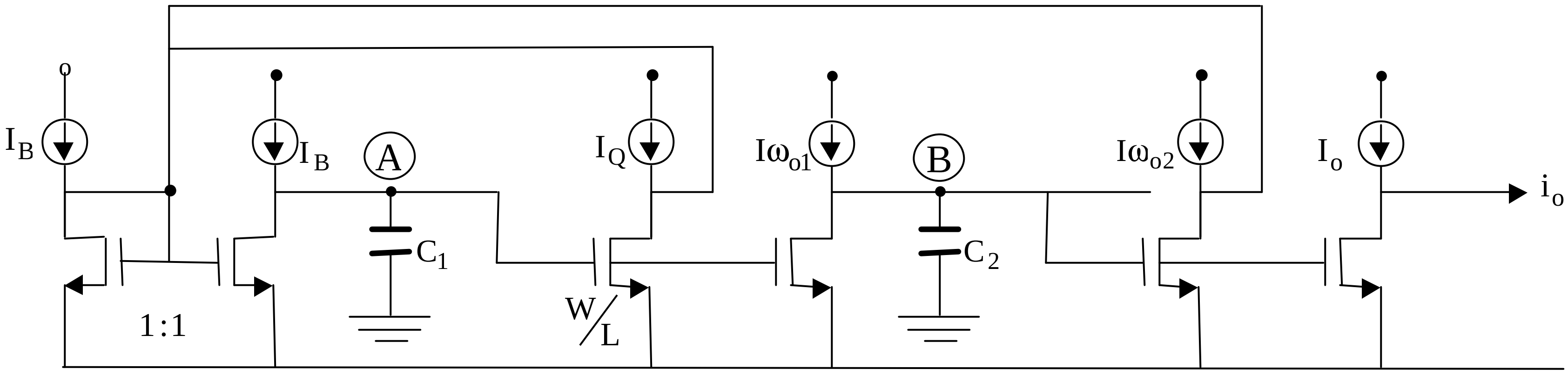
Can you reformulate as an adaptive filter minimizing $(E - Apd)^2$?



Complete AGC 4OTA2c Oscillator



CMOS Peak Detector



- A potential current - mode Quadrature Oscillator

Note that limiters are needed to sustain oscillators. A limiter should be placed at point Ⓐ or Ⓑ.

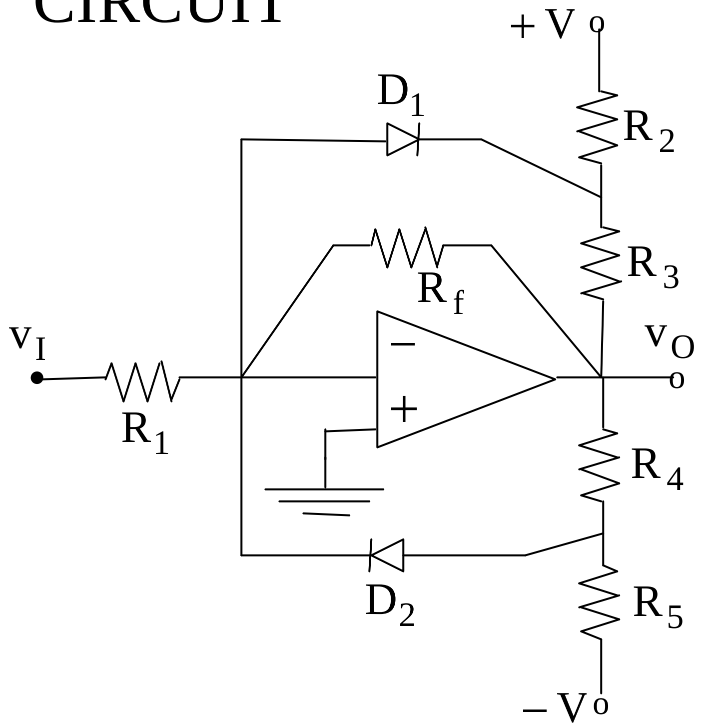
Limiters, Amplitude Stabilization and Control

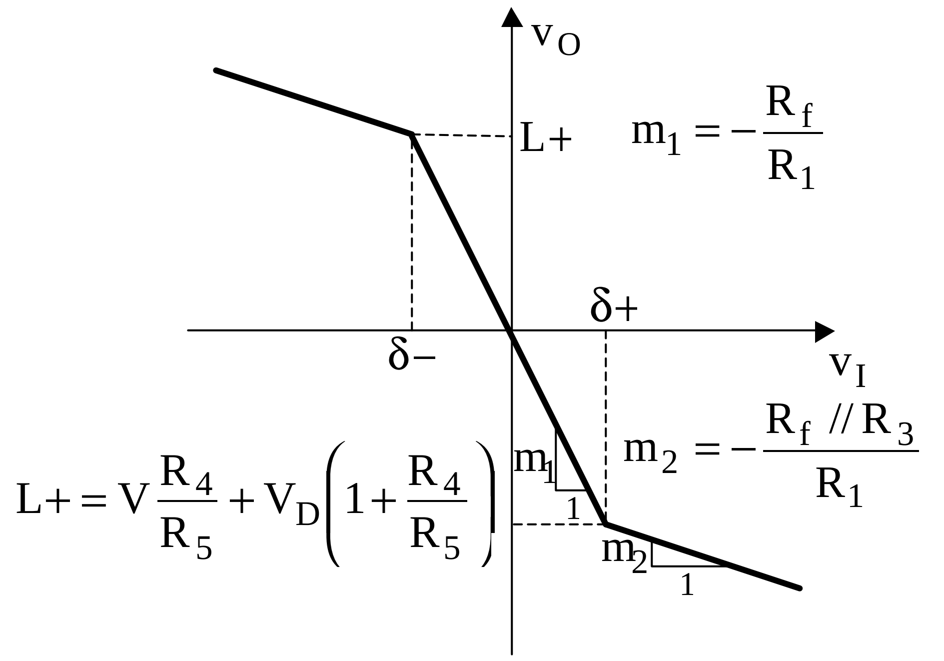
SCHEMES TO
SUSTAIN OSCILLATIONS
AT CONSTANT AMPLITUDE

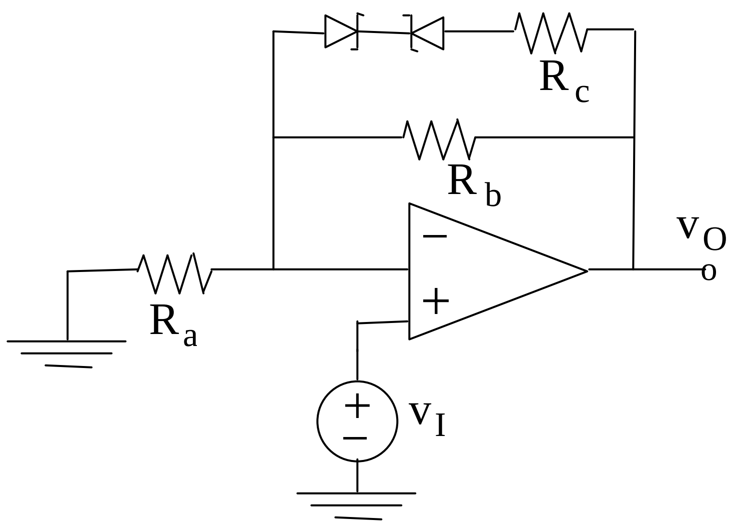
- Nonlinearity in the amplifier's gain characteristics
- Automatic adjustment of the gain characteristic.

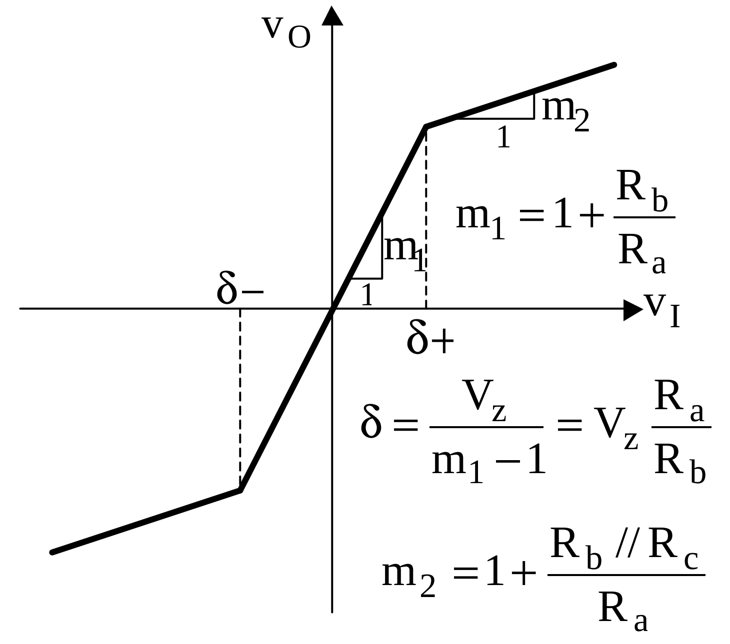
CIRCUIT

I - O CHARACTERISTICS

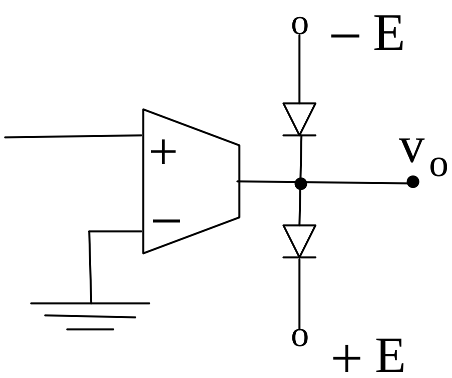




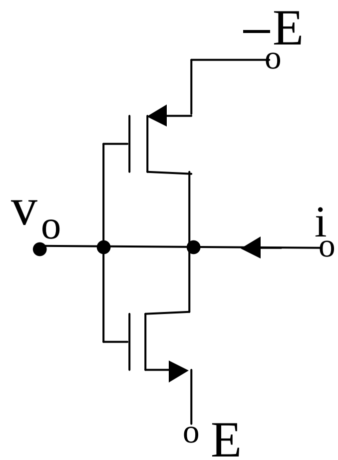




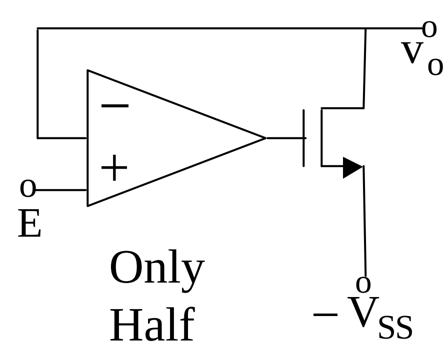
For OTA's



Circuit

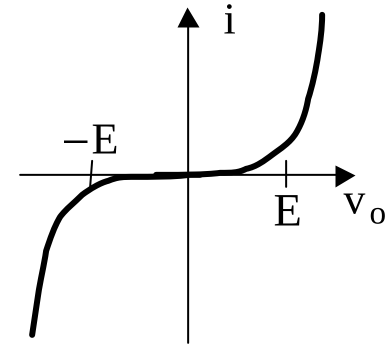


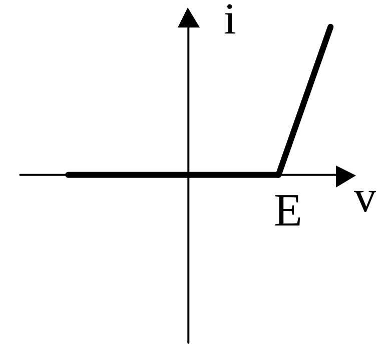
(a)



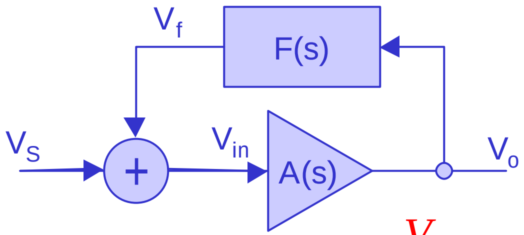
(b)

Implementations
of Limiter





Tuned Oscillators



$$V_o = V_{in} A(s)$$

$$V_f = V_o F(s) = V_{in} A(s) F(s)$$

$$\frac{V_f}{V_{in}} = A(s)F(s)$$

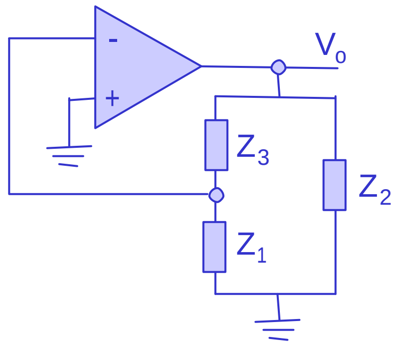
$$\frac{V_o}{V_S} = \frac{A(s)}{1 - A(s)F(s)}$$

Recall the oscillation conditions (Barkhausen)

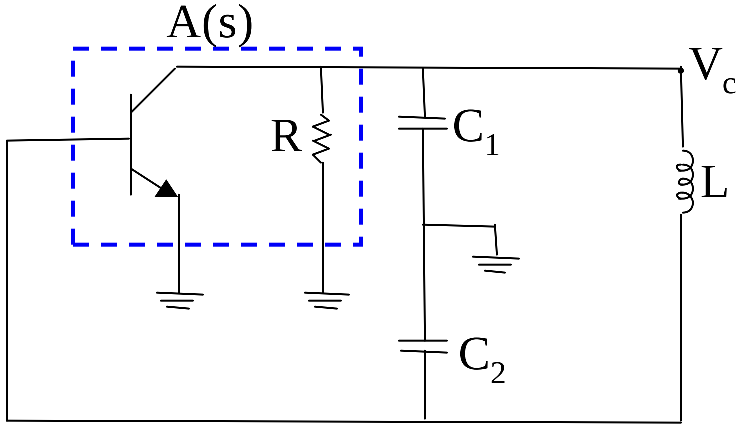
$$\left|\frac{V_f}{V_{in}}\right| = \left|A(jw)\right|\left|F(jw)\right| \geq 1$$

$$Phase \left({V_f}/{V_{in}} \right) = \; Phase \; \left(A(s)\right) \; + \; Phase \; \left(F(s)\right) \; = 0^\circ$$

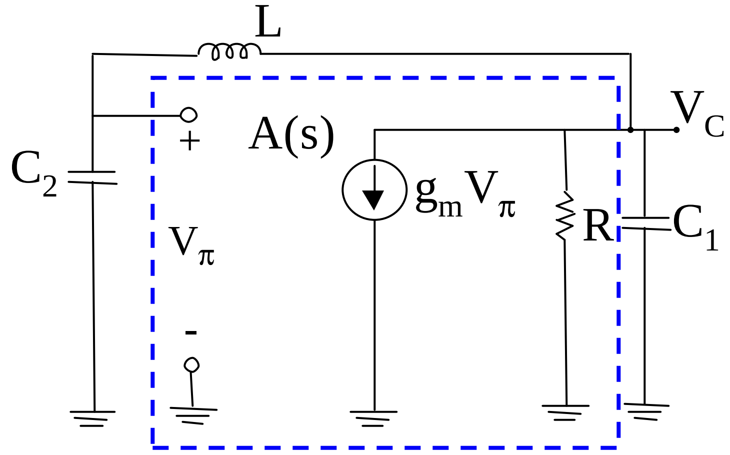
An example:



LC Tuned Oscillator: Colpitts Oscillator Conditions



Bipolar Implementation



Small-Signal Model

$$V_c\left(\frac{1}{SL}+SC_1+\frac{1}{R}\right)-\frac{1}{SL}V_p+g_mV_p=0 \qquad \textbf{(1);}$$

$$-\frac{1}{SL}V_C+V_p\left(SC_2+\frac{1}{SL}\right)=0 \qquad \textbf{(2)}$$

(2) into (1) yields the characteristic equation:

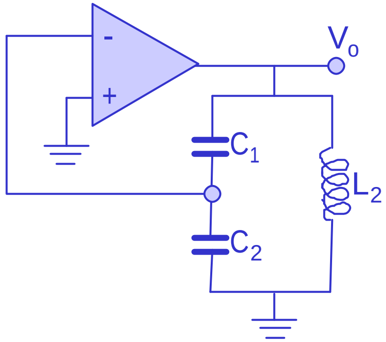
$$(S^2LC_2+1)\left(\frac{1}{SL}+sC_1+\frac{1}{R}-\frac{1}{SL}\right)+g_m=0; \quad S^3LC_1C_2+S^2(LC_2/R)+s(C_1+C_2)+(g_m+1/R)=0$$

For $s=jw;\ \left(g_m+\frac{1}{R}-\frac{w^2LC_2}{R}\right)+j[w(C_1+C_2)-w^3LC_1C_2]=0$

Both real and imaginary part should vanish, then

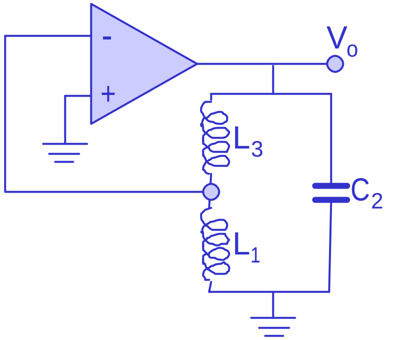
$$\boxed{w_o^2=1/L\left(\frac{1}{C_2}+\frac{1}{C_1}\right) \quad \& \quad C_2/C_1\le g_mR}$$

Particular cases of Negative Feedback Oscillators:



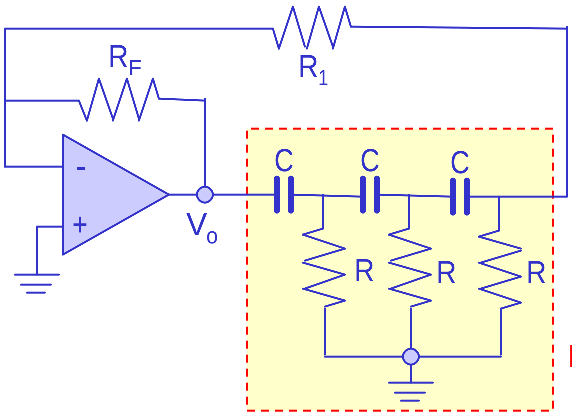
Colpitts

$$f_o = \frac{1}{2p}\left\{\frac{1}{L_2}\left(\frac{1}{C_1}+\frac{1}{C_3}\right)\right\}^{1/2}$$



Hartley

$$f_o = \frac{1}{2p}\left[\frac{1}{C_2\left(L_1+L_3\right)}\right]^{1/2}$$



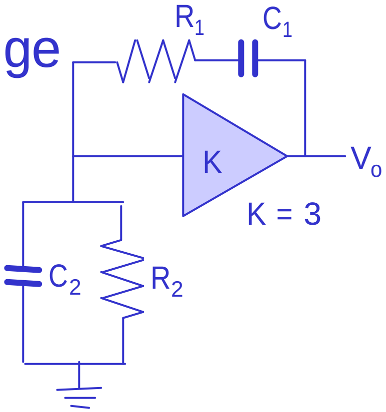
Phase – Shift Network

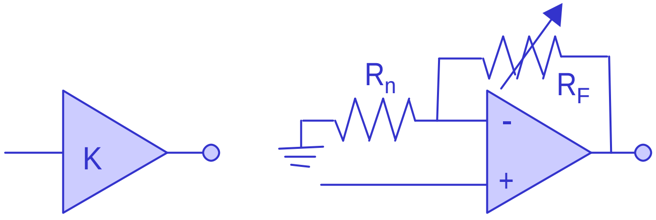
Note that each RC should contribute with 60 degrees, such that the threeRC combination contributes 180º. In addition the amplifier also contributes with 180º

Phase-Shift Oscillator

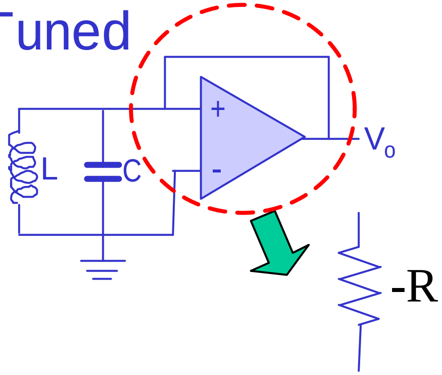
Positive – Feedback Oscillator

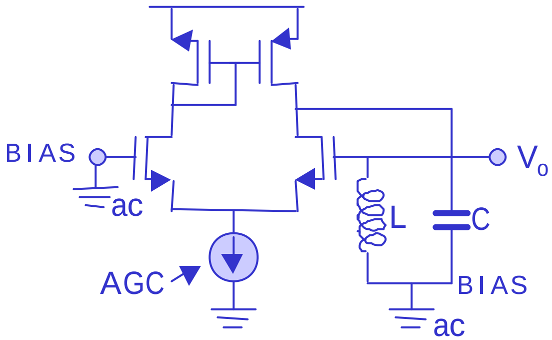
Wien - Bridge





LC - Tuned





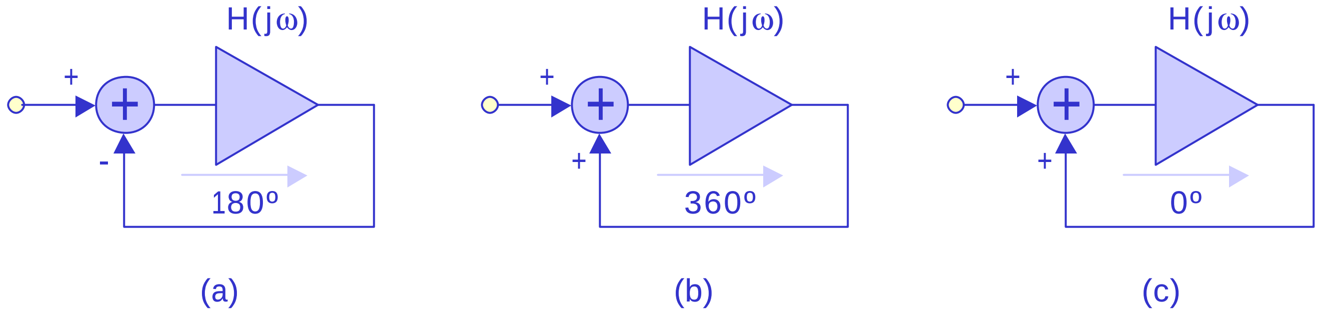
Observe that the positive feedback amplifier has a negative resistance property.

Ring Oscillators

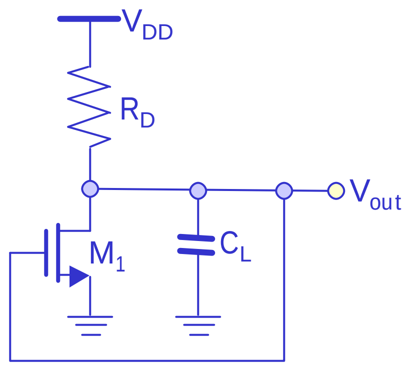
- The main difficulty for using submicron CMOS ring oscillators in wireless communication systems is their relatively poor phase noise response.
- Precaution is required to achieve as low phase noise as possible from CMOS ring oscillators.
  - Dominant noise sources in IC environment are common-mode signals in nature (e.g. power supply noise, substrate-coupled noise).
    - Fully differential design is a must!

Courtesy of Fikret Dulger

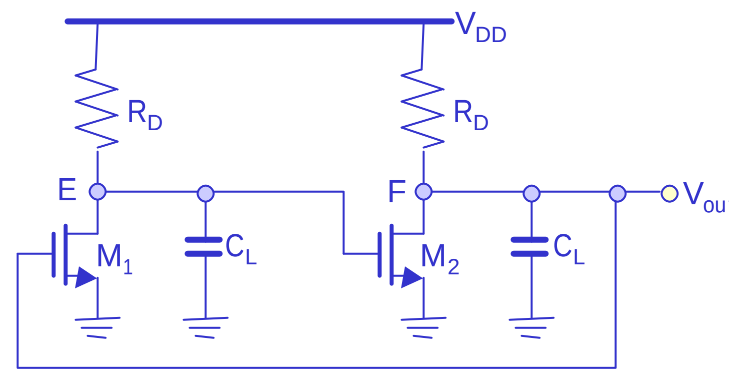
Ring Oscillators



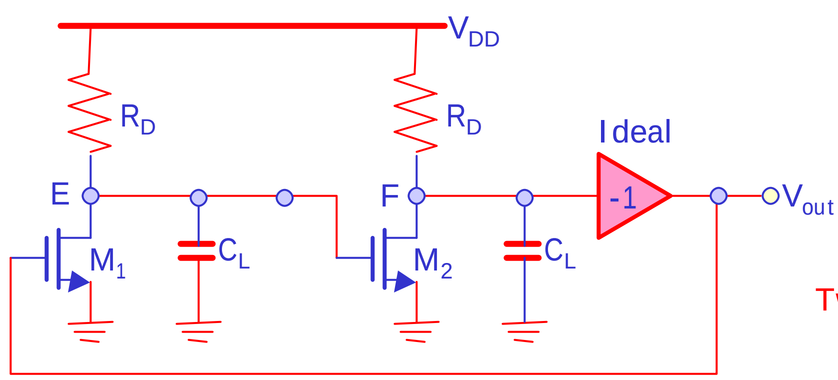
Various views of oscillatory feedback system.



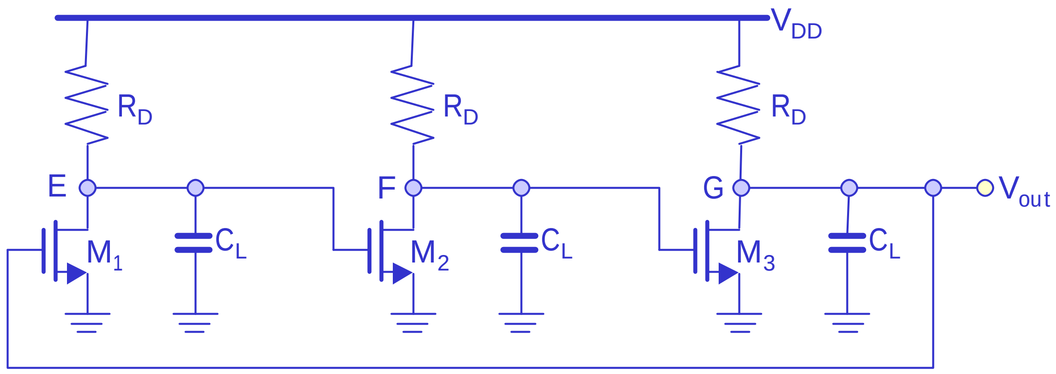
One-pole feedback



Two-pole feedback system



Two-pole feedback system plus an inverter



Three-stage ring oscillator

$$H(s) = -\frac{A_0^3}{\left(1+\dfrac{s}{w_0}\right)^3}$$

$$w_{osc} = \sqrt{3}w_0$$

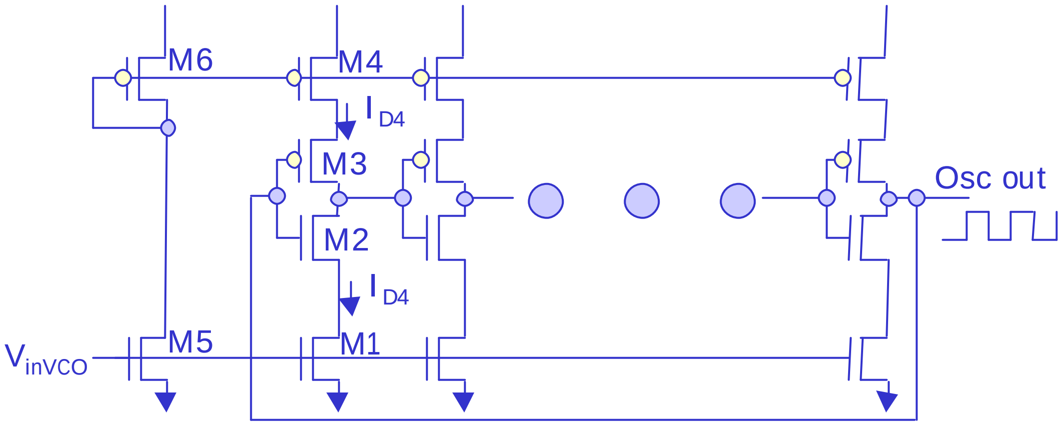
$$\tan^{-1}\frac{w_{osc}}{w_o} = 60^o$$

$$\frac{A_0^3}{\left[\sqrt{1+\left(\dfrac{w_{osc}}{w_0}\right)^2}\right]^3} = 1$$

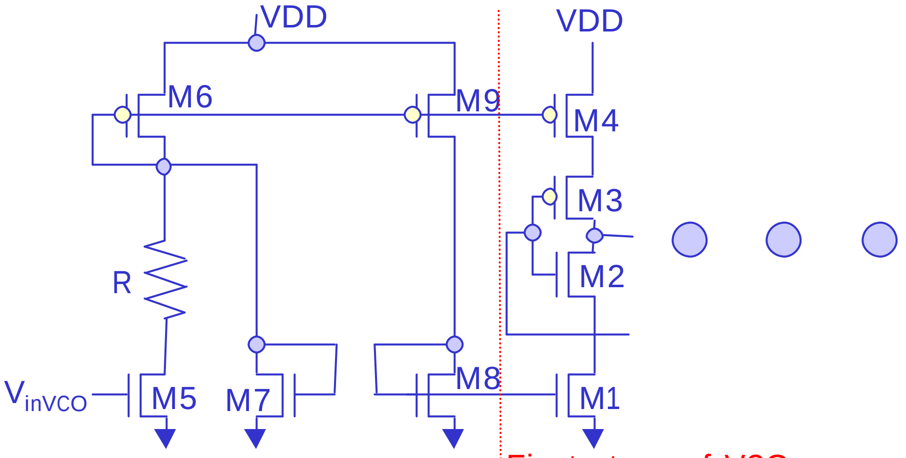
$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{\dfrac{-A_0^3}{(1+s/w_0)^3}}{1+\dfrac{A_0^3}{(1+s/w_0)^3}} = \frac{-A_0^3}{(1+s/w_0)^3 + A_0^3}$$

$$A_0 = 2$$

Single –ended Inverters
(delay elements)

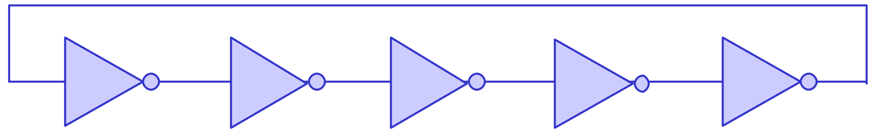


Current – starved VCO.

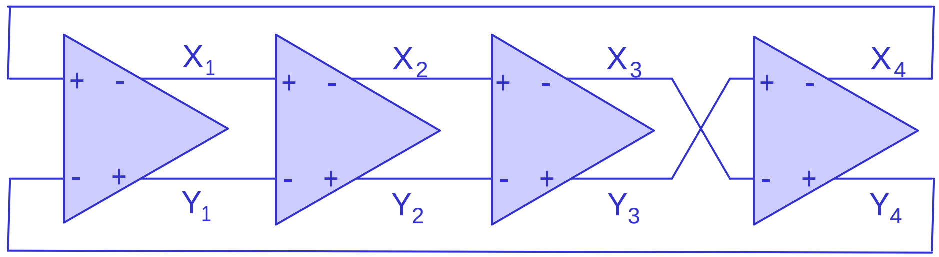


First stage of VCO

Modifications to the current-starved VCO to set minimum and maximum frequencies.

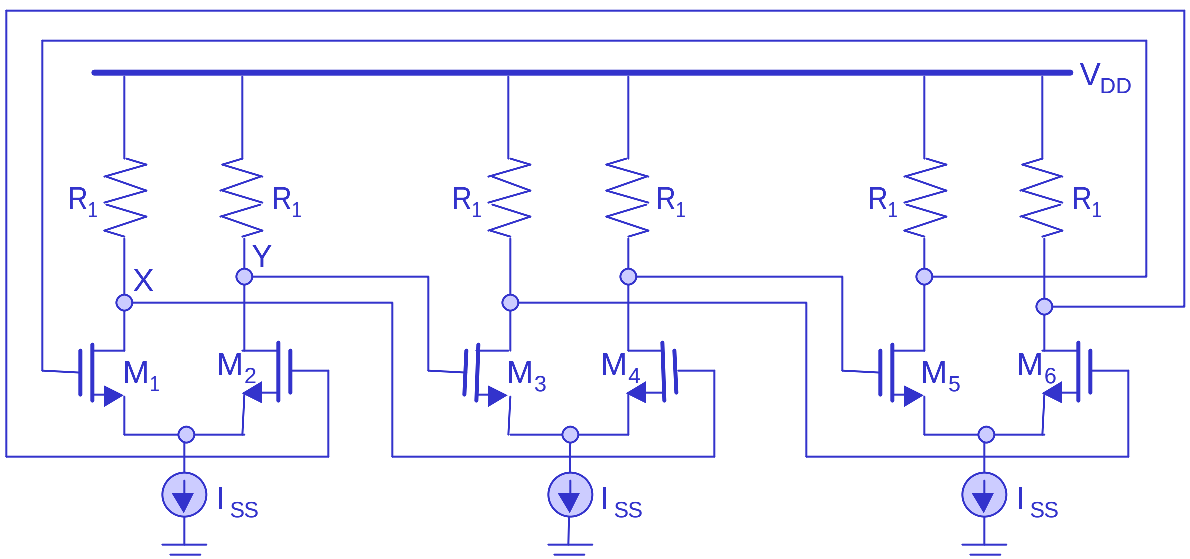


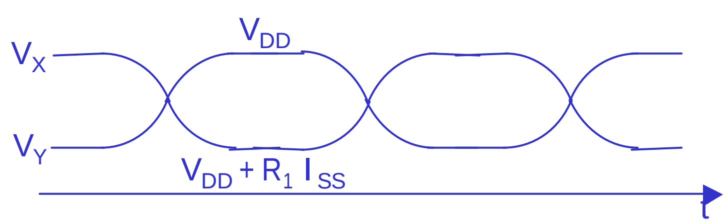
(a)



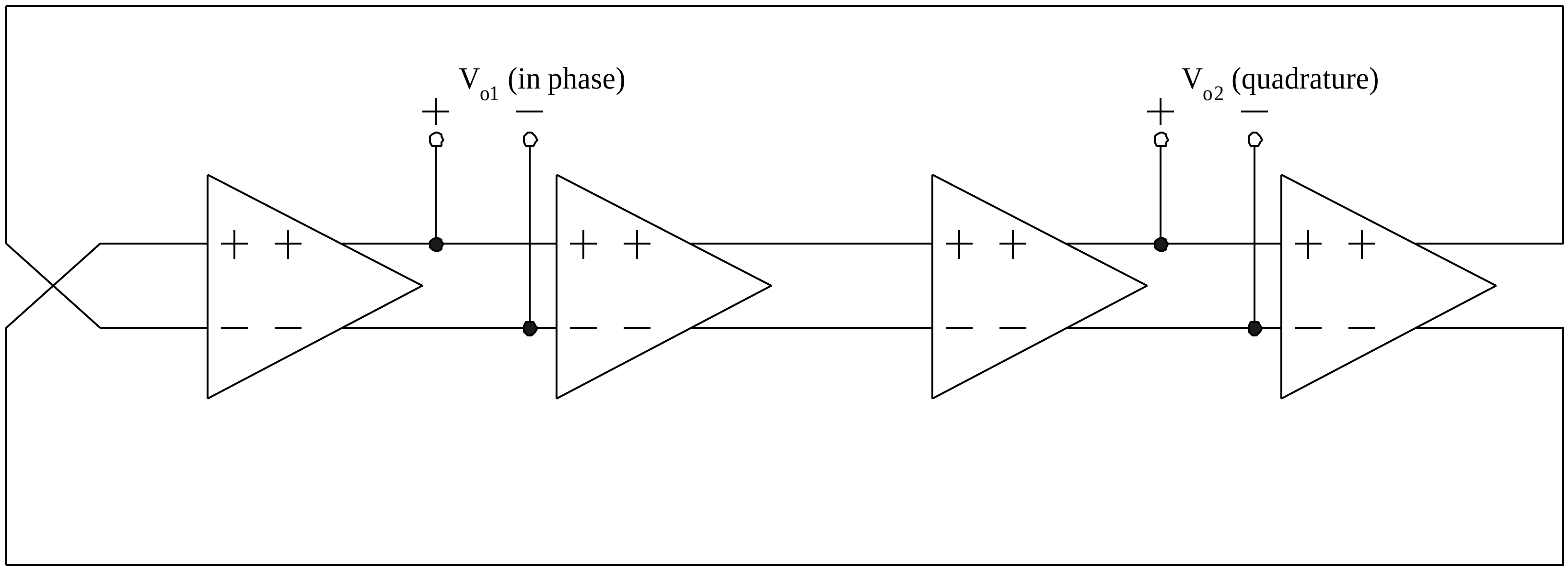
(b)

(a) Five-stage single-ended ring oscillator, (b) four-stage differential ring oscillator

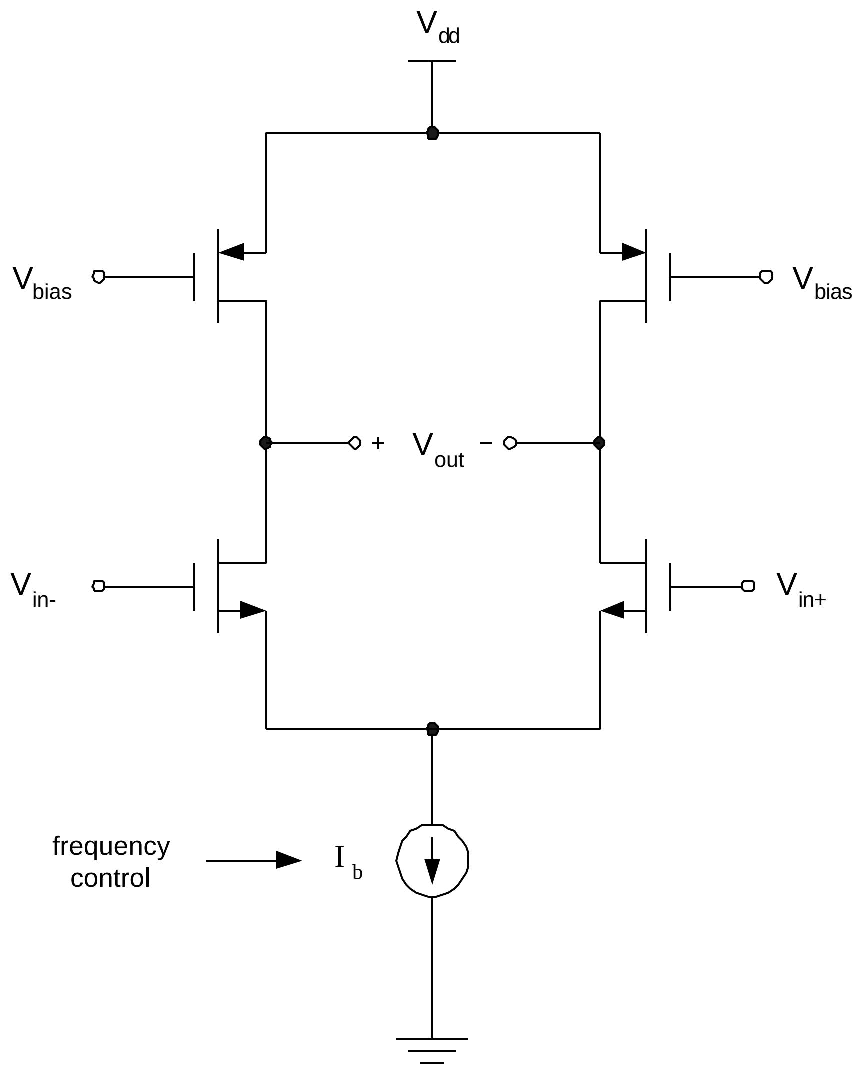




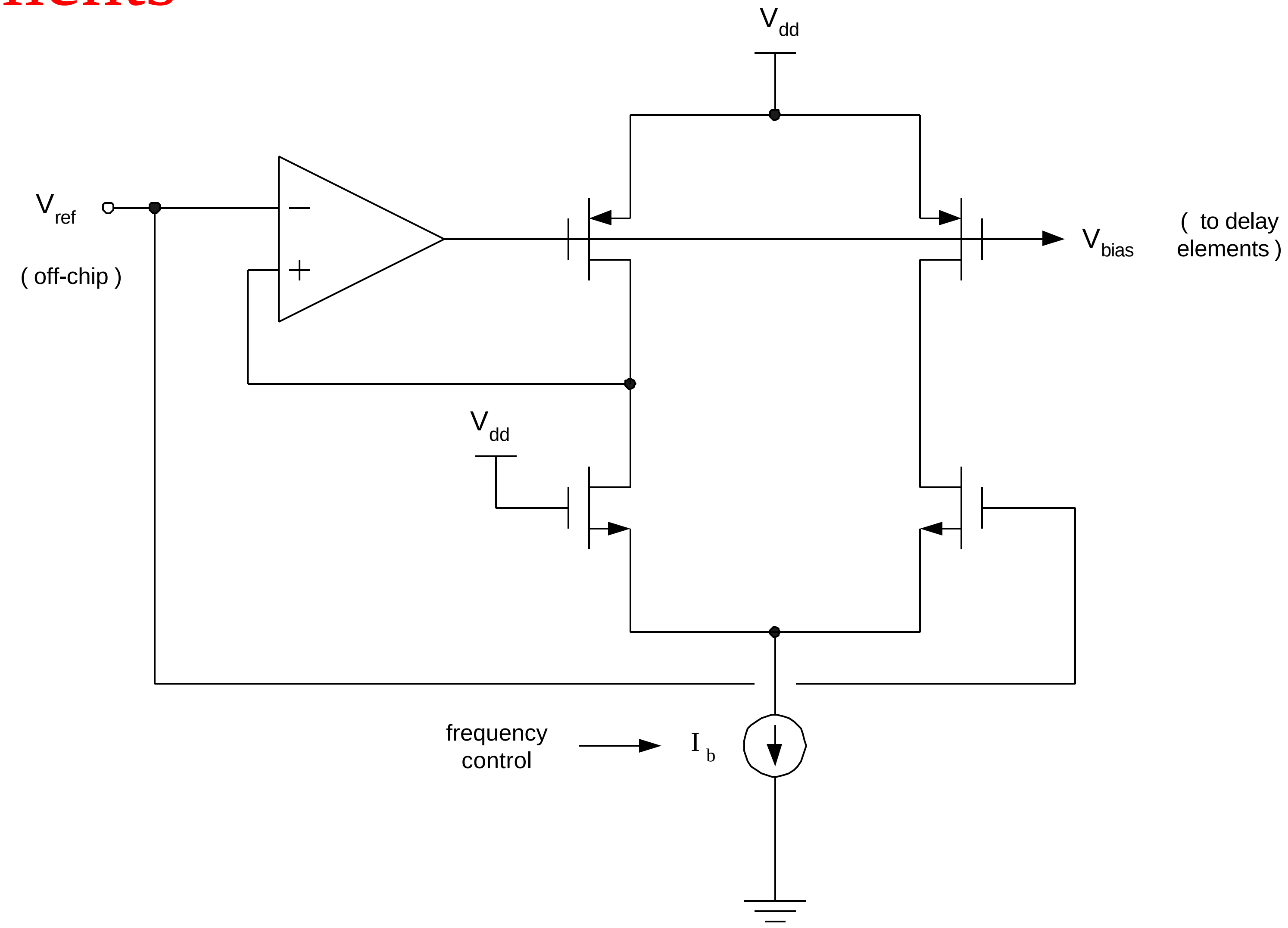
Fully-Differential Ring Oscillator



One potential delay element



Replica Biasing needed for the Delay Elements

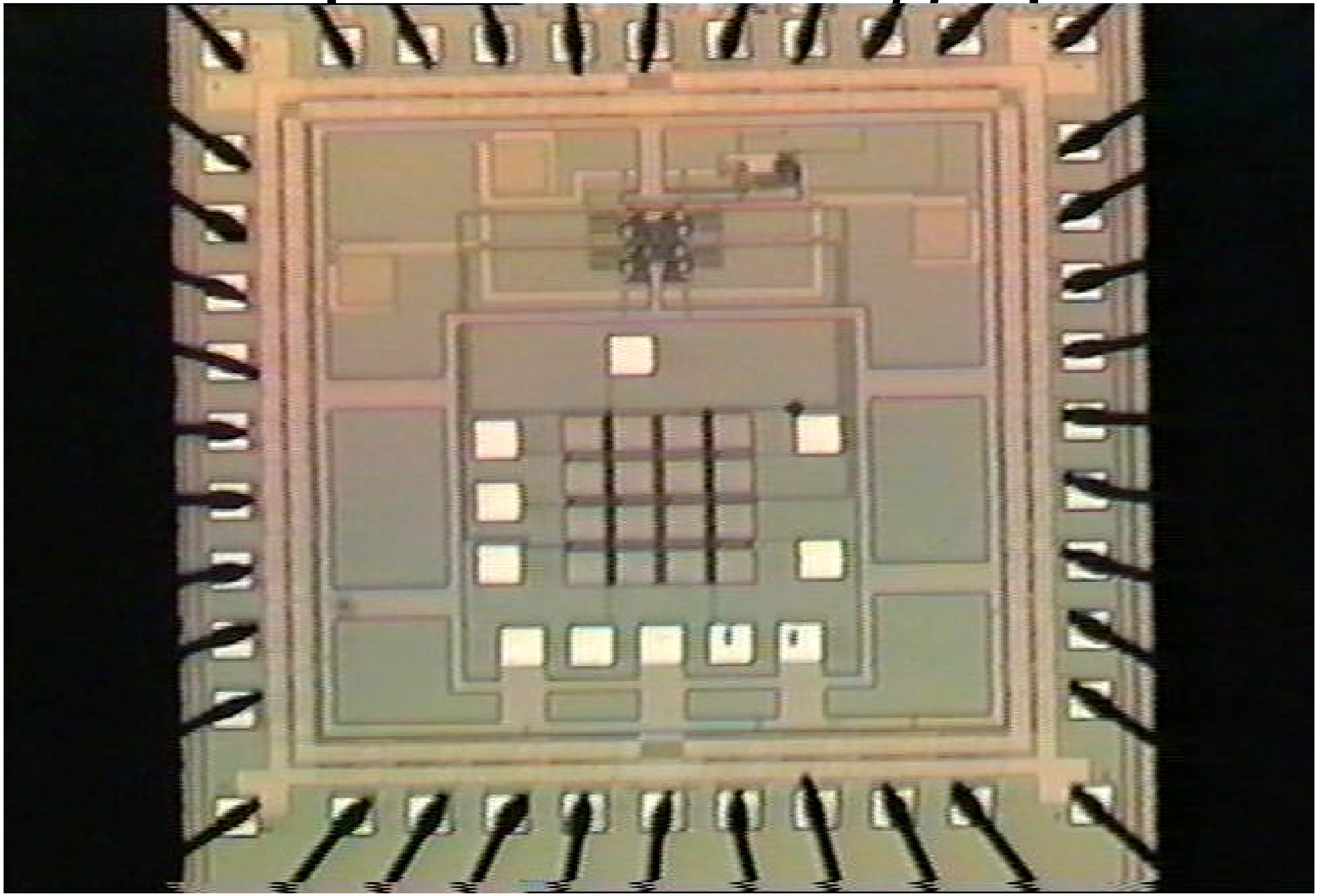


Frequency Control

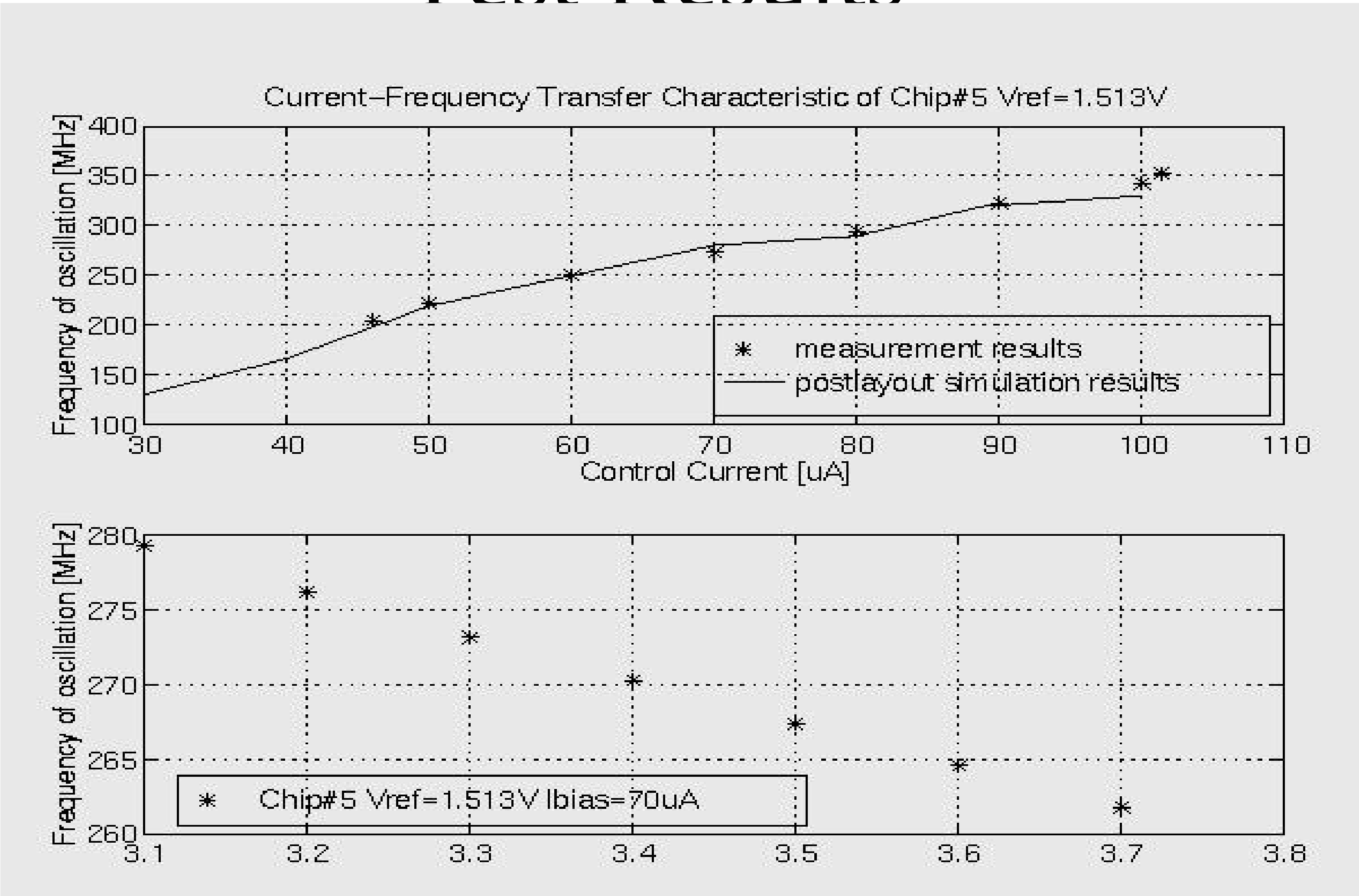
- Frequency of oscillation, (f_{osc}), is controlled through the bias current of a delay element (I_b).
- Maximum peak-to-peak voltage, (V_{pp}), is controlled through the replica biasing.
- Total output capacitance of a delay element, (C_{out}), directly affects the frequency of oscillation.

$$f_{osc} \approx \frac{I_b}{V_{pp}.C_{out}}$$

Chip Photomicrograph



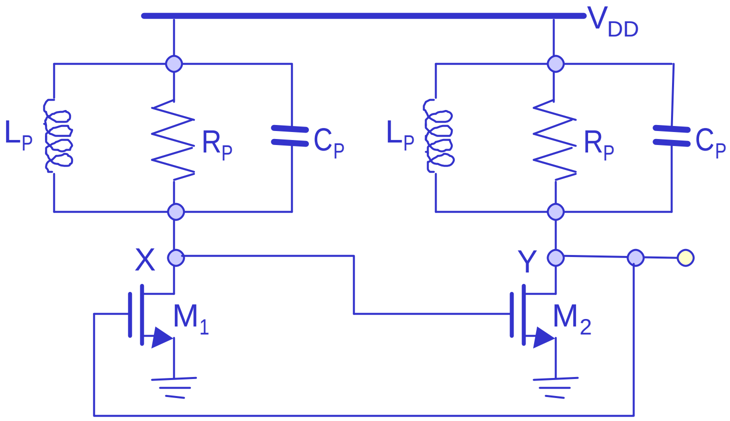
Test Results

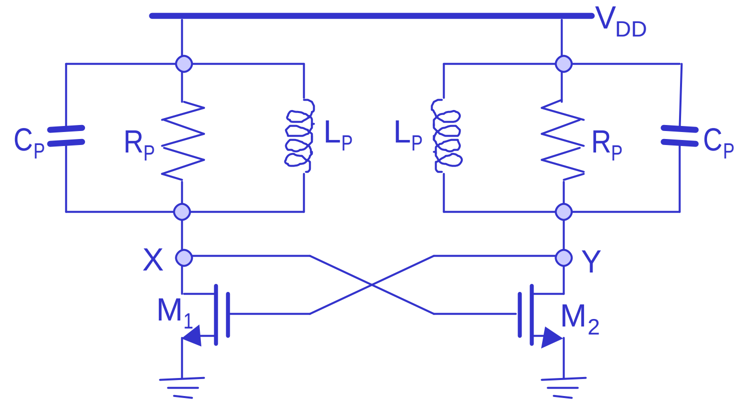


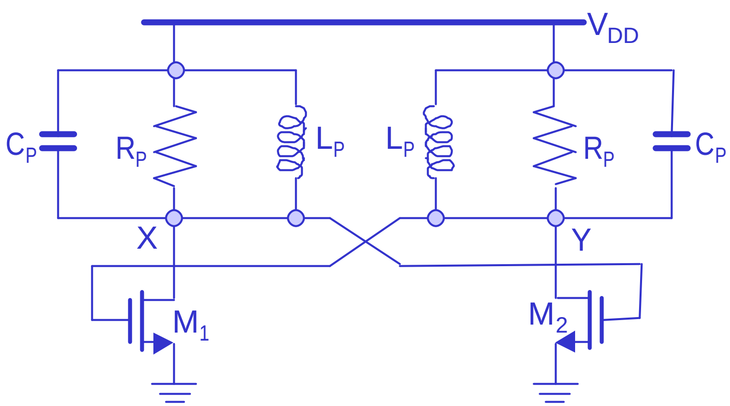
LC Oscillators

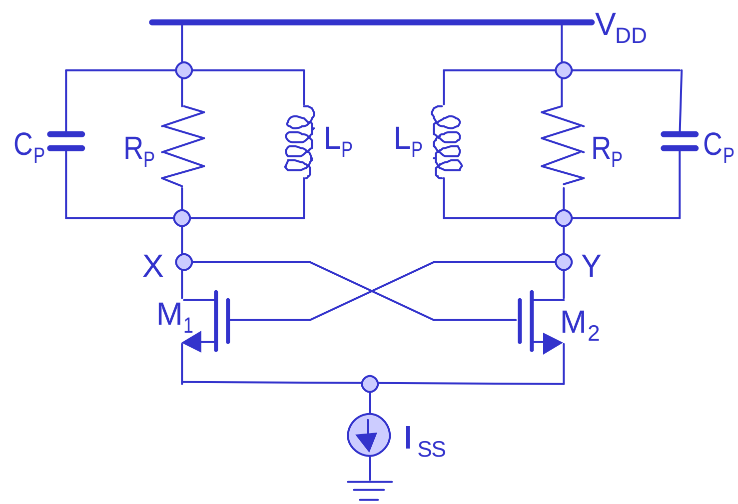
- Negative-g_m (negative conductance) oscillators are known to provide the best phase noise performance among integrated oscillators.
- It is possible to build a fully-differential oscillator with only two transistors in the signal path.
- The phase noise depends on the quality factor of the resonator, the noise figure of the amplifier creating the negative resistance and the energy in the resonator.
- The quality factor of the resonator is usually limited by that of the inductor.

Tuned LC Oscillators

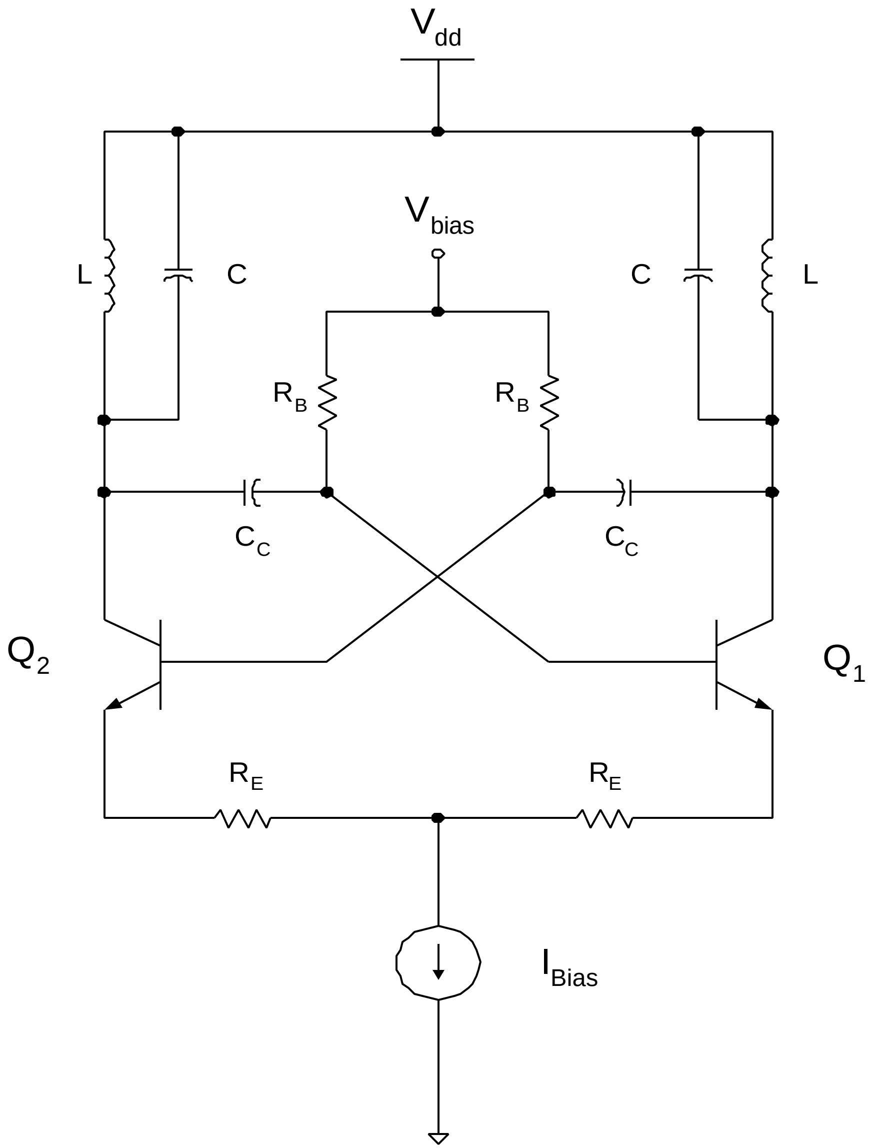






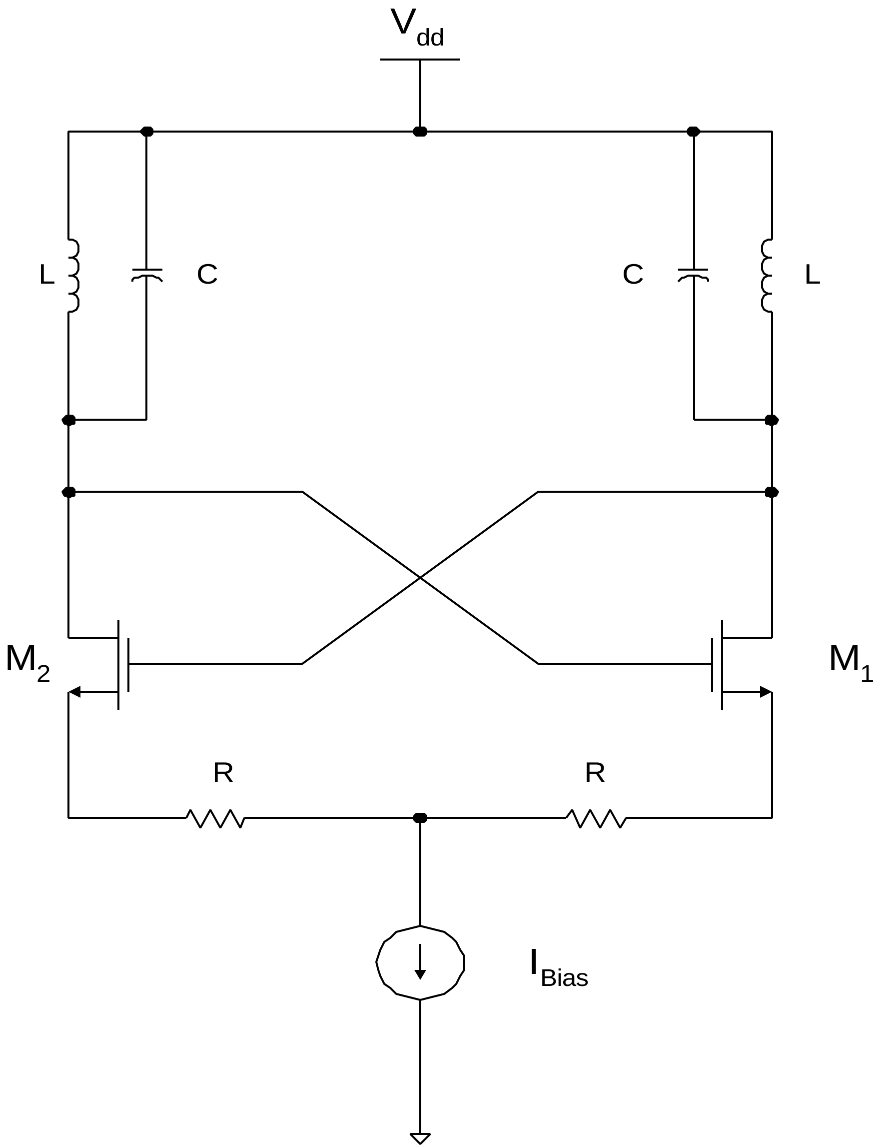


Bipolar LC Oscillator



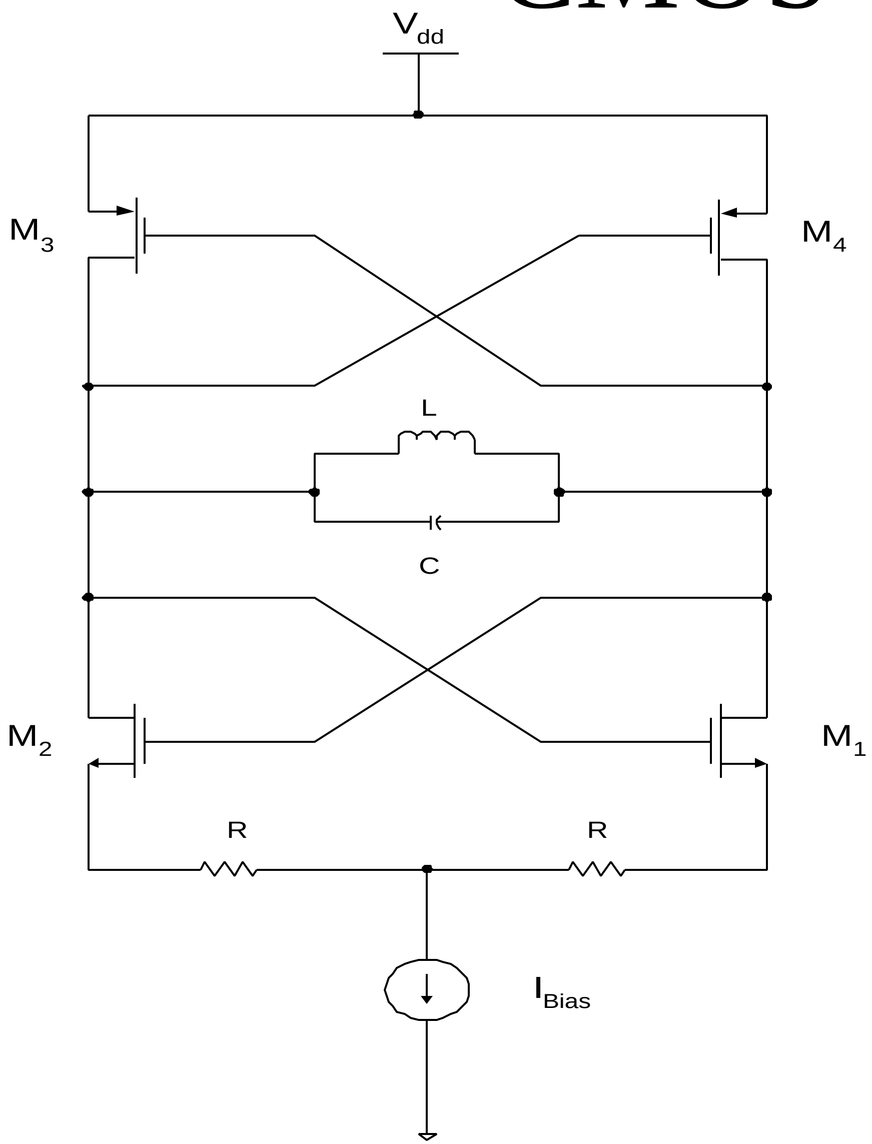
- Capacitive coupling is used to alleviate the forward-biased CB junction problem.
- Higher oscillation amplitude is possible, which reduces the phase noise significantly.
- Further increase in the amplitude is possible through adjusting the value of the bias voltage applied to the base terminals.
- Proper design of the capacitive coupling is vital to ensure oscillation.

NMOS Oscillator



- Direct coupling is possible in the positive feedback amplifier due to the fact that MOS transistors are inherently more linear than the bipolar counterparts.
- Source degeneration resistors reduce the phase noise through linearization.
- *1/f* noise of the NMOS transistors is an important drawback.

CMOS Oscillator



- Less current consumption is possible due to the additional pMOS transistors used for negative conductance generation.
- Better waveform symmetry can be achieved through proper sizing of the transistors.
  - Less phase noise due to less 1/f upconversion!

References

[1] B. Linares-Barranco, A. Rodríguez-Vázquez, E. Sánchez-Sinencio and J. L. Huertas, “A 10 MHz CMOS OTA-C Voltage Controlled Quadrature Oscillator," *Electronics Letters*, Vol. 25, pp. 765-767, 8 June 1989.

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