EE160: Principles of Communication Systems

Experiment 4: Amplitude demodulation and down-conversion

I. INTRODUCTION

a. Objectives

i. Study the operation of a synchronous detector using a nonlinear device and a filter for demodulation of (large carrier) AM signals.

ii. Design an envelope detector and verify it using MATLAB.

iii. Study the operation of an envelope detector for demodulation of conventional AM signals.

b. Required reading

i. Proakis and Salehi, chapter 3

BUILD THE ADDITIONAL CIRCUITRY SHOWN IN FIGURE 4.1
BEFORE YOU COME TO THE LAB

c. List of parts

i. Synchronous detector (see notes)

1. One 68 kΩ resistor for inverting amplifier
2. The diode circuit from experiment 1
3. The lowpass filter circuit from experiment 2

ii. Envelope detector (see notes)

1. Small signal silicon diode (1N914 or equivalent)
2. One capacitor (C10) of value determined in section 4

Reminder: You will NOT be using the spectrum analyzer for this experiment.

Read Sections III and IV of this procedure before attempting to build the circuit

You will need to determine the values of a few components (for C9, C10 and R16) as described in Section IV. The circuit from Experiment 2 is used again to detect AM signals with a synchronous demodulator.

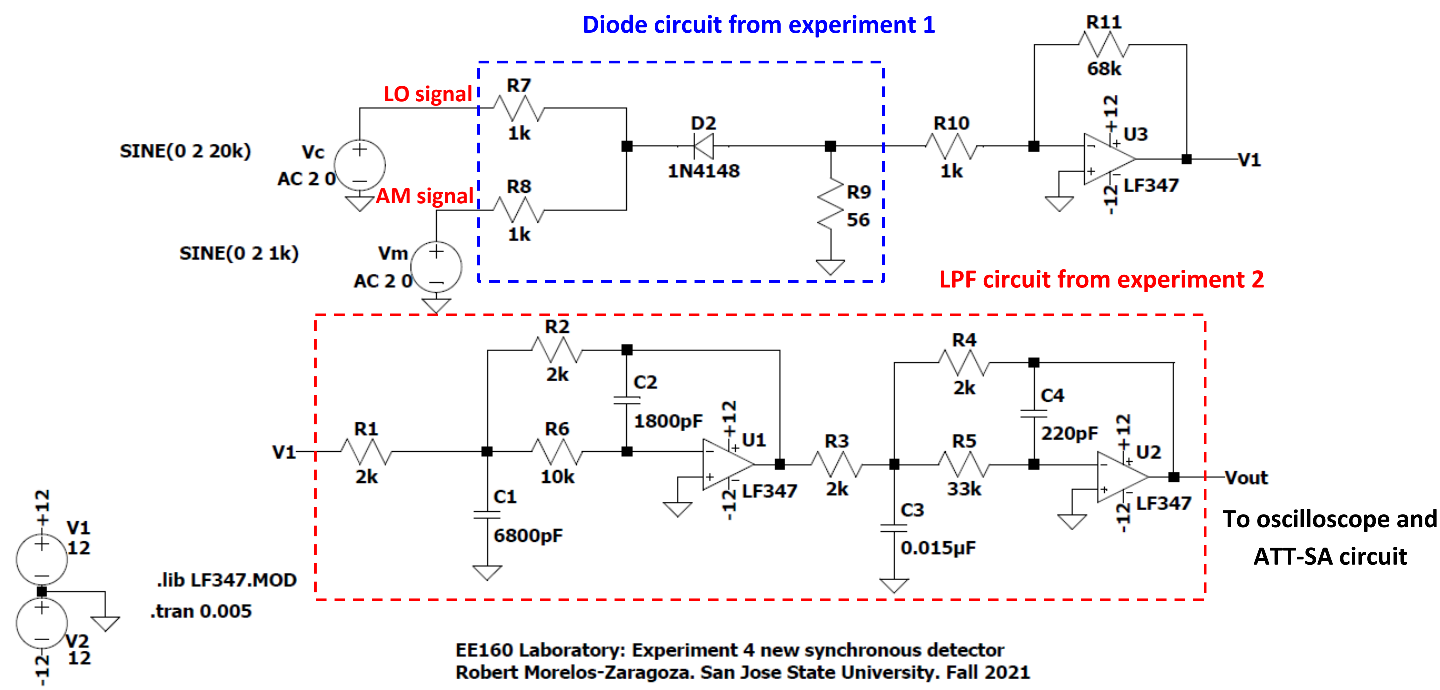


Figure 4.1a: Synchronous detector

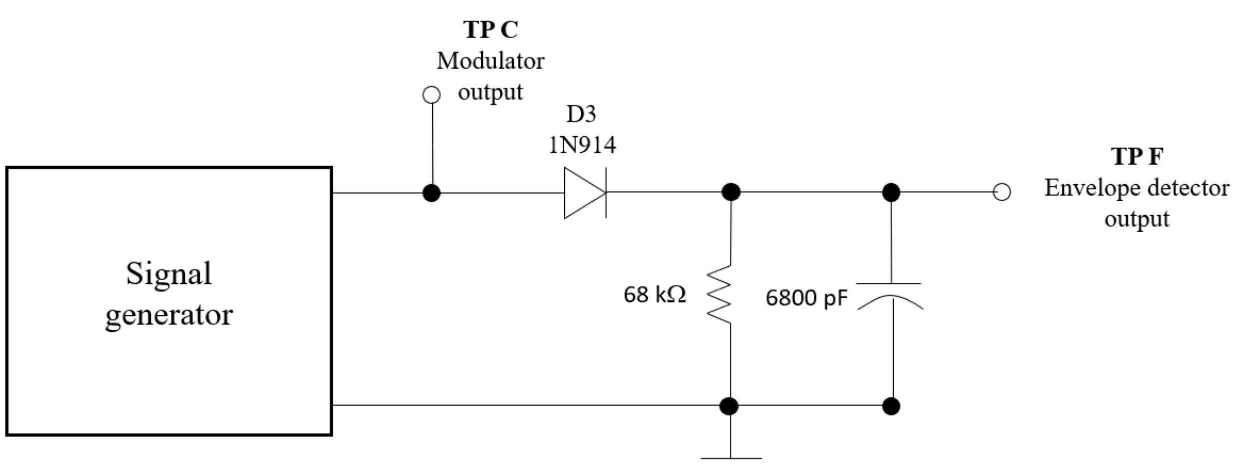


Figure 4.1b: Envelope Detector

II. THEORY

II.1 Synchronous detection of AM signals

A synchronous detector is a circuit for demodulating a DSB-SC or a DSB-LC (AM) signal. The detector recovers the low pass (or "baseband") signal that was used to modulate the carrier in the DSB modulator. In Figure 4.1a, the synchronous detector is implemented as using an adder and a diode. This creates harmonics and intermodulation products that include the product of the input signals to the adder.

When a DSB signal is demodulated at the carrier frequency f_c, the output spectrum contains the DSB sidebands at $-f_c$, $+f_c$ and $f = 0$ (See Figure 4-2). The spectral copy at $f = 0$ is proportional to the message signal. This component can be isolated from the two other mixing products using a low pass filter. Since the bandwidth of the message signal is usually much lower than the carrier frequency f_c (i.e., *narrowband* modulation), this low pass filter can even be implemented as a simple passive RC filter.

As seen in class, a synchronous detector can be used to demodulate either a DSB-SC or a DSB-AM signal. The low pass-filtered detector output looks like the modulating signal $m(t)$ that was supplied to the AM modulator: For DSB-SC, the output will have no DC offset, and for DSB-AM, the output will have a DC offset that is proportional to the carrier amplitude. A synchronous detector can demodulate a conventional DSB-AM signal with any modulation index value, unlike the asynchronous envelope detector.

For either DSB modulation mode, the demodulator must be exactly in phase (or "synchronously") with the carrier. In other words, the demodulator oscillator must be locked in both frequency and phase to the carrier. Since the spectrum of a DSB-SC signal does not contain a carrier line, generating a carrier frequency from a DSB-SC signal is a difficult problem. Typically, a separate "pilot" tone is transmitted outside the DSB-SC channel to aid in local oscillator signal generation, or a phase-locked loop (PLL) at the receiver is employed. In this experiment, we explore this synchronization problem.

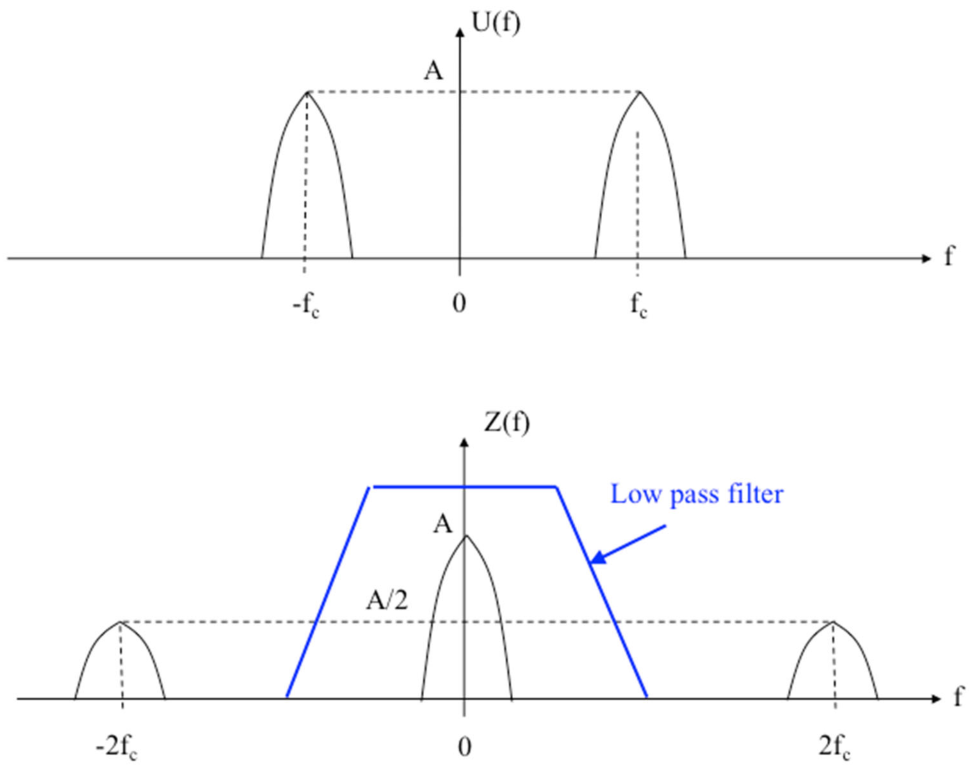


Figure 4.2: Demodulation of a DSB signal

For conventional DSB-LC (AM) signals, a carrier is present and must be somehow separated from the sidebands. A brute-force approach is to greatly amplify and then clip the DSB-LC signal. The clipping removes the envelope amplitude variations, leaving essentially a constant amplitude square wave that has the same frequency and phase as the carrier. Unfortunately, the high gain amplifier before the clipper also introduces a significant noise component in the signal, so that this approach is usable only at very high levels of signal power.

If the detector's local oscillator frequency differs from the carrier by a frequency offset Δf, the detector output is a scaled copy of the modulating waveform, multiplied by a sinusoidal signal:

$$y(t) = b\, m(t) \cos(2\pi \Delta f\, t),$$

where b is a constant and $m(t)$ is the modulating (message) signal. This will result in an unacceptable time varying and multiplicative distortion.

On the other hand, for a clock-carrier constant *phase* offset $\Delta\theta$, and no frequency offset, the output will be less drastically affected:

$$y(t) = b\, m(t) \cos(\Delta\theta).$$

In this case, the output *amplitude* varies with the cosine of the phase offset but otherwise is not time dependent. For small constant phase errors, this effect is not significant. However, as $\Delta\theta$ approaches 90°, the demodulated signal amplitude rapidly falls to zero and disappears completely for a phase offset equal to 90°.

Coherent detection using a mixing diode

An alternative to a multiplier (mixer) is an adder followed by a nonlinear device, such as a diode, to produce harmonics (intermodulation products). The harmonic components include the product of the two signals input to the adder. In this experiment we follow this approach.

II.2 Envelope detector

A basic envelope detector circuit, illustrated in Figure 4.3, consists of a diode feeding a parallel RC circuit. The detector's load resistance, if any, is usually much larger than R, so that the circuit time constant is effectively $\tau = RC$. At first sight, this circuit may seem to be just the cascade connection of a half-wave rectifier and an RC low pass filter. However, the envelope detector is an intrinsically nonlinear device that cannot be correctly analyzed by applying a linear filter transfer function to the spectrum of a half-wave rectified DSB-LC signal. Although it is possible to develop an analytical theory for this circuit, a MATLAB simulation analysis is much more instructive.

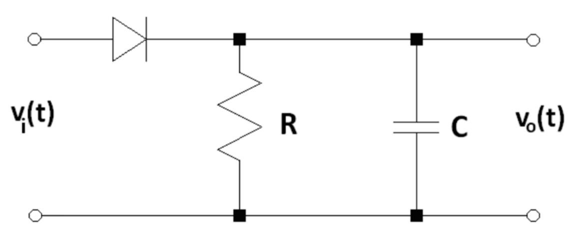


Figure 4.3: Basic envelope detector circuit.

The capacitor C charges very rapidly to $V_p - V_d$, where V_p is the peak voltage of $v_i(t)$ and V_d is the diode forward voltage drop. Then C discharges gradually through R with time constant τ. To design the circuit, one must select an appropriate value of τ. Figures 4.5 through 4.7 show three sample simulations (assuming a constant forward voltage $V_d = 0.7$ V).

For a "correct" value of the time constant τ, shown in Fig. 4-5, the detector output follows the envelope (sinusoidal) of a conventional DSB-AM signal, with some ripple that can be removed with a simple RC low pass filter. The detected envelope is proportional to the modulating waveform offset by a positive DC voltage, which can be removed by a series coupling capacitor.

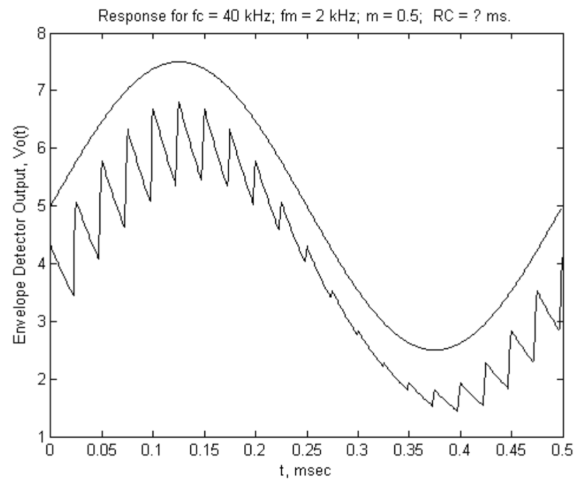


Figure 4.4: Correct value of time constant for the envelope detector

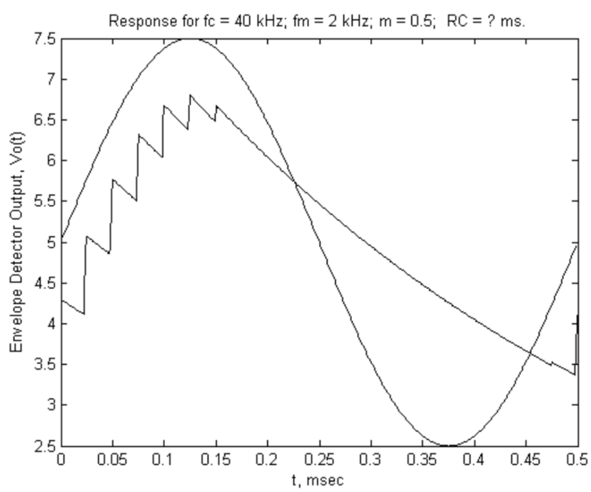


Figure 4.5: Excessively large time constant for the envelope detector

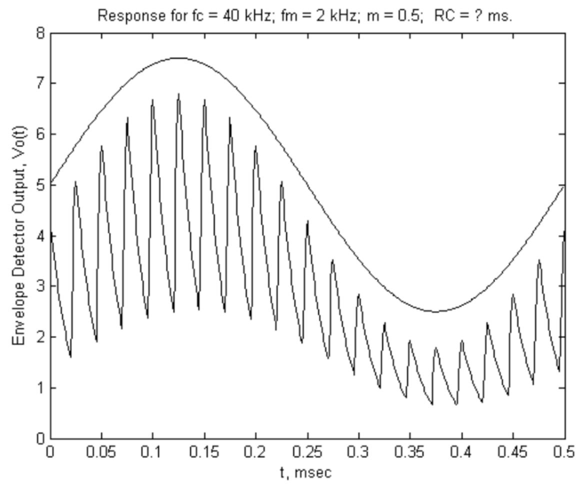


Figure 4.6: Excessively small time constant for the envelope detector

In the case when τ is too large, the detector output does not follow the variations of envelope amplitude and introduces significant distortion (Fig. 4.5). Conversely, when τ is too small, the ripple is excessive, which reduces the detector's output level and lowers the output signal to noise ratio (Fig. 4.6).

The optimal value of the time constant τ of the envelope detector depends on the modulating frequency, modulation index, and other factors. This means that a particular envelope detector may not work equally well for all input signals. Furthermore, the finite diode voltage drop causes the negative envelope peaks to be clipped when the modulation index is large enough to cause the diode to stop conducting during these negative peaks.

III. PRE-LAB WORK

III.1 Synchronous detector design

Build the circuit in Figure 4.1a and 4.1b with the designed values before coming to the lab.

III.2 Synchronous detector: LTspice model

Download LTspice model *mixing_diode_sync_detector.asc* from Canvas. The model simulates the synchronous detector circuit in Figure 4.1a. The two input signals to the adder (via the two 1KO resistors) are sinusoidal signals of peak-to-peak amplitudes both equal to 4 V and fundamental frequencies equal to 20 kHz and 1 kHz. The purpose of the model is to verify the correct functionality of the detector with two sinusoidal signals. Run the model and *attach* *printouts of the waveforms at V1 (adder and diode output) and Vout (lowpass filter output)***)** to your prelab work. You will be needing these as a reference when verifying and measuring the synchronous detector circuit in the lab (section IV.2).

III.3 Synchronous detector: MATLAB Simulink model

(1) Download MATLAB Simulink model *Synchronous_detector_diode_20kHz_testbench.slx* from Canvas. Run the model and *attach to your prelab work all the figures*. Compare the waveforms in the scope lower part "Adder + diode + LPF output" with the LTspice simulation results. Do they agree? Discuss.

(2) Now double-click on the single-pole double-throw switch S2 of the model to bring the pole to the lower input. The input to the detector is now an AM signal with a 100% modulation index. Run the model again *attach to your prelab work all the figures*. These results serve as a reference for the measurements in section IV.2.

III.4 Matlab script to aid in design of envelope detector

Figure 4.7 shows the MATLAB program used to generate the envelope detector simulations in Figures 4.4 to 4.6. This program results in a plot of a simulated envelope detector output waveform after the following information is supplied:

1) Carrier frequency (kHz),
2) Carrier amplitude (peak V),
3) Modulating frequency (kHz),
4) RC time constant (ms), and
5) Modulation index m (>0). (Note the change of letter used to represent modulation index in the script.)

```
%-----------------------------------------------------
% Envelope detector simulation program
% EE161 Laboratory
% Experiment 4
%-----------------------------------------------------
clear;

%Specify detector parameters
fc  = input('Carrier Frequency (kHz)          :');
Ac  = input('Unmodulated carrier amplitude (V):');
fm  = input('Modulating frequency (kHz)       :');
tau = input('RC time constant (ms)            :');
m   = input('Modulation index (m>0)           :');
m   = abs (m);

%Simulate the response
N = 500;                  % Number of points per cycle of fm
tmax = 2/fm;              % Simulate over 2 cycles of fm
tstep = tmax /(2*N);      % tstep = time step
t = [0:tstep:tmax];       % t = time axis values
wc = 2*pi*fc;             % wc = carrier angluar frequency
wm = 2*pi*fm;             % wm = moudlating waveform angular frequency
Vm = Ac*(1+m*sin(wm*t)); % Vm = modulation envelope
Vw = Vm .*cos(wc*t);      % Vw = Complete DSB-LC Waveform
Vr = max(Vw - 0.7, 0);    % Vr = half-wave rectified DSB-LC waveform
                          %      with a 0.7V diode forward drop
Ve(1) = 1;                % Ve = output of envelope detector

fac = exp(-tstep/tau);    % fac = decay factor over one time step

for n = 2:length(Vr),     % Simulate the envelope detector
    Ve(n) = max(Vr(n), fac * Ve(n-1));
end;

% Plot the deteced waveform in the time domain
% Note: We skip the first cycle to get past any transietns
plot (t(1:N), Ve(N+1:2*N), t(1:N), Vm(N+1:2*N));
xlabel ('t, msec');
ylabel ('Envelope Detector Output, Vo(t)');
title ([ sprintf('Response for fc = %g kHz; fm = %g kHz; m = %g; ', ...
    fc, fm, m), sprintf(' RC = %g ms.', tau)]);
pause;
```

Figure 4.7: MATLAB script used to simulate an envelope detector

Use this program to determine the "best" RC time constant under the following conditions:

1) The carrier frequency used in Experiment 3.

2) Carrier amplitude of 3V.

3) The following combinations of modulating frequencies and modulation indices:

f_m = 200 Hz, at m= 0.1, 0.5, 0.9; f_m = 1kHz, at m= 0.5

Print the graphs for the four conditions in (3) with your "best" time constants. **Include these graphs in your lab report.** Then use the "best" time constant τ_0 for f_m= 200 Hz at m = 0.5, to determine the designed value of C9 in the envelope detector circuit of Figure 4.1b. (The time constant is the product of R15 and C9; remember to use R15 = 2 kΩ.) Select a capacitor with a standard value nearest to this designed value within your kit and bring the capacitor to the lab.

Finally, for the same carrier frequency and amplitude, f_m= 200 Hz and time constant τ_0, simulate the envelope detector's response for m= 1.5 and 2. **Print the resulting graphs and include them in your lab report**.

IV. MEASUREMENTS

IV.1 Envelope detector

(1) Generate an AM signal of carrier amplitude 6 V_{pp}, carrier frequency 20 kHz and modulation index 100%, modulated by a 200 Hz sinusoidal signal. *Remember to set the output impedance of the signal generator to HI Z*. Measure the peak-to-peak amplitude and modulation index of the signal at TP C. Measure the peak-to-peak amplitudes of, and sketch, the waveform at TP F. Measure the positive peak voltages at TP C and TP F; then compute the approximate forward voltage drop of your diode (D3) as the difference between these peak voltages.

(2) Vary the signal generator modulation index from 0% to 100% in steps of 20%. For each value, measure, compute and record the peak-to-peak amplitudes at TP C and TP F. Over what range of modulation index values does the envelope detector produce a relatively undistorted waveform at TP F?

(3) Return the function generator modulation index to 100 %. Sketch the waveform at TP F for each of following modulating frequencies: 50 Hz, 500 Hz and 1 kHz. Over what value of

input frequency does the envelope detector produce a relatively undistorted waveform at TP F?

(4) Turn off modulation and generate a 100 Hz 5 V_{pp} and 0V DC offset square wave at TP C. Measure the actual time constant of your envelope detector by observing the signal at TP F on the scope. (Hint: The voltage across C9 will decay to 36.7% of its peak value in one time constant.) Adjust the frequency as needed to get the best accuracy in your final measurements.

IV.2 Mixing diode coherent detector

IV.2.1 Testing

Generate a 20 kHz 4 V_{pp} sinusoidal waveform with signal generator one (SG1). This will be the local oscillator *(LO) signal*. Use one of the oscilloscope channels to monitor this signal. Generate a 1 kHz 4 V_{pp} sinusoidal waveform with signal generator two (SG2). This will be the *AM signal*, which is initially set as the unmodulated message signal for testing. Use the oscilloscope to verify each signal's amplitudes and fundamental frequencies. Then connect the outputs of the signal generators to the inputs of the diode circuit from experiment 1 as indicated in the circuit schematic in Figure 4..1a.

Use the oscilloscope to measure the amplitudes and frequencies of the signals at V1 and Vout. Also record the waveform shapes and include them in your report.

IV.2.2 Demodulation of an AM signal

Modify the output waveform from SG2 to an AM signal of carrier amplitude 2 V_{pp}, carrier frequency 20 kHz and modulation index 100%, modulated by a 1 kHz sinusoidal signal. Use the oscilloscope to verify the signal amplitude and fundamental frequency. (The other oscilloscope input remains connected to the LO signal generated by SG1 to monitor frequency errors.)

The peak-to-peak amplitude of the AM signal should be 4 V_{pp}. <u>NOTE: Since SG1 and SG2 are independent, the carrier frequency values of the LO and AM signals will be different, producing a frequency error. You may need to change the LO frequency slowly in step of 0.00001 Hz to make this frequency error small</u>.

(1) Use the oscilloscope to measure the amplitudes and frequencies of the signals at V1 and Vout (see the schematic in Figure 4.1a). Capture the waveforms shapes and include them in your

report. You may see slow variations in the amplitude at Vout due to the frequency error. Take a note of this and add it to your report.

(2) Vary the signal generator SG2 modulation index from 0% to 100% in steps of 20%. For each value, repeat the measurements of the previous step (1).

V. ANALYSIS OF RESULTS

Section IV.1

- Modify the MATLAB program so that it uses the diode forward voltage drop measured in step (2) instead of 0.7V. Using the time constant value measured in step (5), simulate the detector's response to a carrier of amplitude 3 V, under the following conditions:

  (1) Modulating frequency of 50 Hz, 200 Hz, 500 Hz, and 1 kHz for a 100% modulation index.

  (2) Modulation index of 20%, 40% and 80% at a modulating frequency of 200 Hz.

  Print the simulated output waveforms. (Note that you will have to compute the modulation index for each of these simulation conditions before running the MATLAB program.)

- Using your measurements from step (3), plot the relationship between the envelope detectors' output amplitudes (TP F and TP G) and the input signal amplitude.

- Explain why distortion is produced in the envelope detector for certain types of input signals. Compare your simulated and actual measurements on the envelope detector.

Section IV.2

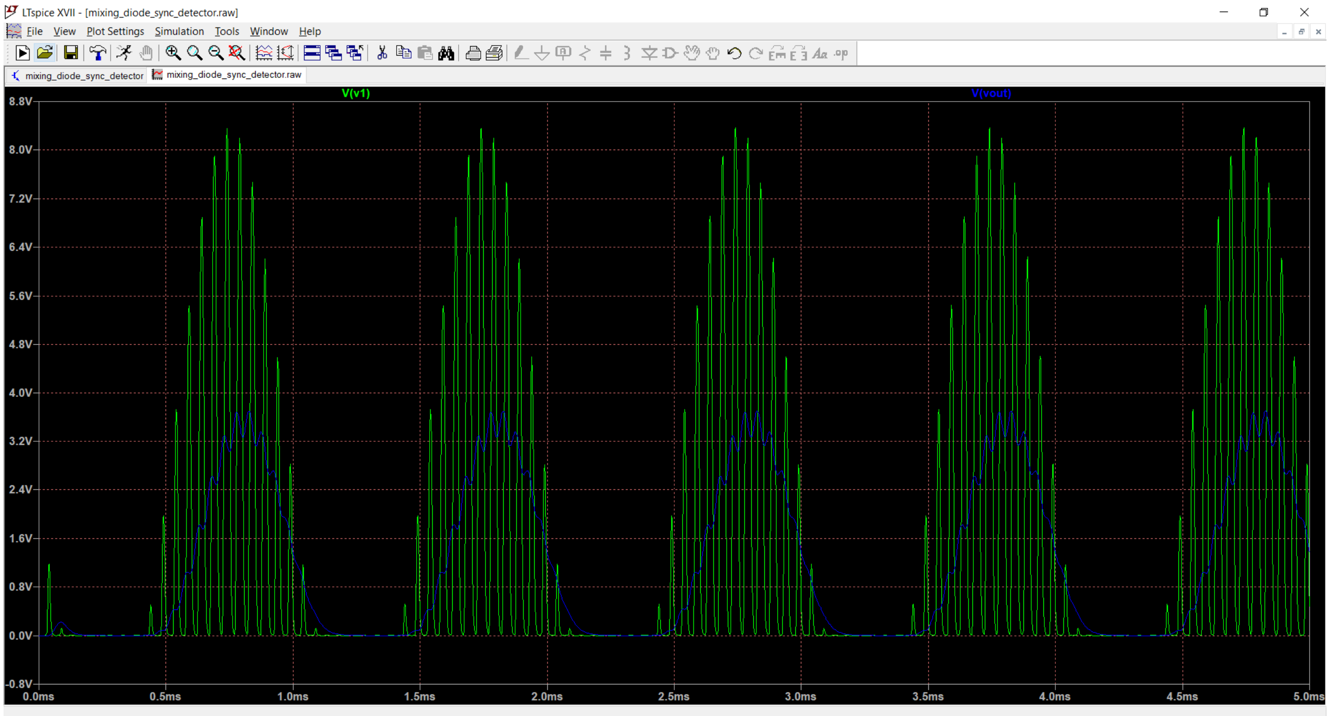
- Compare the waveforms measured in section IV.2.1 with the *LTspice model* simulation results. How do they compare? Discuss any discrepancies.

- Compare the waveforms measured in section IV.2.2 with the *MATLAB Simulink model* simulation results. How do they compare? Discuss any discrepancies.

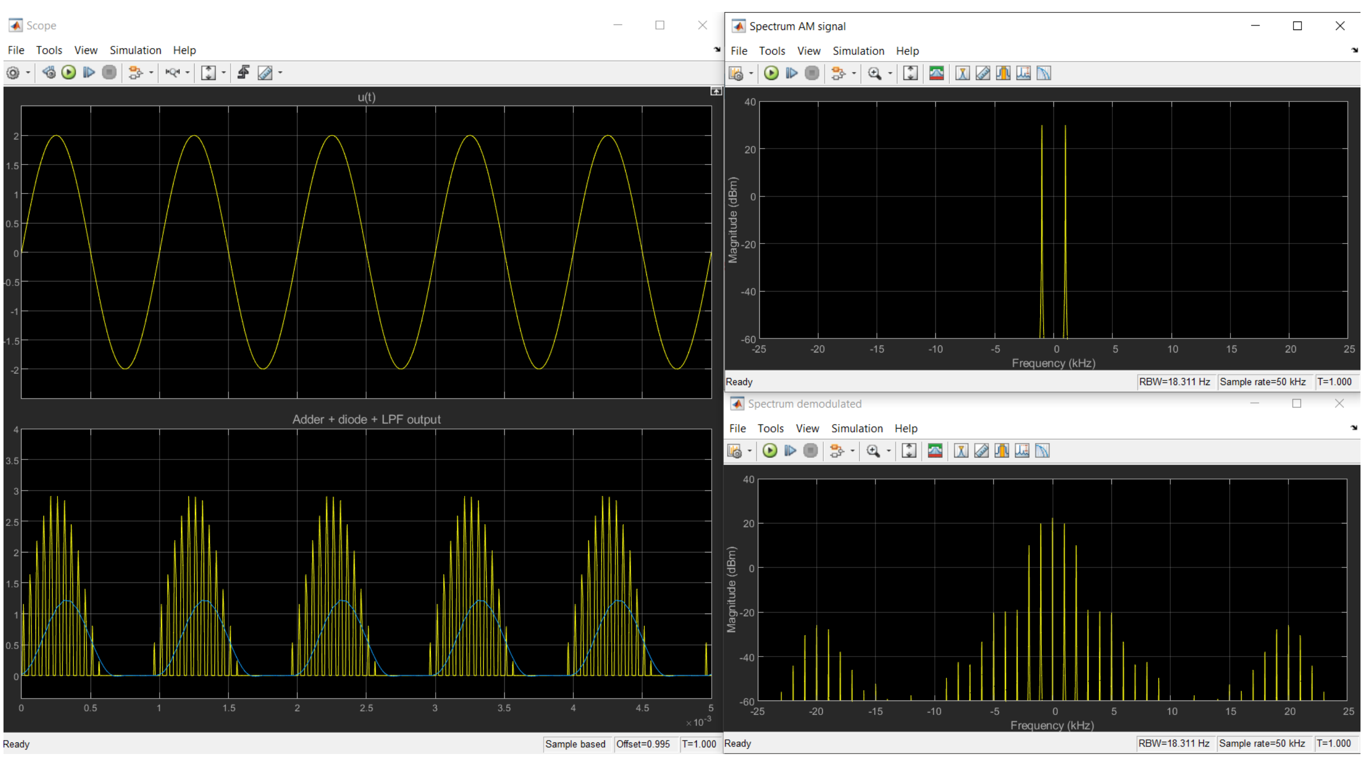
- What was effect of the frequency error on the demodulated waveforms measured in section IV.2.2?

Appendix: Simulation results from the synchronous detector computer models

LTspice output – Local oscillator (20 kHz) and unmodulated message signal (1 kHz):



MATLAB Simulink output – Local oscillator (20 kHz) and unmodulated message signal (1 kHz):



MATLAB Simulink output – Local oscillator (20 kHz) and AM signal (100% and 1 kHz):