Lab 2: Analogue Modulation

ECSE 308 Introduction to Communication Systems and Networks

Chenyi Xu 260948311

Yongru Pan 261001758

Abstract: This laboratory is divided into three sections. The first section is designed to understand the basic principles of amplitude modulation and demodulation through DSB-SC and DSB-LC System. The second section of the lab focused on the basic principles of frequency modulation and demodulation. The third section concentrated on understanding the possibility of power and bandwidth trade-off in FM systems respectively.

Introduction

Amplitude Modulation is the process in which the amplitude of a carrier wave is adjusted according to the amplitude of a baseband modulating signal.

Double-sideband with large carrier (DSB-LC) is represented with the following formula

$$s(t) = A_c[1 + k_a a(t)]\cos(2\pi f_c(t))$$

DSB-LC system is simple but not power efficient. Full transmitted power can be applied to the sidebands by removing the carrier from DSB-LC before power amplification resulting in double-sideband suppressed carrier. It is represented with the following formula

$$s(t) = A_c[k_a a(t)]\cos(2\pi f_c(t))$$

Frequency modulation happens when modulating signal changes the instantaneous frequency of the carrier while the amplitude remain constant. It can be represented using the following formula

$$s(t) = A_c\cos\left[2\pi\left(f_c t + k_f\int_{-\infty}^{t} a(x)dx\right)\right]$$

Analysis

Part I: Presentation of Signals and Noise

A). DSB-LC AM System

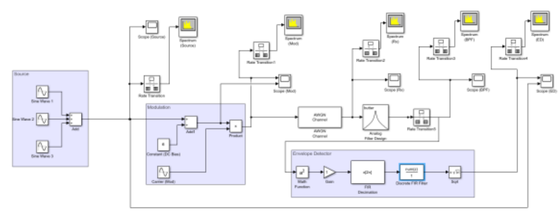

Figure 1: double-side band (DSB) large-carrier (LC) AM system

Q1: Observe the output on Spectrum (Source). What are the fundamental and harmonic components of the source signal?

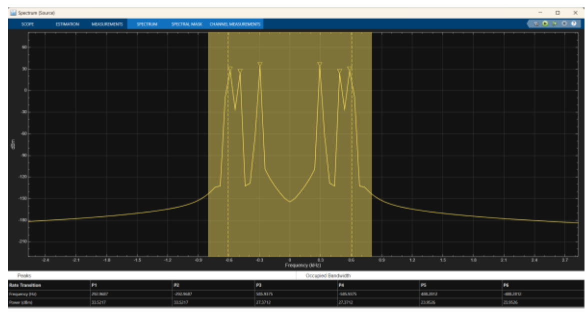

Figure 2: Spectrum (Source)

From the observations on the signal, the fundamental frequency is 292.06 Hz, and the harmonic components are thus 488.28Hz and 585.94 Hz.

Q2: Observe the outputs on Scope (Source) and Scope (Mod). Explain the relationship between the amplitude of the AM signal and that of the source signals.

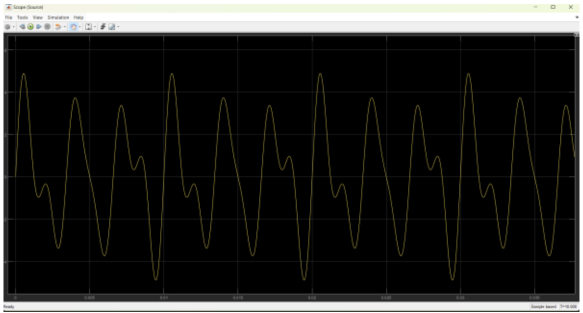

Figure 3 Scope of the Source

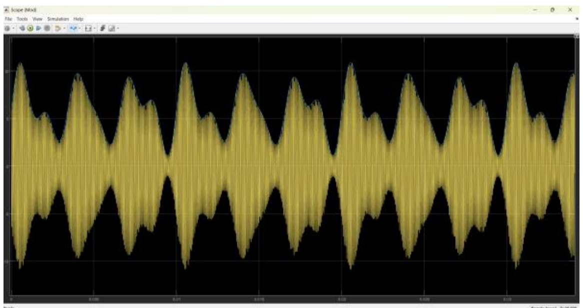

Figure 4 Scope after Modulation

The relationship between the amplitude of the AM signal and that of the source signals is that the AM signal's amplitude is 2 times larger than that of the source signal.

Q3: Observe the outputs on Spectrum (Source) and Spectrum (Mod). Explain the relationship between the spectrum of the AM signal and that of the source signal. Comment on the transmission bandwidth of AM signals.

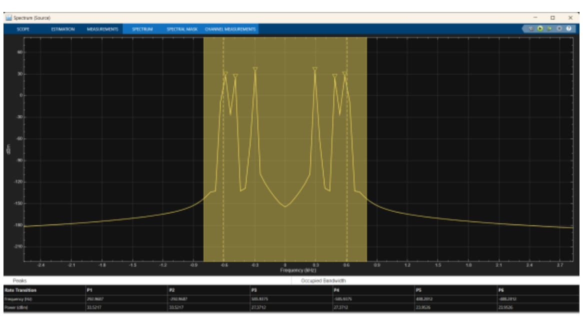

Figure 5: Spectrum(Source)

Figure 6: Spectrum (Mod) one side close up

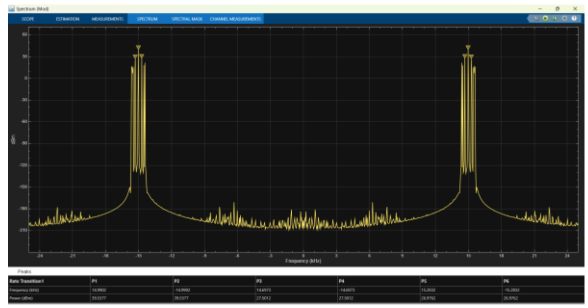

Figure 7: Overall view of the Spectrum (Mod)

Compared to the source spectrum, the modulator's spectrum is centered at different positions. The source spectrum center at 0 kHz while the modulator spectrum centers at 15 kHz.

The transmission bandwidth of an AM signal is two times the bandwidth of the source signal. As shown in the spectrum (source), the bandwidth of the source signal is 0.9-(-0.9)=1.8kHz, the bandwidth modulated signal is (15.8-14.2) = 1.6kHz which is approximately 2 times the source bandwidth.

Q4: Compare the outputs on Spectrum (Rx) and Spectrum (BPF). Comment on what information is needed to filter out the noise without distorting the desired signal. Explain how and why the SNR at the output of Analog Filter Design (BPF) changes compared with the SNR at the input of Analog Filter Design (BPF)?

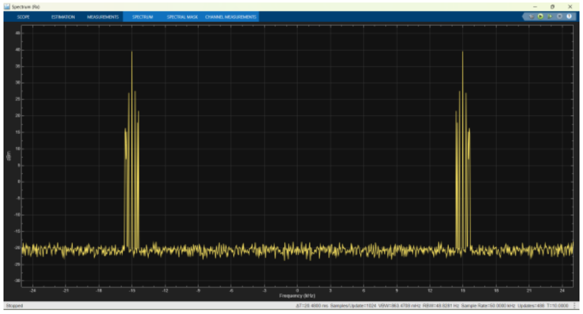

Figure 8: Spectrum (Rx) Overall

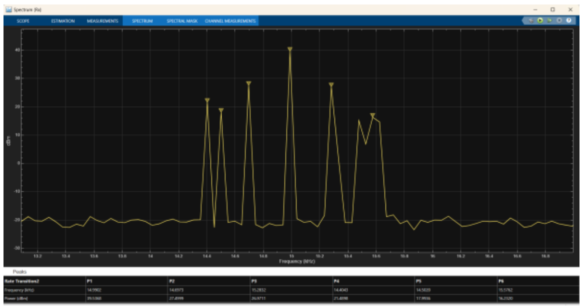

Figure 9: Spectrum (Rx) Close up

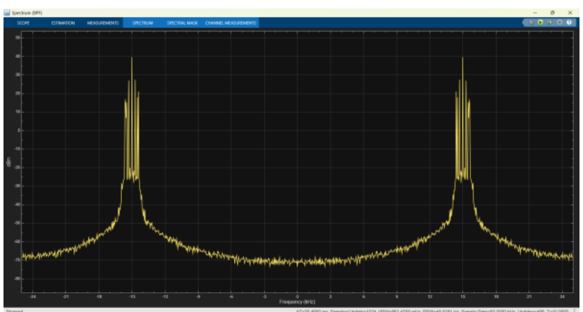

Figure 10: Spectrum (BPF) Overall

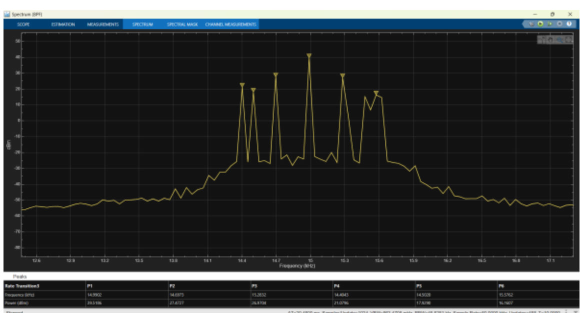

Figure 11: Spectrum (BPF) close up

The Spectrum Rx is the spectrum from the receiver and before any filtering. From the Spectrum Rx, the frequency range of the signal spikes needs to be located. In this case, according to observation to the graph, the frequency interval is between |13.5| kHz to |16.5 | Hz. From the bandpass filter's setting, we obtained that the frequency interval that the bandpass filter is actually taking is from |14.3| kHz to |15.8| kHz. Thus, after filtering, we obtained the image in Spectrum (BPF). The bandpass filter takes a very accurate frequency interval to filter in order to obtain a filtered result without distorting the signal.

Since the BPF eliminates the out-of-band noise, and the frequency that are irrelevant are removed, thereby increasing the SNR at the output because there is less noise in the signal.

Q5: Observe the outputs on Spectrum (ED) and Spectrum (BPF). Explain the principle of double-sideband large carrier (DSB-LC) AM demodulation.

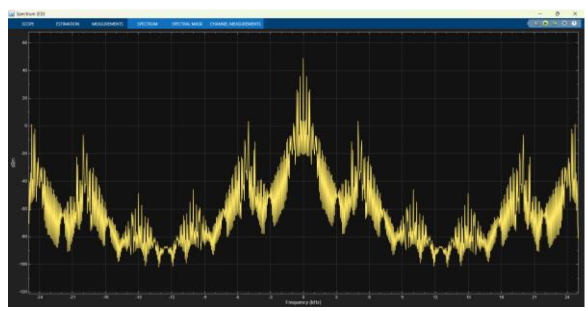

Figure 12: Spectrum (ED) DC bias of 6

During the process of demodulation, the signal is first handled using an envelope detector and then by the bandpass filter. In the Spectrum (ED), the figure shows the rough envelope of the detected message. However, some high frequency components from carrier and noise may still be present at this stage. In the Spectrum (BPF), the figure shows a filtered version of the message, removing any noises and high frequency components.

Q6: Change the value of Constant (DC Bias) and observe how it affects the signal recovered from Envelope Detector in comparison with the source signal. Explain what a feasible DC bias in relation to the amplitude of the source signal is so that successful demodulation can be guaranteed.

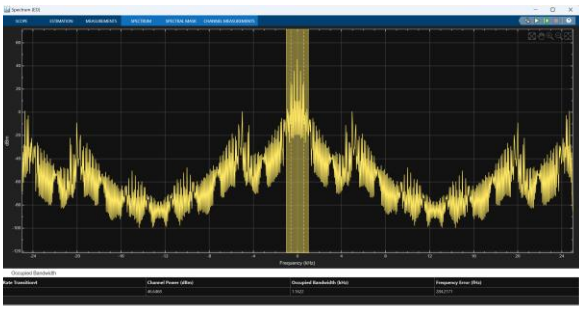

Figure 13: Spectrum (ED) at Gain 4

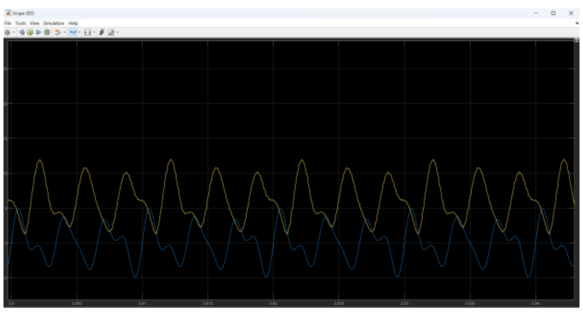

Figure 14: Scope(ED) at gain 4

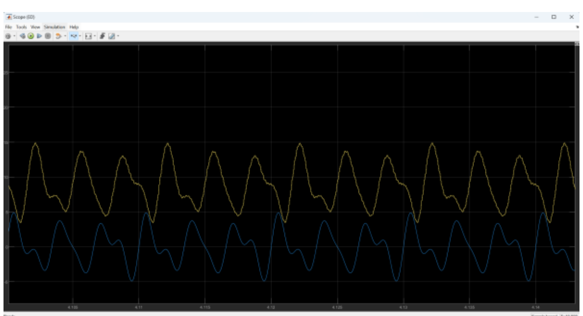

Figure 15: Scope(ED) at DC Bias of 6

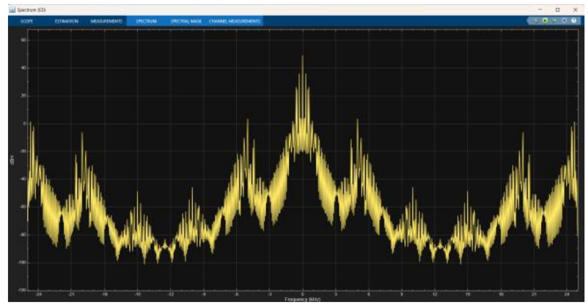

Figure 16: Spectrum (ED) at DC bias of 6

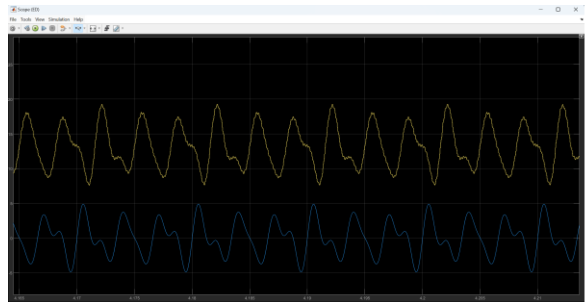

Figure 17: Scope (ED) at gain 9

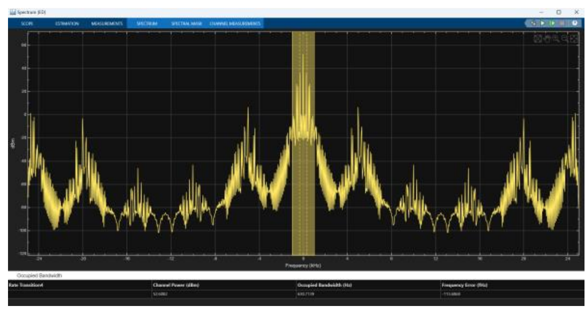

Figure 18: Spectrum (ED) at gain 9

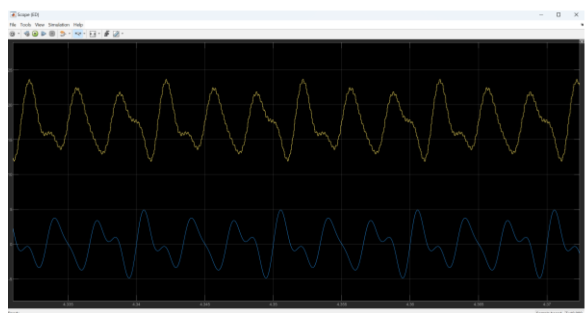

Figure 19: Scope (ED) at gain 12

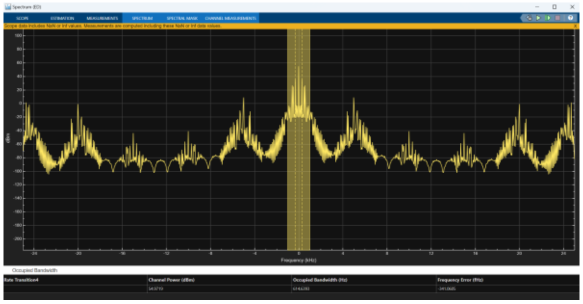

Figure 20: Spectrum(ED) at gain 12

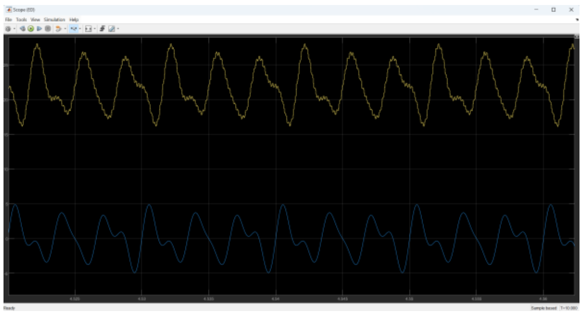

Figure 21: Scope (ED) at gain 12

In AM signal demodulation, the DC bias shifts the amplitude of the modulating signal to above 0. This ensures that the modulated signal is never below zero in order to be properly demodulated using an envelope detector. When DC bias is low, the envelop detector will struggle to recover the signal accurately. If the bias is too high, it will lead to a weak recovery of the original source signal. For successful demodulation, DC bias should be set such that the modulated signal remains positive throughout. It should be at least equal to the maximum amplitude of the message signal to prevent the modulated waveform from becoming negative. As a result, all points will visible and contained after demodulation. Here we tried a variation of gains of 4, 6, 9, and 12. All of them appeared to be larger than 0.

B). DSB-SC AM System

Q7: Observe the outputs on Scope (Source) and Scope (Mod). Explain the relationship between the amplitude of the AM signal and that of source signals.

Figure 22 Scope source DSB-SC AM

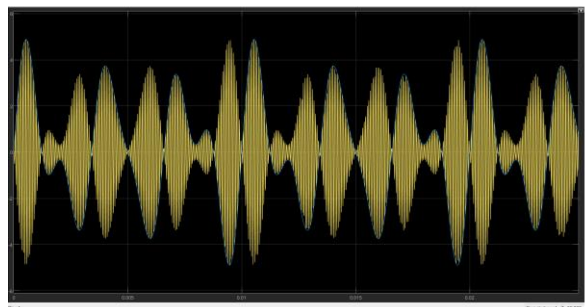

Figure 23 Scope Mod DSB-SC AM

The amplitude between the AM signal and that of the source signal are the same. The modulated signal is an envelope of the source signal. The content of the modulated signal is the product of the source signal and a cosine wave (the carrier).

Q8: Observe the outputs on Spectrum (Source) and Spectrum (Mod). Explain the relationship between the spectrum of the AM signal and that of the source signal. Comment on the transmission bandwidth of AM signals.

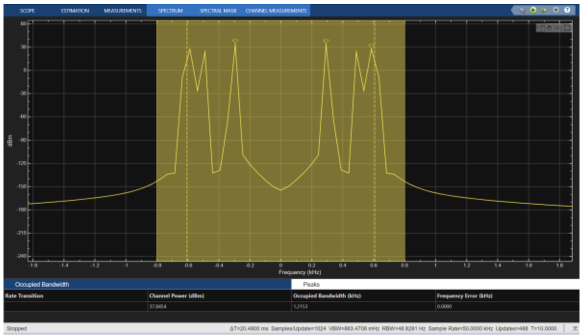

Figure 24 Spectrum Source DSB-SC AM

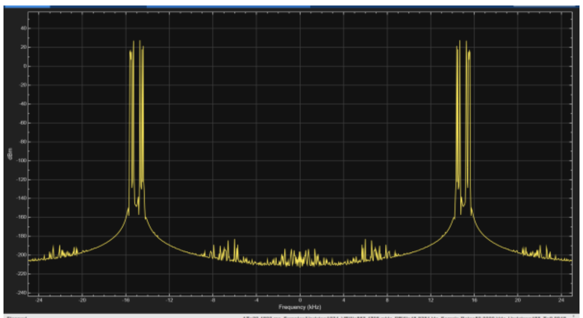

Figure 25 Spectrum (Mod) DSB-SC AM

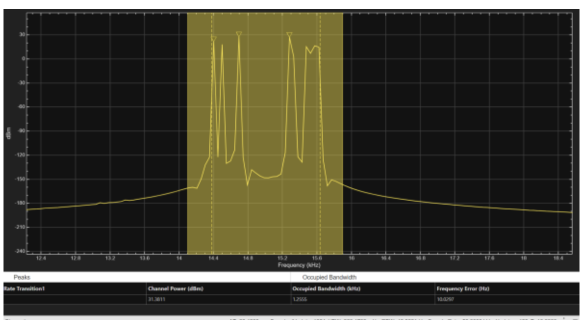

Figure 26 Spectrum (Mod) DSB-SC AM Zoom in on one side

The modulated bandwidth of an AM signal is twice the bandwidth of the source signal due to the presence of both sidebands. The spectrum of the AM signal includes the carrier frequency and two sidebands, which are mirror images containing the source signal.

Q9: Explain the differences between DSB-SC and DSB-LC in terms of modulation. Explain how such differences affect the transmit power efficiency and the demodulation process at the receiver.

In DSB-SC, the carrier signal is suppressed after modulation. Therefore, the output signal only consists of upper and lower sidebands. In DSB-LC, the carrier is included along with the sidebands. The output signal consists of both the carrier and sidebands. DSB-LC is simple but has low power efficiency. A significant portion of the power is spent in the carrier which does not contain any information. On the other hand, DSB-SC is more efficient since the carrier that does not contain any information is suppressed. None of the power is wasted. DSB-LC has a simple demodulation process. Carrier allows for envelop detection. DSB-SC has a more complex demodulation process. Coherent demodulation is needed to extract the original signal.

Part II: Frequency Modulation (FM)

Q1: From the block configuration and the parameter setup, describe in mathematical terms the process of FM modulation and demodulation.

We multiplied our sine input pulse with a gain of 3000. Therefore, we obtain 3000 * DSP (t). Next, we added the carrier frequency which is 9000.

$$3000 * DSP(t) + 9000$$

Then we integrated the sum equation and multiplied it with 2π

$$2\pi \int_0^t 3000 * DSP(t) + 9000\, dt$$

Then we cosine the result we just obtained

$$s(t) = \cos\left[2\pi \int_0^t 3000 * DSP(\tau) + 9000\, d\tau\right]$$

$$s(t) = \cos\left[2\pi(9000t) + \int_0^t 3000 * DSP(\tau) d\tau\right]$$

For demodulation process, the goal is to extract the changes in the instantaneous frequency of the FM signal. The signal is first fed into the VCO to create signal that contains both the original modulating signal and some high frequency components. VCO we used has a gain of 3000 and a carrier frequency of 9000 Hz. Differentiating the argument with respect to the phase, we derived the following equation:

$$\frac{ds_{FM}(t)}{dt} = 2\pi(9000 + 3000\, DSP(\tau))\, sin\left[2\pi(9000t) + \int_0^t 3000 * DSP(\tau) d\tau\right]$$

The signal is then sent through a low-pass filter to remove the high frequency components and extract the low frequency component with the information.

Q2: Observe the output on Scope(Mod). Explain how the FM signal is related to the modulating signal in the time domain. Use a sum signal of two sine waves as a modulating signal and compare the output with the syn of those when each of the sine wave is used as a modulating signal separately. Comment on the linearity of FM modulation in comparison with AM modulation.

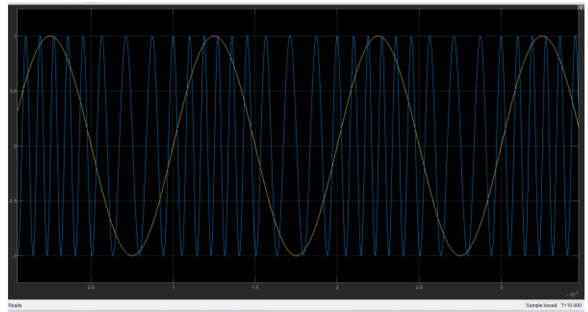

Figure 27 Scope (Mod) FM System

The signal output on Scope (Mod) is a cosine wave. They have the same amplitude. The frequency changes with respect to the input signal as shown in the figure above.

A second sine wave with an amplitude of 2 with everything remains the same with the existing sine wave input has added to the system.

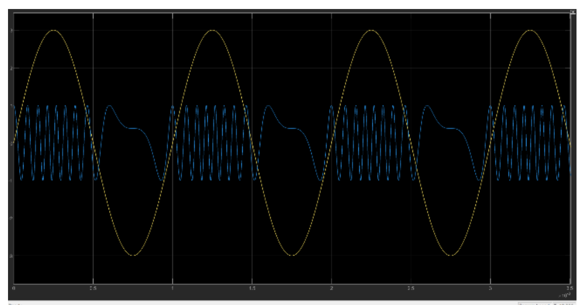

Figure 28 Sum of 2 sine signals

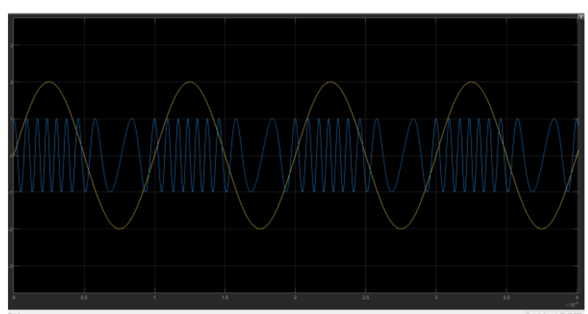

Figure 29 Second sine alone

In regions where the combined amplitude of the modulating signal is high, the blue signal is closer together, indicating an increase in frequency. In regions where the amplitude of modulating signal is lower, the peak of blue signal is more widespread. When a single sine wave was used, the frequency directly mirrored the change in amplitude of the sample. With the combined sine waves, the frequency change are more complex and less period and are influenced by the sum of instantaneous amplitude of both waves. FM modulation is nonlinear since they depended on the instantaneous amplitude of the modulating signal. AM modulation is a linear process since amplitude is linearly related to the message signal.

Q3: Vary Gain (Sensitivity Factor) from small to large. Comment on the sensitivity of the carrier to the modulating signal in terms of amplitude and frequency variation.

Gain sensitivity factor of 0.5, 1, and 3.5 are tested. Amplitude stays at 1 for all of them as amplitude is not affected by the modulation. For a low gain sensitivity factor, frequency change slightly in response to modulating signal. Spacing didn't vary much. The carrier is less sensitive to the modulating signal. For a moderate gain sensitivity, there's a more noticeable change. Carrier's frequency deviates more with change in modulating signal. For a high gain sensitivity, peaks of the FM signals are tightly packed during the high amplitude regions of modulating signal and spread out significantly during low amplitude regions. There's a much larger frequency deviation.

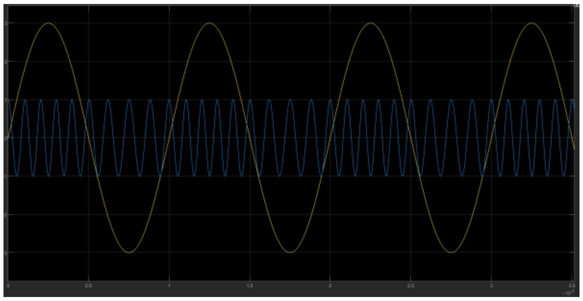

Figure 30 Gain Sensitivity Factor of 0.5

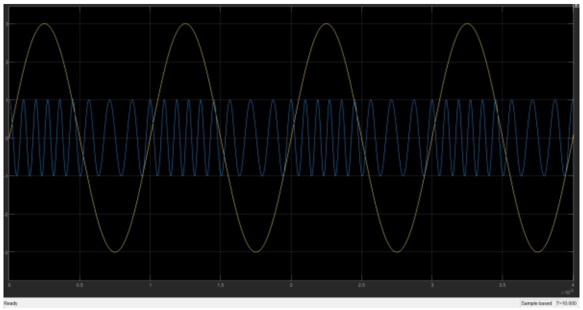

Figure 31 Gain Sensitivity Factor is 1

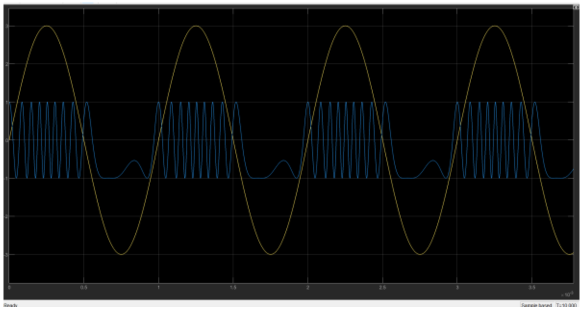

Figure 32 Gain Sensitivity Factor of 3.5

Q4: Vary the modulating frequency and the amplitude of Sine Wave (Modulating Signal). Observe the variations of the spectrum (Mod). Explain how the transmit power changes accordingly and why. Comment on the difference between an FM signal and an AM signal in terms of transmit power in relation to the modulating signal.

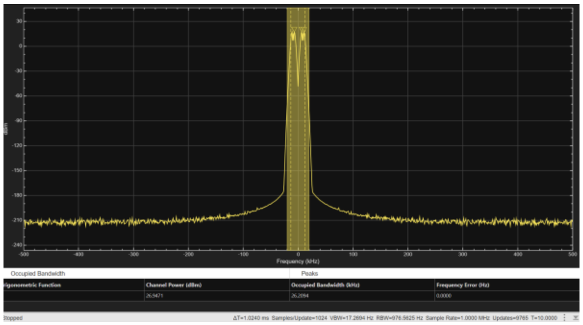

Figure 33 Spectrum of 1kHz and Amplitude of 1

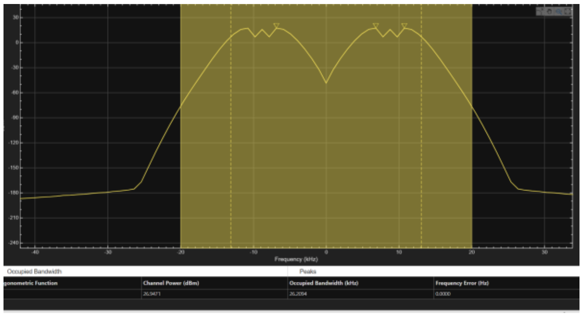

Figure 34 Spectrum of 1kHz and Amplitude of 1

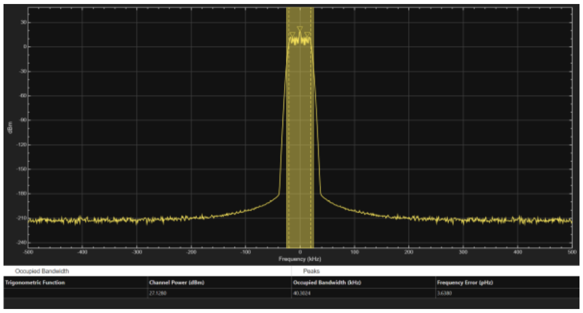

Figure 35 Spectrum of Frequency 1k Hz, Amplitude 3

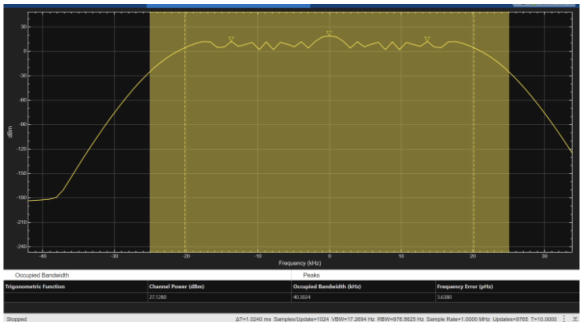

Figure 36Spectrum of Frequency 1k Hz, Amplitude 3

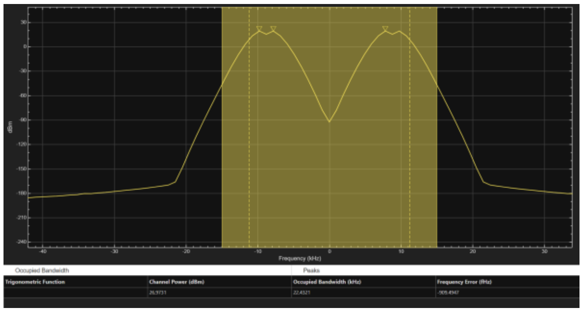

Figure 37 Spectrum Frequency 1k Hz, Amplitude 0.5

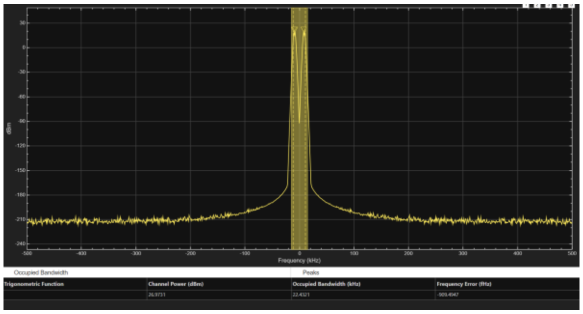

Figure 38 Spectrum of Frequency 1k Hz, Amplitude 0.5

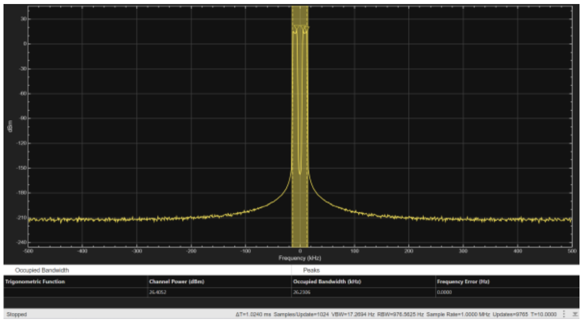

Figure 39 Spectrum of Amplitude 1 frequency 100

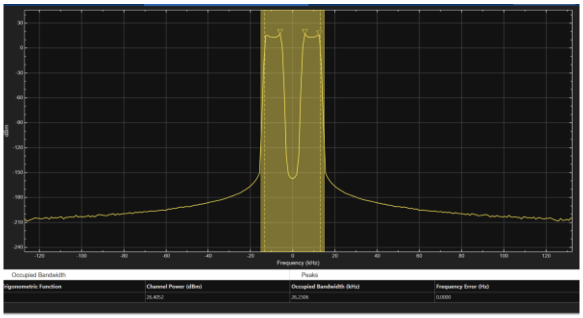

Figure 40 Spectrum of Amplitude 1 frequency 100

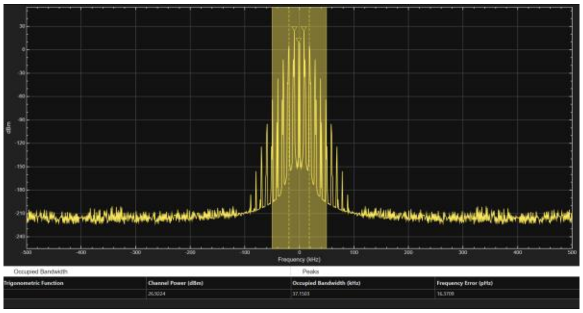

Figure 41 Spectrum of Amplitude 1 Frequency 10kHz

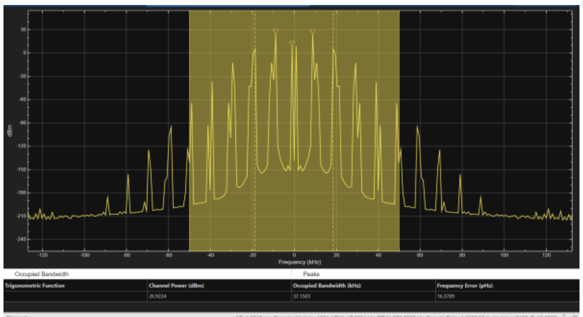

Figure 42 Spectrum of Amplitude 1 Frequency 10kHz

Vary the modulating frequency does not change the transmitting power. It stays around 27 dB. FM modulates frequency rather than amplitude, so the carrier's amplitude stays the same. Similarly, change the amplitude of modulating signal change the frequency deviation of carrier. The total transmit power remain constant since carrier amplitude is constant. In comparison with AM transmit power, the carrier's amplitude is directly affected by the modulating signal. Hence, the transmit power of AM signal changes. With an increase in amplitude, there will be a higher transmit power. Vice versa.

Part III: Power/Bandwidth trade-off in FM

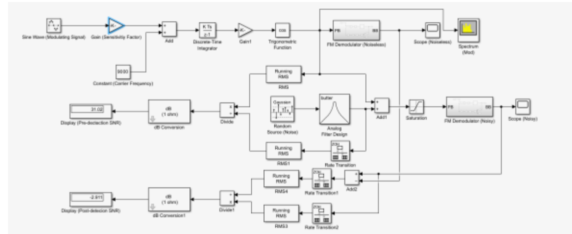

Figure 43:Part 3 Configuration

Q1: Denote the modulating frequency as fm. Vary Gain (Sensitivity Factor) Δf as $\Delta f = 0.1 f_m$, $0.5 f_m$, f_m …, $10 f_m$. Observe the output on Specturm (Mod) and comment on how the number of significant sideband pairs (i.e., peaks with power above -10 dBm) varies with Δf. Explain how and why the power of the carrier component varies in the frequency domain.

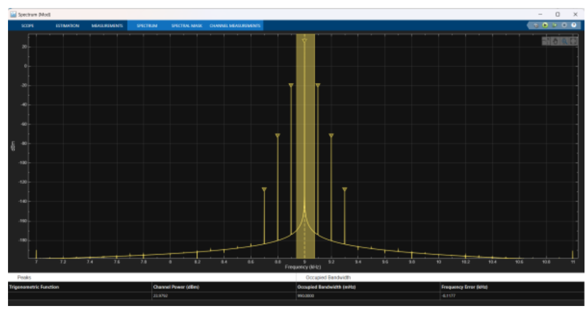

Figure 44: Gain 1

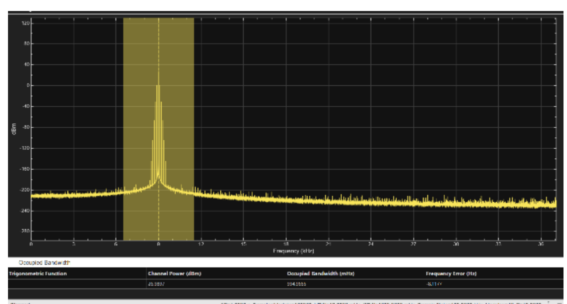

Figure 45: 0.1fm

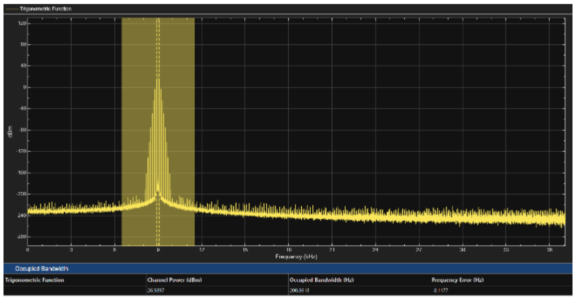

Figure 46: 0.5 fm

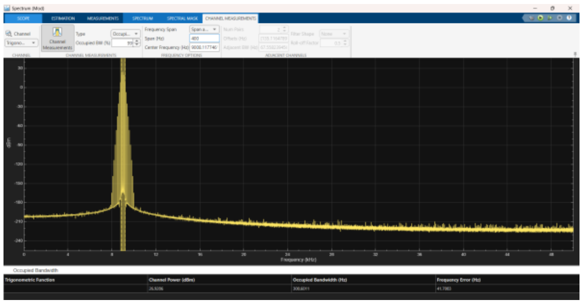

Figure 47: fm

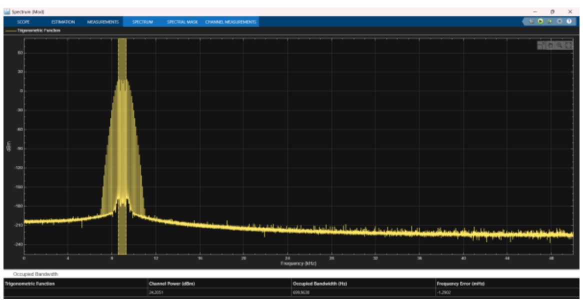

Figure 48: 5 fm

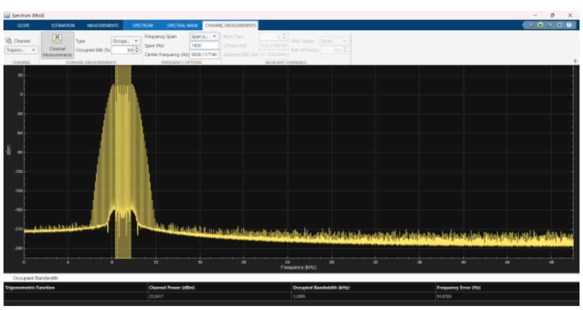

Figure 49: 10 fm

With the sample per period being 1000 and the sample time being 10^-5, the period is 0.01 and thus the frequency of the modulating signal is 100 Hz.

We varied frequency of the gain in this section of the lab. According to the results recorded in the figure above, as the gain increases, the number of significant side bands increases, but the height of the highest peaks decreases. The vertical axis is in dBm, which represents the channel power. The higher the channel power, the higher the peak. On the other hand, the more peaks there are, the more bandwidth there are. Overall, the results align with the fact that there is a tradeoff between bandwidth and power, which complies with Carson's Rule.

Q2: For each $\Delta f = 0.1 f_m, 0.5 f_m, f_m, \ldots, 10 f_m$, determine the actual transmission bandwidth. Record the amount of power in percentage contained in the bandwidth as estimated by Carson rule.

$$B_{fm} \approx 2(1+\beta)W = 2W + 2\Delta f$$
$$= 200 + 2\Delta f$$

$$\beta = \frac{\Delta f}{W}$$

For $\Delta f = 0.1 f_m$: $B_{fm} \approx 200 + 2\Delta f = 220 Hz$

The recorded power is 26.9897 dBm at a transmission bandwidth of 0.995 Hz.

To find the percentage contained, we have

100 * (0.995/220) = 0.45%

For $\Delta f = 0.5 f_m$: $B_{fm} \approx 200 + 2\Delta f = 250 Hz$

The recorded power is 26.9897 dBm at a transmission bandwidth of 200.8618 Hz.

To find the percentage contained, we have

100 * (200.8618/250) = 80.35%

For Δ f = 1 f_m: $B_{fm} \approx 200 + 2\Delta f = 300\ Hz$

The recorded power is 26.9286 dBm at a bandwidth of 300.6011 Hz.

100 * (300.6011/300) = 100%

For Δ f = 5 f_m: $B_{fm} \approx 200 + 2\Delta f = 700\ Hz$

The recorded power is 24.2151 dBm at a bandwidth of 699.9630 Hz.

100 * (699.9630/700) = 100%

For Δ f = 10 f_m: $B_{fm} \approx 200 + 2\Delta f = 1200 Hz$

The recorded power is 23.5617 dBm at a bandwidth of 1200 Hz.

100 * (1200/1200) = 100%

As Δf increases, the transmission bandwidth also increases. The percentage of power contained in the bandwidth increases until it reaches 100% as the bandwidth approaches the value predicted by Carson's rule.

Conclusion

This lab explored amplitude and frequency modulation techniques, focusing on the trade-offs between power efficiency, bandwidth, and system complexity. In the amplitude modulation section, we compared DSB-LC and DSB-SC systems. While DSB-LC is simple to demodulate, it is inefficient due to the carrier's power consumption. In contrast, DSB-SC improves power efficiency by removing the carrier but requires more complex demodulation.

In the frequency modulation section, we examined how the carrier's frequency varies with the modulating signal's amplitude, showing the advantages of FM in terms of noise resistance and sound quality. Adjusting the Gain Sensitivity Factor revealed how increasing frequency deviation improves signal robustness but requires more bandwidth, aligning with Carson's Rule.

Overall, the lab demonstrated the importance of choosing the right modulation technique based on specific system requirements, such as bandwidth, power, and noise tolerance.