Analog Lab
Experiment 11: Double Balanced Mixer

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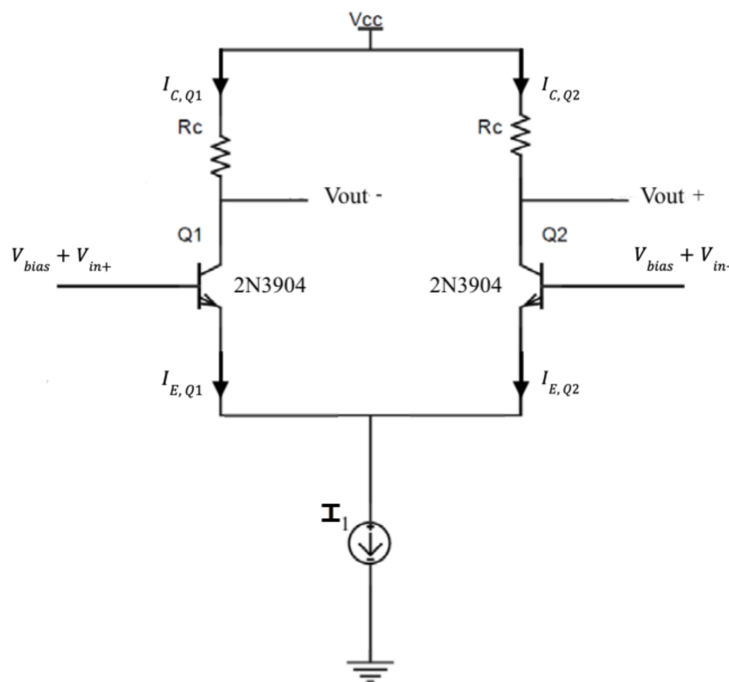
1. To implement the circuit in Experiment 8 using MC1496 with
Input Signal Frequency: 11kHz
Carrier Frequency: 10kHz

The output of a mixer circuit is the product of the two input signals, and these circuits are heavily used in wireless systems. When we multiply a known periodic signal and an input signal containing data, convolution occurs in the frequency domain. The resultant signal is centered around the periodic signal's frequencies and the process is called frequency translation.

As LTI systems cannot perform this frequency translation, the MC1496 IC uses BJTs biased in active region and some resistances.

Working of a Differential Amplifier-

It is a device that amplifies the difference in inputs using BJTs in active mode.



The two input signals are given at the base of Q1 and Q2 and the output is taken as the difference of the collector voltages.

I_C and V_{BE} for a BJT are related as follows-

$$I_C = I_S \times exp\left(\frac{V_{BE}}{V_T}\right)$$

Also I_C and I_E are related as follows-

$$I_C = \alpha I_E$$

Note that there is a biasing voltage V_{bias} at the input to ensure that V_B is greater than 0.7V for BJT to be in active mode.

Also from KCL: $I_1 = I_{E,Q1} + I_{E,Q2}$

So writing the equations for the two BJTs –

$$I_{C,Q1} = I_S\, exp\left(\frac{V_{bias} + V_{in+} - V_E}{V_T}\right) = \alpha I_{E,Q1}$$

$$I_{C,Q2} = I_S\, exp\left(\frac{V_{bias} + V_{in-} - V_E}{V_T}\right) = \alpha I_{E,Q2}$$

Dividing the above two equations –

$$I_{E,Q1} = I_{E,Q2}\, exp\left(\frac{V_{in+} - V_{in-}}{V_T}\right)$$

Substituting the above result in the KCL equation and taking $\left(V_{in+} - V_{in-}\right) \ll V_T$, we can use the power series expansion for e^x and approximate it as $1 + x$. So we get –

$$I_{E,Q1} = \frac{I_1}{2 - \frac{V_{in}}{V_T}} \quad \text{and} \quad I_{E,Q2} = \frac{I_1}{2 + \frac{V_{in}}{V_T}}$$

where $V_{in} = V_{in+} - V_{in-}$ and V_T is the thermal voltage.

Now writing KVL from V_{CC} to V_{out+} and V_{CC} to V_{out-} we get-

$$V_{CC} - I_{C,Q1} R_C = V_{out-}$$

$$V_{CC} - I_{C,Q2} R_C = V_{out+}$$

Subtracting the above two equations and substituting the values for I_C from the above results, we finally get that –

$$V_{out} \approx \frac{\alpha R_C}{2V_T} I_1 V_{in}$$

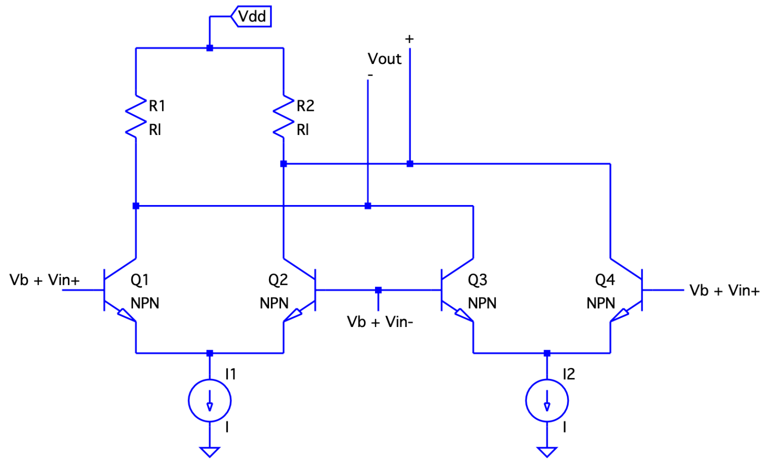
where $V_{out} = V_{out+} - V_{out-}$

In essence the output is the amplified difference between the input signals and can be controlled by changing the constants.

Also note that (this will be useful later) –

$$I_{C,Q1} - I_{C,Q2} = \frac{\alpha I_1}{2V_T} V_{in}$$

The adjacent circuit is a cross-coupled differential amplifier.



Using the superposition theorem, we can find V_{out} as the sum of V_{out} due to differential amplifier 1 (having Q1 and Q2) and differential amplifier 2 (having Q3 and Q4).

So-

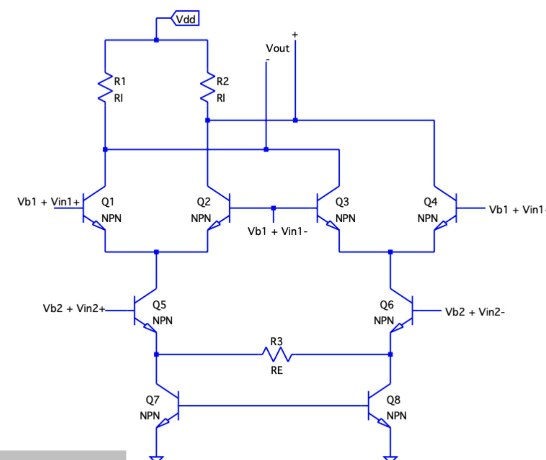
$$V_{out} = \left(V_{out}\right)_{diff1} + \left(V_{out}\right)_{diff2}$$

$$V_{out} = \frac{\alpha R_C}{2V_T} I_1 \left(V_{in+} - V_{in-}\right) + \frac{\alpha R_C}{2V_T} I_2 \left(V_{in-} - V_{in+}\right)$$

(using results from above)

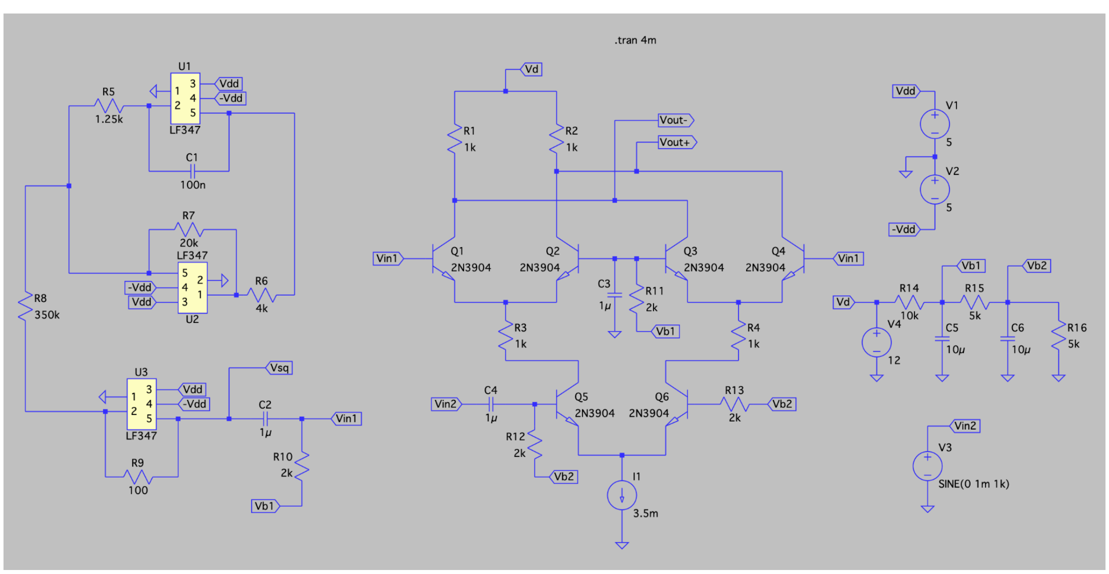
$$V_{out} = \frac{\alpha R_C}{2V_T} \left(I_1 - I_2\right) V_{in}$$

Now the $R_C(I_1 - I_2)$ term can be replaced with another BJT differential amplifier with tail resistances which effectively acts as a current source.



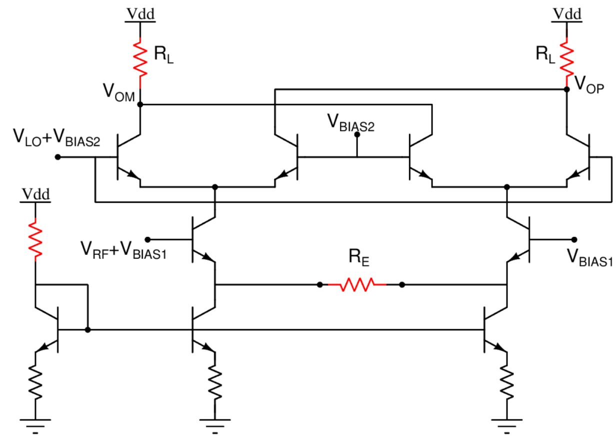
So we get-

$$V_{out} = \frac{\alpha^2 R_L}{4V_T^2 R_E} V_{in1} V_{in2}$$



Implemented Circuit from Experiment 8

Now looking at the IC ports in LTSpice, we need to connect in the following way-

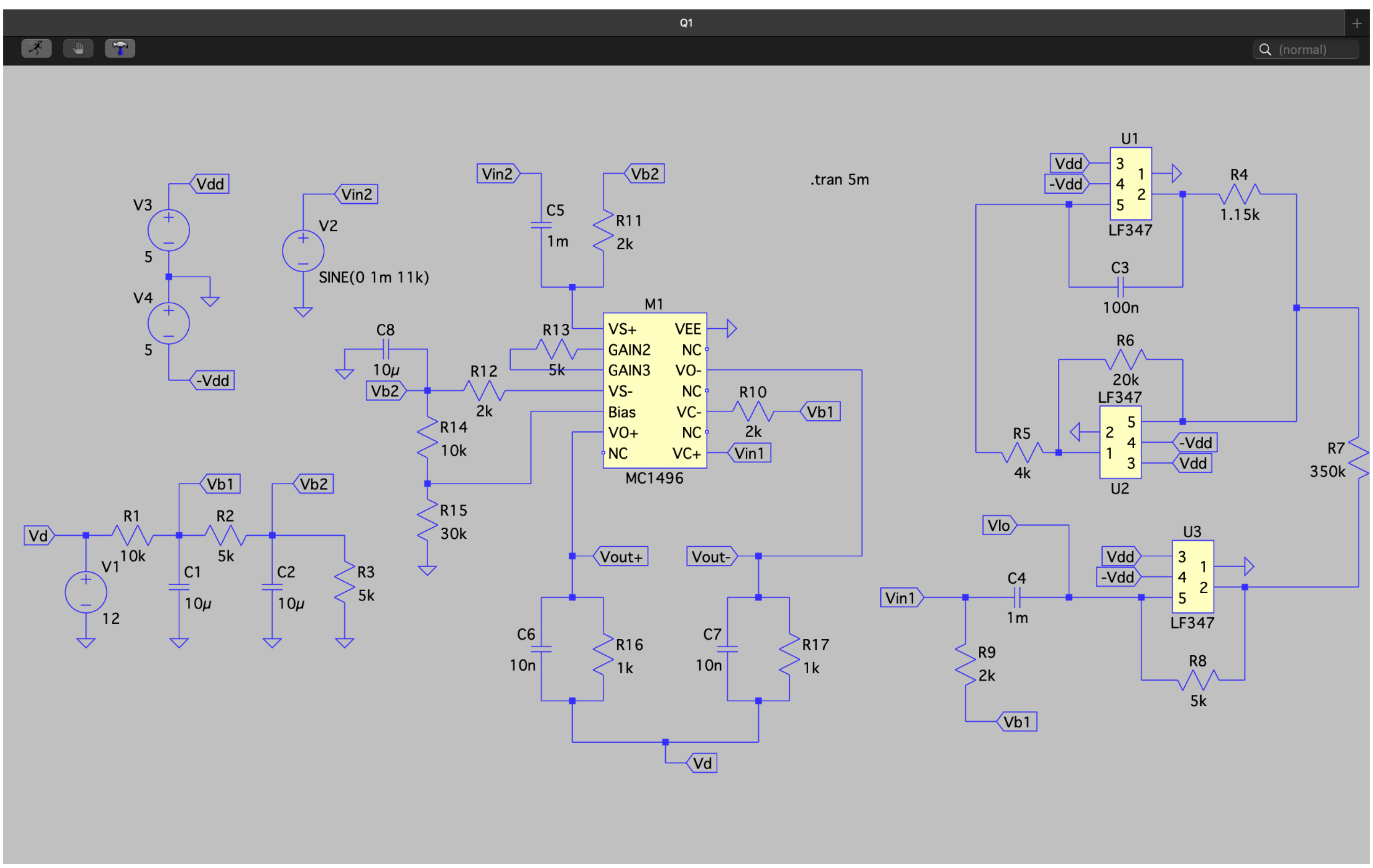


1) $V_{in1} \rightarrow V_{C+}$
2) V_{b1} with R_{11} and $C_3 \rightarrow V_{C-}$
3) $V_{EE} \rightarrow$ GND
4) V_{in2} with C_4 and $R_{12} \rightarrow V_{S+}$
5) V_{b2} with $R_{13} \rightarrow V_{S-}$
6) V_{O+} and V_{O-} are used as output nodes for V_{out1} and V_{out2}
7) Use a resistance divider network with 10kΩ and 30kΩ resistance connected with source as V_{b2}

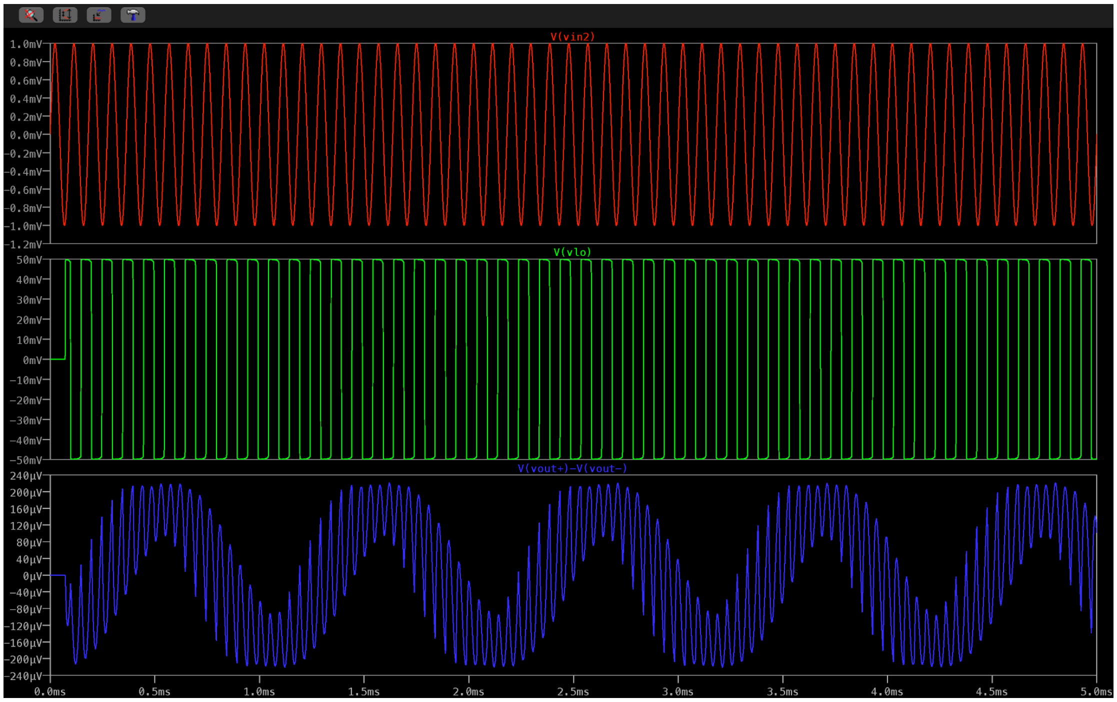
We connect capacitors across R_L to filter out the undesired frequency components like 19kHz, 21kHz and above (since the frequencies present are 10kHz * m $\pm$ 11kHz where m is an odd natural number). So the cutoff frequency of the parallel RC component must be at most 19kHz. So

$$\frac{1}{2\pi R_L C} < 19kHz \quad \Rightarrow \quad C > 8.376nF$$

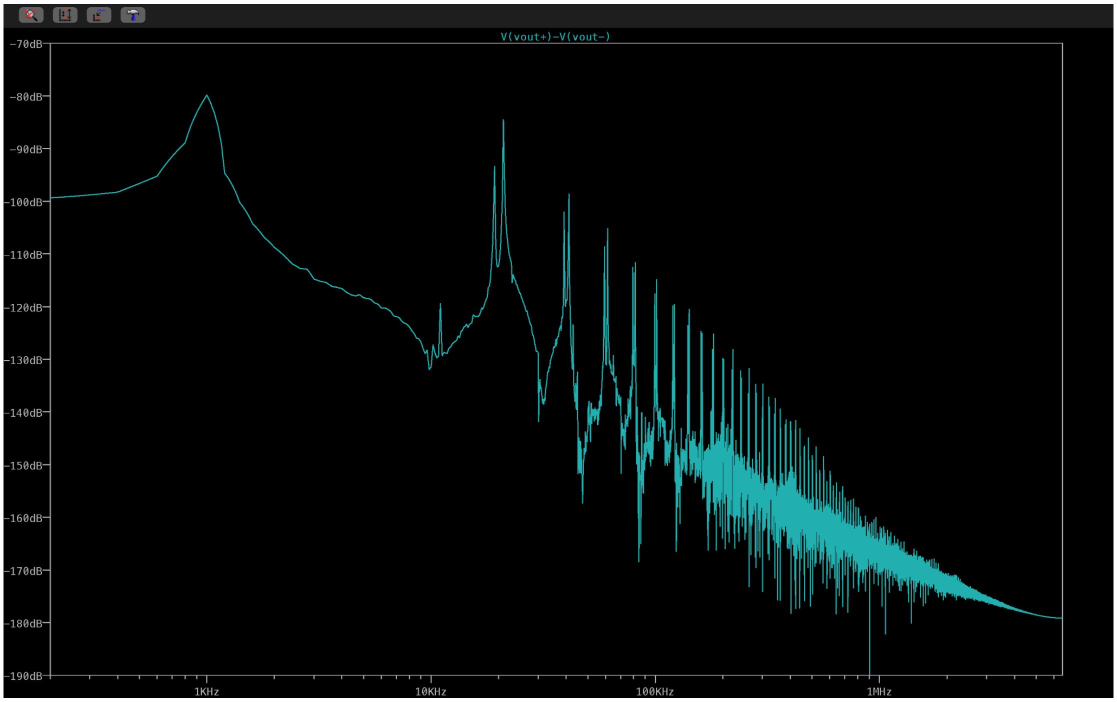
Implementation in LTSpice



Transient Plots



FFT of the output



Some observations-

1) There is a significant peak at 1kHz which was expected.
2) The peaks at 19kHz, 21kHz and above have been damped due to the parallel RC circuit.
3) The output is a sine wave at 1kHz with some disturbances due to higher frequency components not being eliminated completely.

2. Converting the differential output of the mixer to single ended output using Op-Amp

First we find the relation between single ended output and currents i_1 and i_2 .

Writing KVL across R_L (feedback one)-

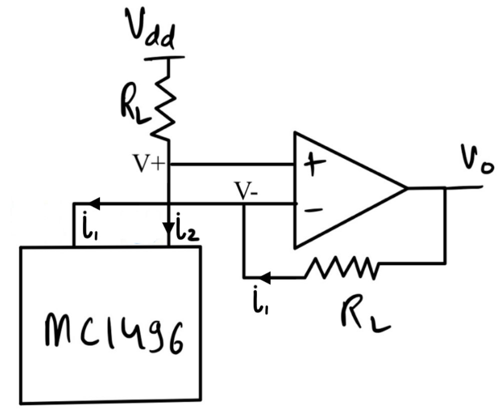
$$V_o - i_1 R_L = V_-$$

Writing KVL across R_L (connected to V_{dd})-

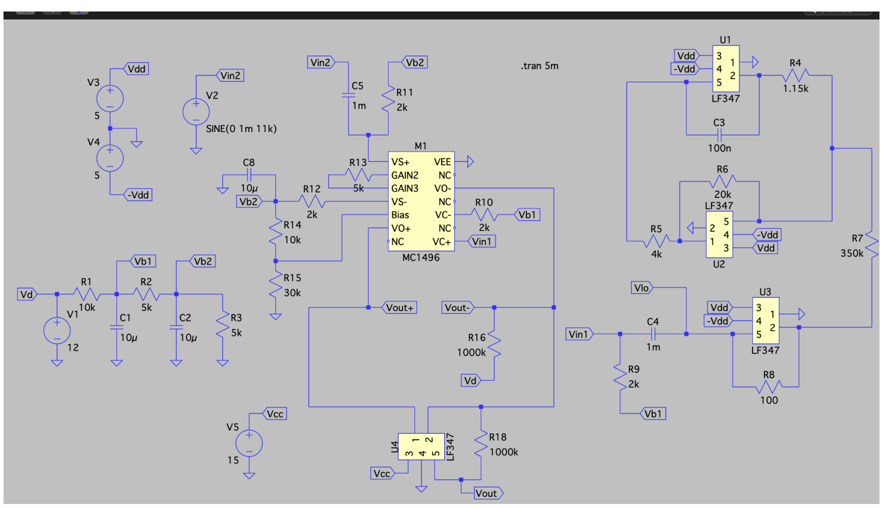
$$V_{dd} - i_2 R_L = V_+$$

And since the Op-Amp is in negative feedback, we can equate V_+ and V_- , so we get-

$$V_o = V_{dd} + \left(i_1 - i_2\right) R_L$$

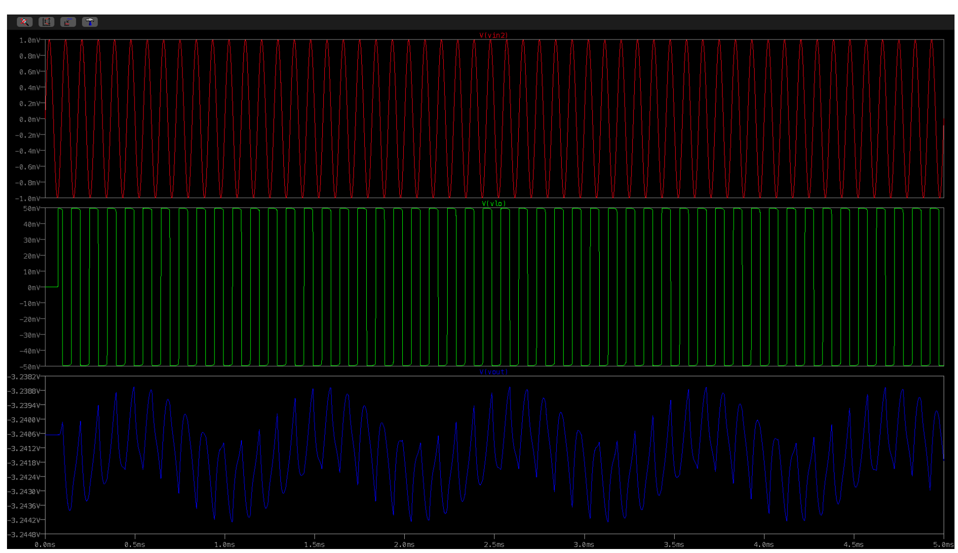


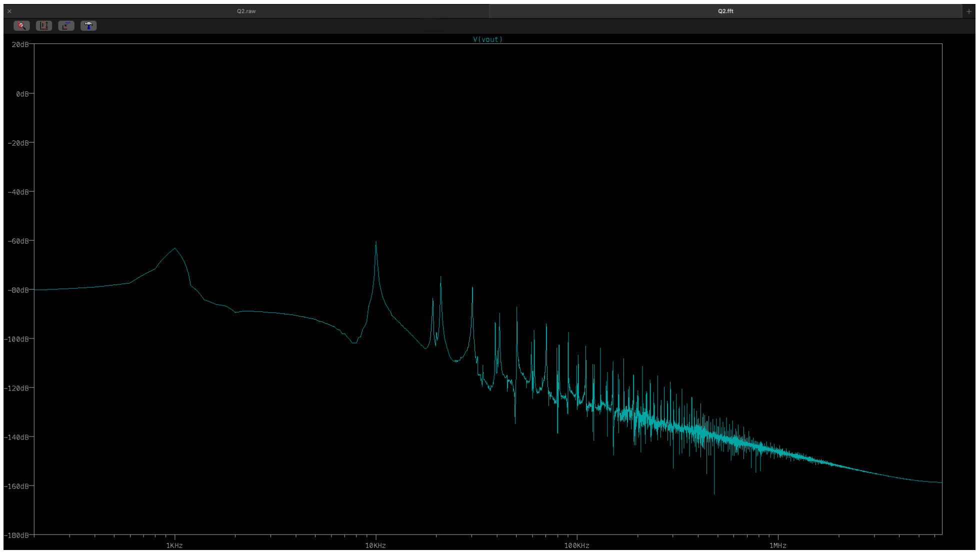
So dropping the $V_{dd} + R_L$ connection to V_{out+} , implementing the Op-Amp circuit as shown above and taking $R_L = 1000k\Omega$ for high amplification we get-



Implementation in LTSpice

Transient Plots





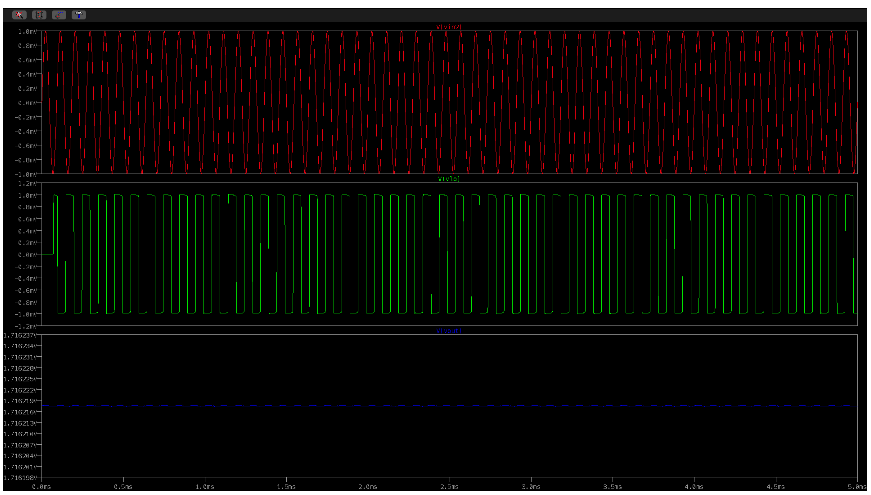
FFT of the output

Some observations-

1) Output plot has an envelope that looks like a sine wave with 1kHz frequency.
2) There are peaks at 1kHz, 10kHz, 19kHz and 21kHz as we removed the capacitances which acted as filters.

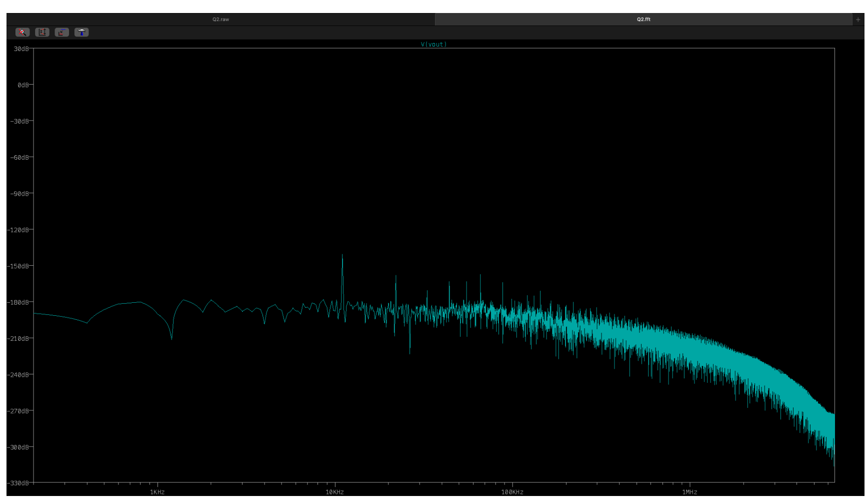
When only V_{RF} is applied

Implemented this by removing the 1mF capacitor connecting the VCO and V_{C+}



Transient plot

FFT of the output

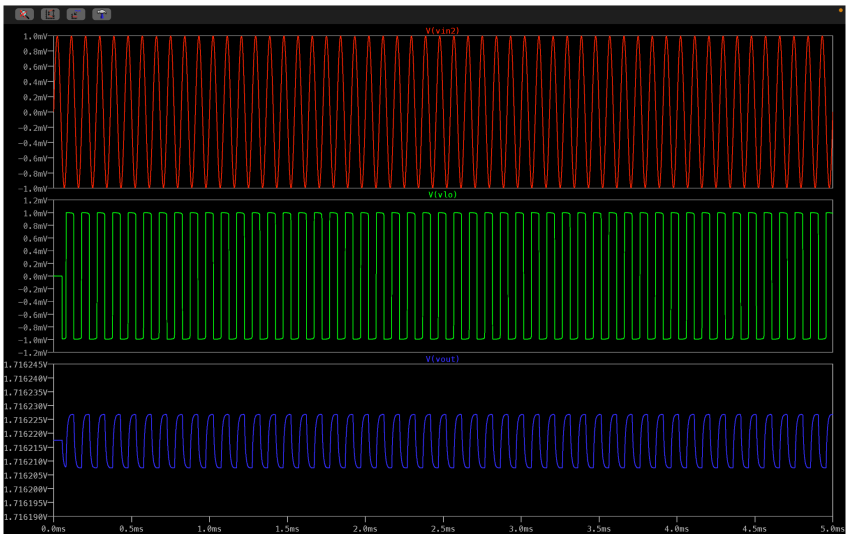


Some observations

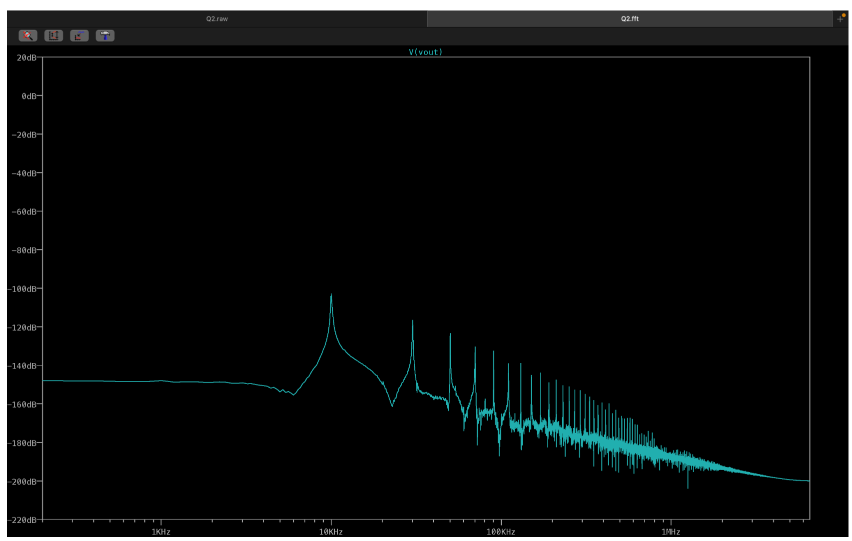
1) The output voltage is non-zero with very small amplitude as we applied a bias voltage instead of grounding.
2) There is a peak at 11kHz in the frequency domain which suggests that the output plot is a sine wave but it has a very small amplitude.
3) So there is no significant RF to LO feedthrough.

When only V_{LO} is applied

Implemented this by removing the V_{in2} flag from the 1mF capacitor



Transient Plots



FFT of the output

Some observations-

1) The output plot is a square wave.
2) Peaks in the FFT plot are at odd harmonics of 10kHz, i.e. 10kHz, 30kHz, 50kHz, etc.
3) So even though only the constant bias is applied at V_{RF} , the output is still a square wave and so we can say that there is LO to RF feedthrough.