Experiment 4: Amplitude Modulation

This experiment examines the characteristics of the amplitude modulation (AM) process. The demodulation is performed by an envelope detector. Overmodulated AM signals and its requirement for coherent detection are also considered.

1 Introduction

In Experiment 3, DSB signals were generated by the multiplication of a message signal with a carrier waveform. This resulted in the translation of the message spectrum to the carrier frequency location. The simplicity of the modulation process contrasted with the strict requirement for a synchronous local carrier at the receiver. This problem can be alleviated by sending a carrier frequency component along with the sidebands at the expense of decreasing the transmitted power efficiency.

1.1 AM signal generation

The generation of AM signals consists simply of the addition of the carrier waveform to the DSB signal, for this reason AM modulation is referred to as DSB-LC (DSB with large carrier). The *message* signal $x(t)$ is modulated by a *carrier* waveform $A_c \cos(2\pi f_c t)$. The amplitude modulated waveform $x_c(t)$ is

$$
\begin{aligned}
x_c(t) &= A_c x(t) \cos(2\pi f_c t) + A_c \cos(2\pi f_c t) & (1) \\
&= A_c[1 + x(t)] \cos(2\pi f_c t) & (2) \\
&= A(t) \cos(2\pi f_c t) & (3)
\end{aligned}
$$

where $|A(t)|$ is the *envelope* of the AM signal. The message signal amplitude must be small and must have a DC component equal to zero in order to use simple demodulation schemes. The spectrum of the modulated signal is

$$
X_c(f) = \frac{A_c}{2}[X(f + f_c) + X(f - f_c)] + \frac{A_c}{2}[\delta(f - f_c) + \delta(f + f_c)] \tag{4}
$$

Thus, the carrier waveform is transmitted along with the sidebands to make it available at the receiver for coherent demodulation without needing complex carrier recovery circuits. However, this advantage of AM over DSB demodulation comes at the expense of using some portion of transmitted power in the carrier waveform which does not convey any information.

1.2 Modulation index of AM signals

The two main differences of AM with respect to DSB signals are the presence of a carrier component and that the envelope $|A(t)|$ of the modulated carrier has the shape of $x(t)$ under the conditions that $f_c >> f_x$ and $A(t) > 0$ for all values of t. Thus, having $|x(t)| < 1$ with no DC component guarantees that $A(t)$ is always positive. The *modulation index* m of an AM signal is defined as

$$
m = \frac{[A(t)]_{max} - [A(t)]_{min}}{[A(t)]_{max} + [A(t)]_{min}} \tag{5}
$$

When $m > 1$ the envelope has no longer the shape of $x(t)$ resulting in envelope distortion. This condition is referred to as *overmodulation*. In the particular case when the message signal is a sinusoid of frequency f_x, its amplitude is equal to the modulation index m of the corresponding AM signal

$$
x_c(t) = A_c[1 + m \sin(2\pi f_x t)] \cos(2\pi f_c t) \tag{6}
$$

1.3 AM signal power and bandwidth

The (one-sided) spectrum of the AM signal consists of two sidebands that occupy the frequency range $f_c - f_x$ to $f_c + f_x$ plus the carrier component at f_c, hence the bandwidth B_T required for transmission is

$$B_T = 2f_x \tag{7}$$

The average transmitted power S_T of the AM signal is

$$S_T = S_c S_x + S_c \tag{8}$$

where $S_c = A_c^2/2$ is the average carrier power and S_x is the average message signal power. When the message signal is a sinusoid of amplitude A_x, $S_x = A_x^2/2$. The fraction of the transmitted power that conveys information to the receiver is

$$E = \frac{S_c S_x}{S_c + S_c S_x} \tag{9}$$

and it is used as a measure of the *power efficiency*.

1.4 Demodulation of AM signals

The recovery of the message signal can be performed coherently just like in DSB demodulation. The transmission of a carrier component in AM alleviates the need for complex carrier recovery circuits necessary for DSB demodulation. However, a simpler demodulator for AM signals is the *envelope detector*.

1.4.1 Coherent demodulation

Since the carrier component is part of the received AM signal $x_r(t)$, it can be extracted and used in a coherent demodulator to recover the message signal. Assuming that the received signal $x_r(t)$ has the same form as $x_c(t)$ except for an attenuation factor a_c/A_c introduced by the channel, the product signal is

$$z(t) = \{a_c[1 + x(t)]\cos(2\pi f_c t)\}2\cos(2\pi f_c t) = a_c[1 + x(t)] + a_c[1 + x(t)]\cos(4\pi f_c t) \tag{10}$$

whose spectrum $Z(f)$ is

$$Z(f) = a_c[\delta(f) + X(f)] + \frac{a_c}{2}[X(f - 2f_c) + X(f + 2f_c) + \delta(f - 2f_c) + \delta(f + 2f_c)] \tag{11}$$

Notice that scaled replicas of the message spectrum appear at the baseband frequency range and at $2f_c$. Additionally, components at $2f_c$ and 0 Hz also appear. Therefore, a bandpass[1] filter is necessary to remove the DC and high frequency components. The output $y(t)$ of the filter is

$$y(t) = a_c x(t)$$

which is the message signal scaled by a factor a_c.

1.4.2 Demodulation with envelope detector

Since the envelope of the modulated signal has the shape of the message signal (as long as $|x(t)| < 1$ and has no DC component), the received signal can be rectified by a diode and the rectified signal can then be smoothed by an RC network in order to recover the message signal. Fig. 2 shows the *envelope detector* circuit for AM demodulation. The requirements for best operation of this demodulator are that $f_c >> f_x$, and that the discharge time constant RC is adjusted such that the negative rate of the envelope never exceeds the exponential discharge rate of the RC network. For the specific case of tone modulation (the message signal is a sinusoid), the time constant RC is related to the parameters of the AM signal by

$$RC \le \frac{\sqrt{1 - m^2}}{2\pi f_x m} \tag{12}$$

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[1]During the lab a lowpass filter will be used for simplicity.

2   Prelab instructions

The prelab for this experiment is based on PSPICE modeling and simulations. Enclosed in brackets is the number of points assigned to each question/plot.

1. From the functional block diagram of Fig. 1 in the AD633 data sheet, build a PSPICE model of this multiplier circuit considering the following hints: [4]

   - All the amplifiers shown in the block diagram provide unity gain and the inputs $X2$ and $Y2$ will be connected to ground (in the circuits for this experiment), hence all the amplifiers and the terminals $X2$ and $Y2$ can be neglected to build the PSPICE model.

   - The multiplier block can be implemented by the `MULT` part included in the PSPICE libraries. Similarly, the summation block can be implemented by the `SUM` part. The constant $1/10$ V block can be implemented with the `CONST` block with a value of 0.1.

   - Notice that because of the $1/10$ V block, and just for the circuits in this experiment, the signal applied to the $X1$ input (pin 1) is actually 10 times the message signal $x(t)$. In the following, the signal applied to pin 1 is called simply the message signal, but keep in mind it is a scaled version of $x(t)$.

2. Using your PSPICE model of the AD633, (a) simulate the output of the circuit of Fig. 1 of this experiment. The parameters for the message signal $x(t)$ are: Sine wave, $A_x = 8$ V, $f_x = 500$ Hz, and for the carrier signal: Sine wave, $A_c = 5$ V, $f_c = 9$ kHz. Use a time span of $TS = 5$ ms. For the simulation you need to connect a resistor (> 1 kΩ) from the output to ground in order to obtain the simulated output [4]. (b) To observe an overmodulated signal, repeat the previous step with $A_x = 13$ V, $f_c = 18$ kHz, and $TS = 4$ ms [4].

3. Using Eq.(12), (a) calculate the range of values of R when $C = 10$ nF, $m = 0.5$, $f_x = 1$ kHz [2]. (b) Use a value of $R = 18$ kΩ to simulate the output of the envelope detector of Fig. 2 from 0 to $TS = 2$ ms. The parameters for the message signal are: Sine wave, $A_x = 5$ V, $f_x = 1$ kHz, and for the carrier signal: Sine wave, $A_c = 5$ V, $f_c = 98$ kHz [4]. (c) Repeat part (b) changing $TS = 10$ ms (this time-domain plot is *not* required), and from the `Trace` menu select `Fourier`, then from the `Plot` menu select `Axis settings...` and set the `Data range` from 0Hz to 100KHz in the `X-Axis` and set the `Scale` to `Log` in the `Y-Axis`. The resulting plot is the spectrum of the output of the envelope detector, include this plot in your prelab [4].

4. Simulate the output signal of the coherent detector of Fig. 4 (neglect the op-amp amplifier). The parameters for the *message* signal are: Sine wave, $A_x = 13$ V, $f_x = 500$ Hz, and for the carrier signal: Sine wave, $A_c = 5$ V, $f_c = 18$ kHz, $TS = 4$ ms [4].

3   Lab procedure

GENERAL INSTRUCTIONS:

- Load the virtual instrument TIMEFREQ.VI by double-clicking the shortcut located in the computer desktop.

- **After taking each plot make sure to ask your TA to verify that your results are correct. This also serves to monitor your progress and performance.**

3.1   AM signal generation

In this section AM signals are generated by multiplying message signals with a carrier and adding the carrier to this product. The amplitude of the message signal is varied to produce different values of the modulation index.

1. With the power supply off, assemble the circuit of Fig. 1. Use FG1 as the message signal and FG2 as the carrier signal. Set the following parameters in FG1: Amplitude=8 V, Frequency=500 Hz, sine wave. For FG2: Amplitude=5 V, Frequency=9 kHz, sine wave. Connect channel 1 probe of the oscilloscope to the output of the modulator (at pin 7).

2. Turn the power supply on and capture the AM signal and its spectrum by executing TIMEFREQ.VI with the following parameters: Channel=1, TS=5m, FS=10, Save data=ON, a proper file name. [Plot P1, 5 points].

3. Change the amplitude of FG1 to 2 V and capture the AM signal and its spectrum, use a different file name. [P2, 5].

3.2   Demodulation of AM signals using envelope detection

In this section the message signal is recovered by using an envelope detector.

1. Assemble the circuit of Fig. 2 using a value of $R = 18$ kΩ. Use FG1 as the message signal and FG2 as the carrier signal. Set the following parameters in FG1: Amplitude=5 V, Frequency=1 kHz, sine wave. For FG2: Amplitude=5 V, Frequency=98 kHz, sine wave. Use the channel 1 probe of the oscilloscope to observe the output signal.

2. Capture the output signal and its spectrum by executing TIMEFREQ.VI with the following parameters: Channel=1, TS=2m, FS=100, Save data=ON, a proper file name. [P3, 5].

3. Increase the carrier frequency (FG2) to 450 kHz. Capture the output signal and its spectrum by executing TIMEFREQ.VI with the following parameters: Channel=1, TS=2m, FS=500, Save data=ON, a proper file name. [P4, 5].

3.3   Overmodulated AM signals

In this section the case of AM signals with modulation index $m > 1$ is considered.

1. With the power supply off, assemble the circuit of Fig. 3. Use FG1 as the input signal and FG2 as the carrier signal. Set the following parameters in FG1: Amplitude=6.5 V, Frequency=500 Hz, sine wave. For FG2: Amplitude=5 V, Frequency=18 kHz, sine wave. Use the channel 1 probe of the oscilloscope to observe the AM signal.

2. Turn on the power supply and use channel 2 to measure the peak amplitude (make sure that the attenuation factor of this probe is at 10) of the signal applied to pin 1 of the AD633. This is the *message* signal and its amplitude is ten times the modulation index m. Record this value $m = _____$.

3. Capture the AM signal and its spectrum with the following parameters: Channel=1, TS=4m, FS=20, Save data=ON, a proper file name. [P5, 5].

3.4   Coherent detection of overmodulated AM signals

In this section the need for using coherent detection to demodulate AM signals with modulation index $m > 1$ is considered.

1. With the power supply off, assemble the circuit of Fig. 4. Use FG1 as the input signal and FG2 as the carrier signal. Set the following parameters in FG1: Amplitude=6.5 V, Frequency=500 Hz, sine wave. For FG2: Amplitude=5 V, Frequency=18 kHz, sine wave. Use the channel 1 probe of the oscilloscope to observe the product signal and the channel 2 probe to observe the output signal.

2. Turn on the power supply and capture the product signal and its spectrum with the following parameters: Channel=1, TS=4m, FS=40, Save data=ON, a proper file name. [P6, 5].

3. Now capture the output signal and its spectrum with the following parameters: Channel=2, TS=4m, FS=40, Save data=ON, a proper file name. [P7, 5].

4   Analysis

This section contains questions regarding the results obtained during the lab.

1. Include in your report all the plots obtained during the lab. Make sure to label properly all the plots. The number of points assigned to each plot is specified in the lab procedure. Refer to Appendix B section 3.4 for instructions regarding the plotting of experimental results.

2. From plots P1 and P2: (a) estimate the modulation index of each AM signal.[4 points]. (b) Describe the effect of the modulation index on the magnitude of the sidebands in the spectra of these signals. [2].

3. Comparing the time signals in plots P3 and P4, and giving arguments *from* their spectra, (a) explain why the signal of P4 shows less ripple. [2]. (b) Would you connect the LPF of Fig. 4 to the output of the envelope detector in order to remove the ripple in the case of P3? Justify your answer. [2].

4. Could the message signal be recovered from the AM signal of plot P5 using an envelope detector? Justify your answer. [2].

5. From plot P7: (a) explain the presence of a DC offset in the output signal. [2]. (b) How would you eliminate the DC offset at the output? [2].

6. (a) Compute the power efficiency E for the AM signals of plots P1, P2 and P5. [6][Hint: Keep in mind that the AD633 divides the product of the input signals by 10]. (b) Without considering the value of the carrier frequency, but considering *everything* else, which of these signals would you choose to use in a practical system? Justify your answer. [2].
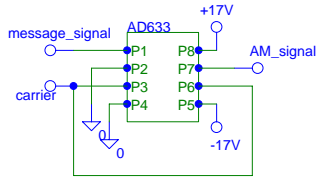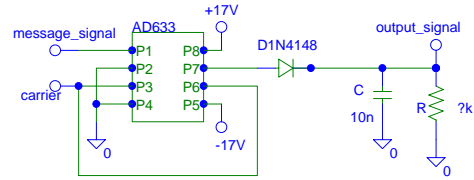
B

Fig. 1 AM modulator

message_signal
carrier
AD633
P1 P8
P2 P7
P3 P6
P4 P5
+17V
-17V
AM_signal
0

Fig. 2 Envelope detection of AM signals.

message_signal
carrier
AD633
P1 P8
P2 P7
P3 P6
P4 P5
+17V
-17V
D1N4148
output_signal
C 10n
R ?k
0
0
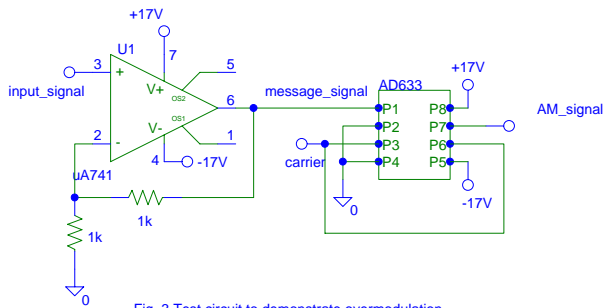
Fig. 3 Test circuit to demonstrate overmodulation.

input_signal
U1
+17V
3 +
V+
OS2
2 -
V-
OS1
7
5
6
1
4 -17V
uA741
1k
1k
0
message_signal
AD633
P1 P8
P2 P7
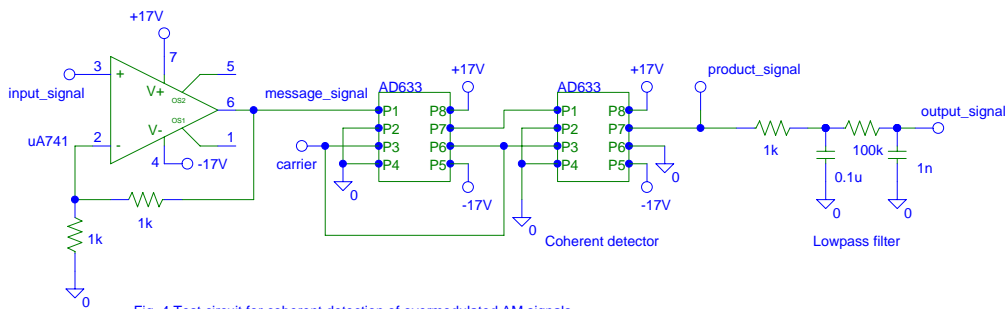P3 P6
P4 P5
carrier
+17V
-17V
AM_signal
0

Fig. 4 Test circuit for coherent detection of overmodulated AM signals.

input_signal
+17V
3 +
V+
OS2
2 -
V-
OS1
7
5
6
1
4 -17V
uA741
1k
1k
0
message_signal
AD633
P1 P8
P2 P7
P3 P6
P4 P5
carrier
+17V
-17V
0
AD633
P1 P8
P2 P7
P3 P6
P4 P5
+17V
-17V
0
Coherent detector
product_signal
1k
100k
0.1u
1n
output_signal
0
0
Lowpass filter

A