# ECSE308 Lab 2

# Analog Modulation Techniques

Zhanyue Zhang:260944809

Zhiheng Zhou: 260955157

ECSE308

Professor Tho Le-Ngoc

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# Part 1: Amplitude Modulation (AM)

## Introduction:

The objective of the first part of this lab is to understand the basic principles of amplitude modulation and demodulation. We need to build a double-sideband (DSB) large-carrier (LC) AM system and a DSB suppressed-carrier (SC) AM system using Simulink in Matlab to achieve our goal. We will observe and discuss the output to understand DSB-LC more deeply.

## Experiments:

**a**) We started with building a DSB-LC AM system as illustrated (Fig. 1)

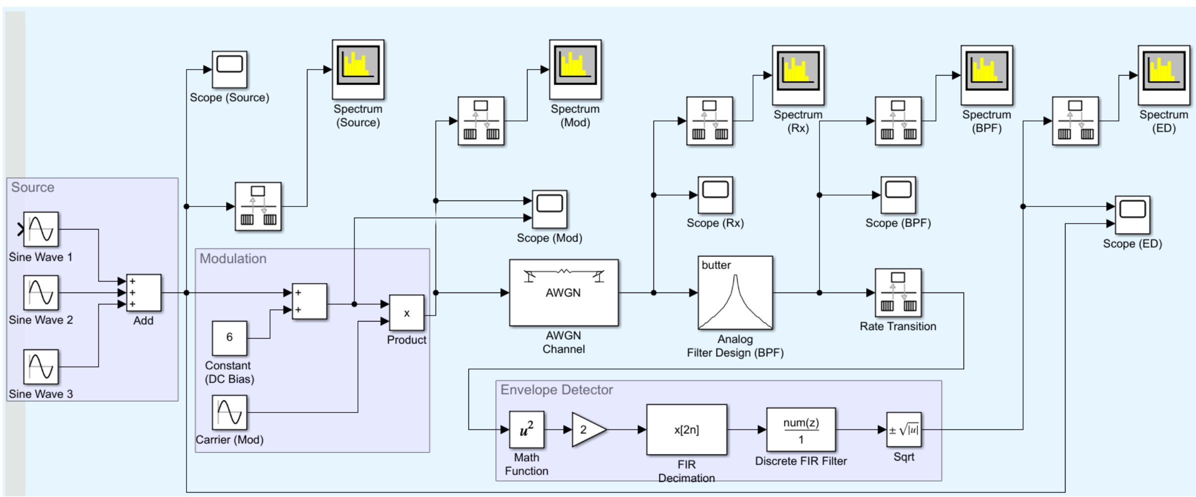



***Fig. 1: DSB-LC AM System***

We set up the parameters as follows:

- Sine Wave 1:

  Sine type: Time-based | Amplitude: 1 | Frequency (rad/sec): 1000π

- Sine Wave 2:

  Sine type: Time-based | Amplitude: 3 | Frequency (rad/sec): 600π

- Sine Wave 3:

  Sine type: Time-based | Amplitude: 1.5 | Frequency (rad/sec): 1200π

- Constant (Mod): Constant values: 6
- Carrier (Mod):

Sine type: Time-based | Amplitude :1 | Frequency (rad/sec): 30000π | Phase (rad): $\frac{\pi}{2}$

- AWGN Channel: We set the initial seed to one instead of randseed as required in the instruction due to a compilation error encountered when using 'randseed'. It's worth noting that this adjustment would not affect the outcome of the experiment.

  Initial seed: 1 | Mode: Variance from mask | Variance: 1e-2

- Analog Filter Design:

  Design method: Butterworth | Filter type: Bandpass | Filter order: 8 | Lower passband edge frequency (rad/s): $14300 \times 2\pi$ | Upper passband edge frequency (rad/s): $15800 \times 2\pi$

- Rate Transition: Output port sample time: 2e-5
- Math Function: Function: square
- FIR Decimation: We retained the default FIR filter coefficients in Simulink. It's worth noting that this adjustment would not affect the outcome of the experiment.

  Decimation factor: 2

- Discrete FIR Filter Coefficients: firpm(20, [0 0.03 0.1 1], [1 1 0 0])
- Sqrt Function: signedSqrt

**b**) After building the DSB-LC AM System, we changed some blocks and built a DSB-SC AM system as shown in Fig. 2. Compared to DSB-LC, DSB-SC is more power efficient: it removes the carrier from DSB-LC before power amplification allows full transmitter power to be applied to the sidebands

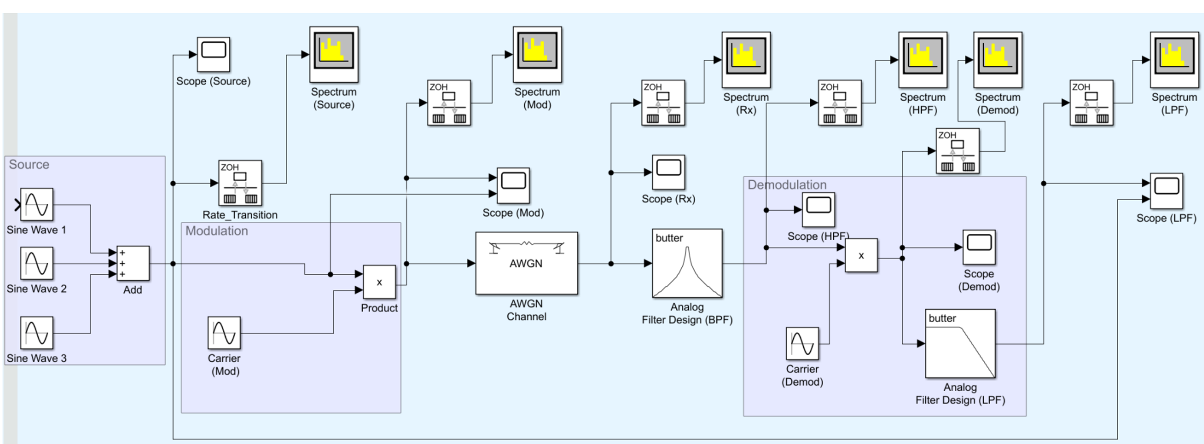



*Fig. 2: DSB-SC AM System*

We set up the parameters as listed:

- Sine Wave 1:

  Sine type: Time-based | Amplitude: 1 | Frequency (rad/sec): $1000\pi$

- Sine Wave 2:

  Sine type: Time-based | Amplitude: 3 | Frequency (rad/sec): $600\pi$

- Sine Wave 3:

  Sine type: Time-based | Amplitude: 1.5 | Frequency (rad/sec): $1200\pi$

- Carrier (Mod):

  Sine type: Time-based | Amplitude :1 | Frequency (rad/sec): $30000\pi$ | Phase (rad): $\frac{\pi}{2}$

- Carrier (Demod):

  Sine type: Time-based | Amplitude :1 | Frequency (rad/sec): $30000\pi$ | Phase (rad): $\frac{\pi}{2}$

- AWGN Channel: We set the initial seed to one (the same as (a)).

  Initial seed: 1 | Mode: Variance from mask | Variance: 1e-2

- Analog Filter Design (BPF):

  Design method: Butterworth | Filter type: Bandpass | Filter order: 8 | Lower passband edge frequency (rad/s): $14300 \times 2\pi$ | Upper passband edge frequency (rad/s): $15800 \times 2\pi$

- Analog Filter Design (LPF):

  Design method: Butterworth | Filter type: Lowpass | Filter order: 8 | Passband edge frequency (rad/s): $800 \times 2\pi$

- Rate Transition: Output port sample time: 2e-5

## Questions:

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

**Answer:**
The output on the Spectrum(Source) is shown in Fig. 3

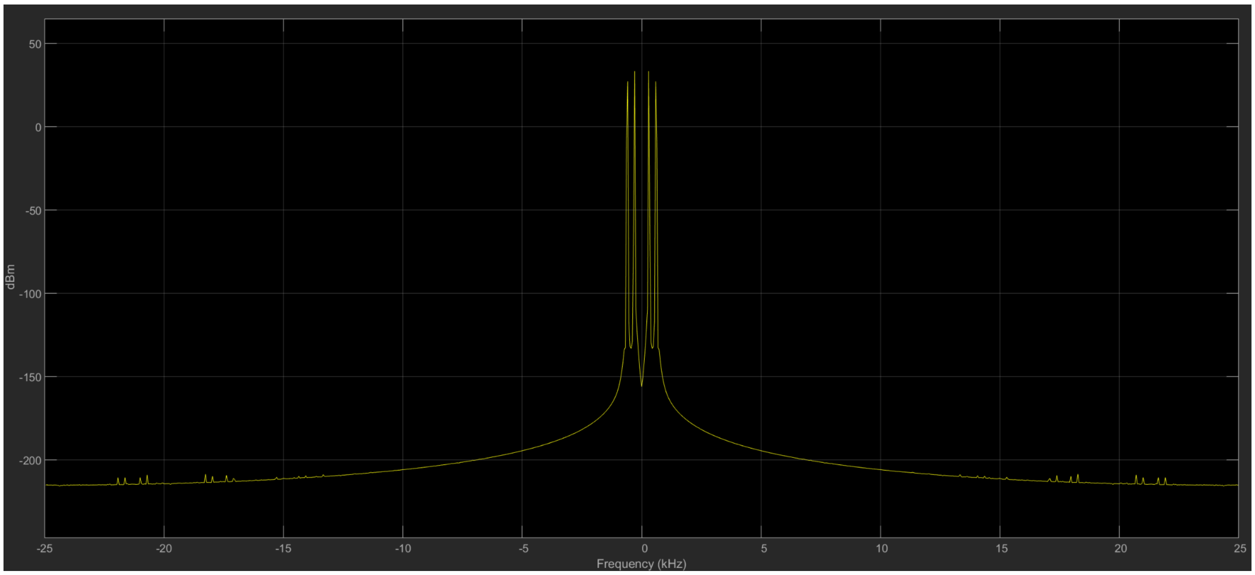



***Fig. 3: output on Spectrum (Source) of DSB-LC AM system***

From the peak finder, we observed that the fundamental period is 2kHz. The second harmonic is then 4kHz, and the third harmonic is 6kHz.

**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 signal.**

**Answer:**
The outputs on Scope (Source) and Scope (Mod) are shown in Fig. 4 and Fig. 5, respectively.

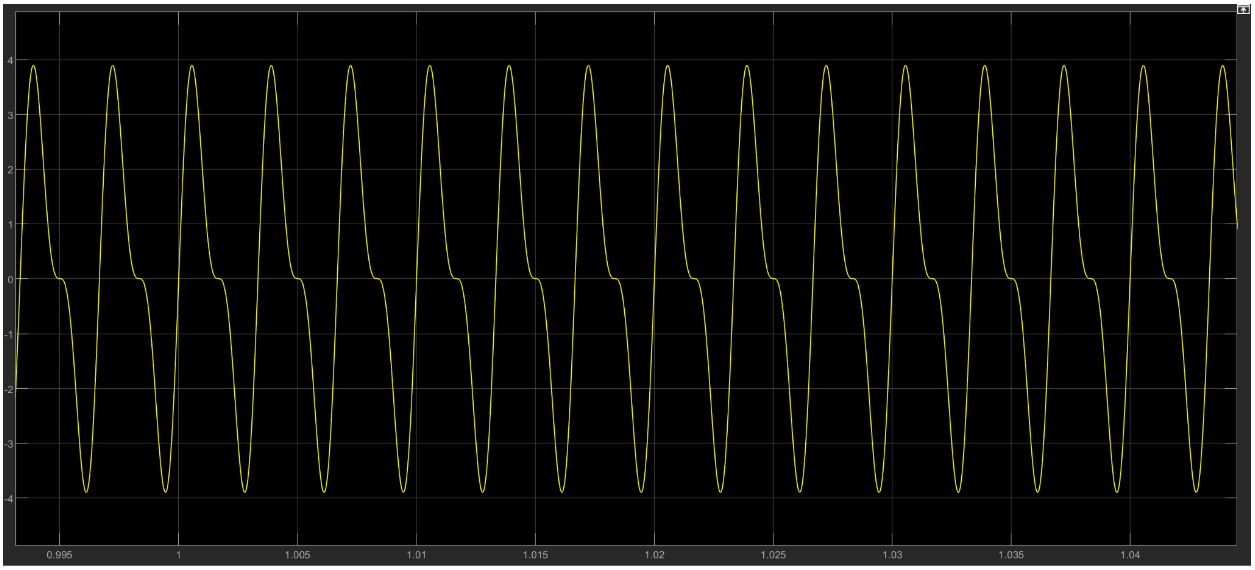



***Fig. 4: output on Scope (Source) of DSB-LC AM system***

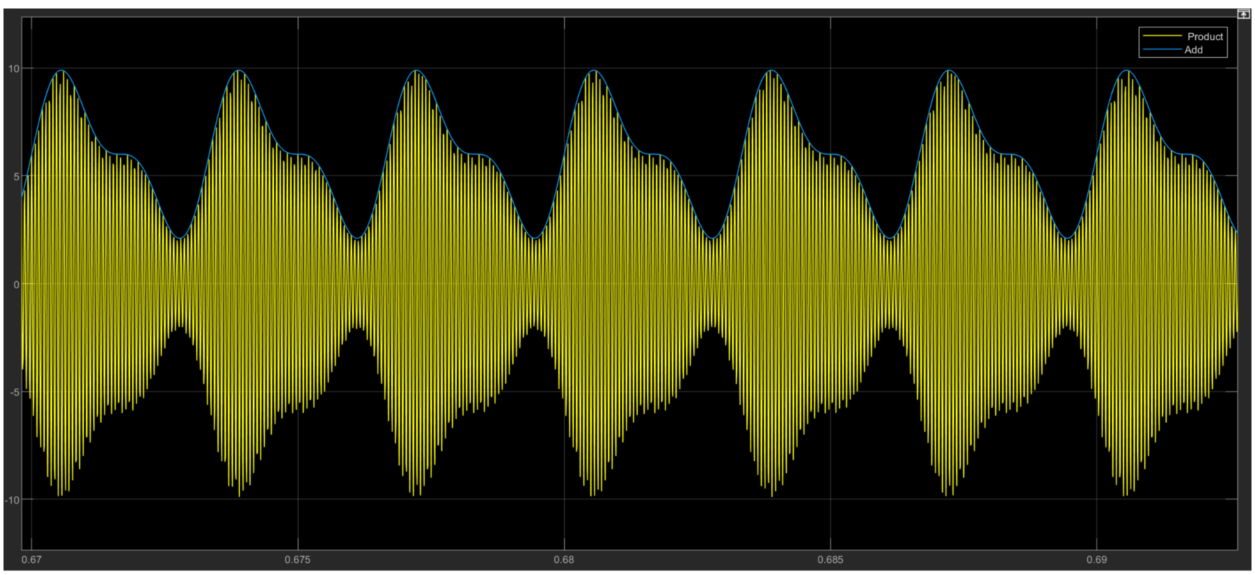



***Fig. 5: output on Scope (Mod) of DSB-LC AM system***

Observing the outputs on scopes, we noticed that the amplitude of the AM signal directly follows the variations in the amplitude of the modulating signal. The AM signal will have its highest amplitude when the modulating signal is at its peak amplitude. Conversely, when the modulating signal is at its lowest amplitude, the AM signal will also be at its lowest amplitude.

**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.**

**Answer:**

The outputs on Spectrum (Source) and Spectrum (Mod) are shown in Fig. 3 and Fig. 6, respectively.

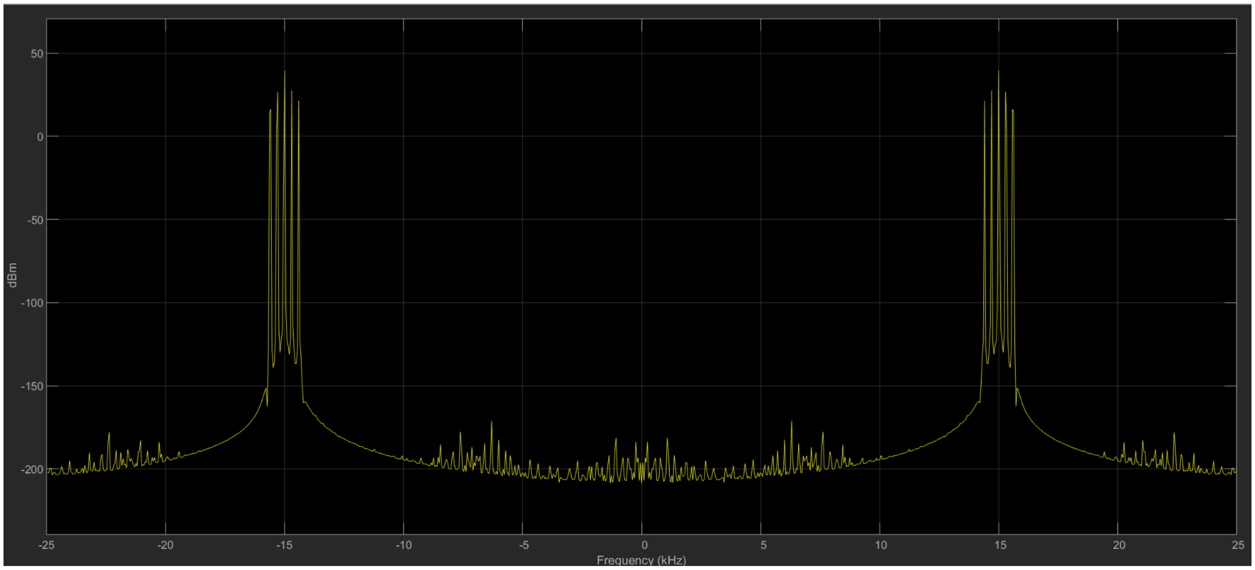



***Fig. 6: output on Spectrum (Mod) of DSB-LC AM system***

The carrier frequency ($f_C$) is centered at 0kHz, and the maximum modulation frequency ($f_M$) is 15kHz.

The spectrum of the AM signal will display the carrier frequency, along with the sidebands that appear in pairs and frequency components from the modulating signal. The transmission bandwidth of AM signals is directly related to the maximum frequency component in the modulating signal, and it is twice the highest frequency component.

**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)?**

**Answer:**

The outputs on Spectrum (BPF) and Spectrum (Rx) are shown in Fig. 7 and Fig. 8, respectively.

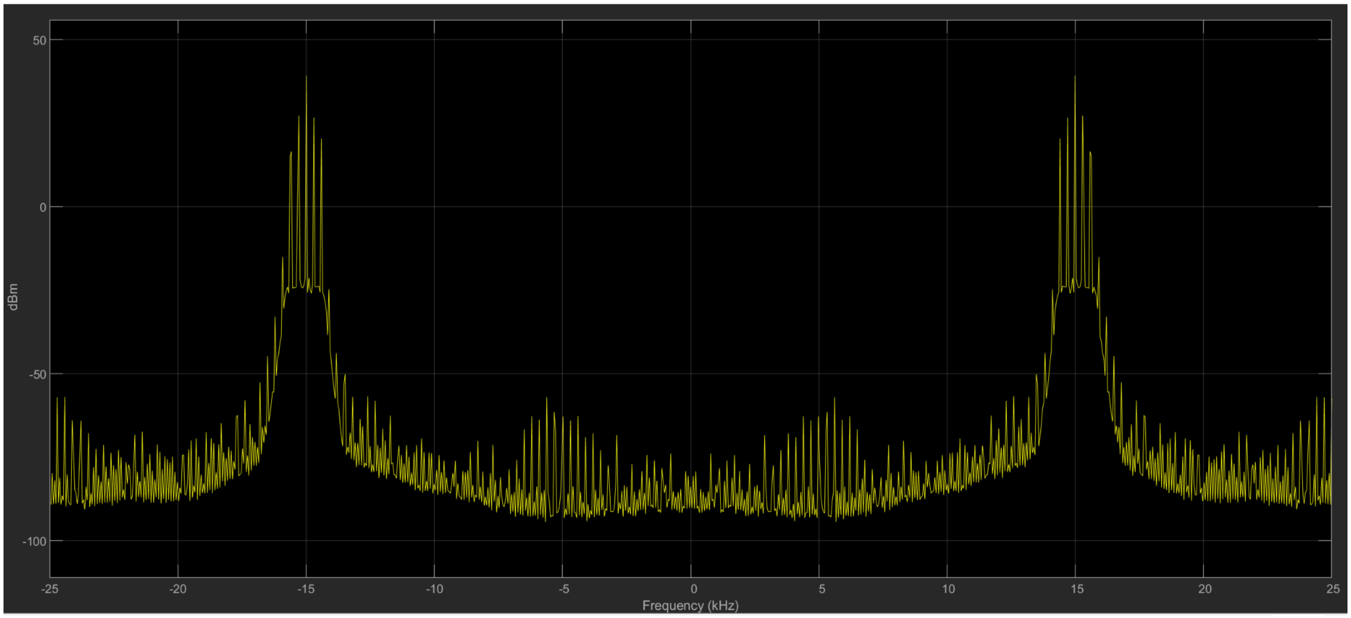



*Fig. 7: output on Spectrum (BPF) of DSB-LC AM system*

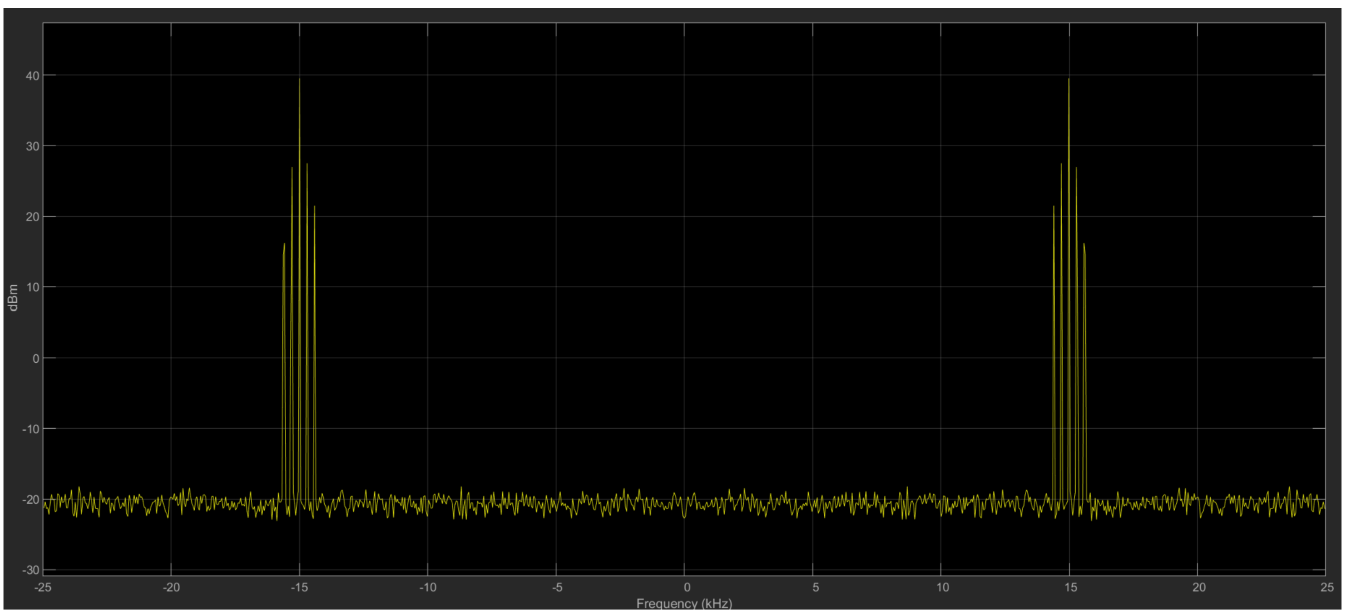



*Fig. 8: output on Spectrum (Rx) of DSB-LC AM system*

To filter out the noise without distorting the desired signal, we need to know the fundamental and harmonic frequencies. Understanding the amplitude of the noise can help attenuate noise selectively while preserving the desired signal. Moreover, it is necessary to have knowledge of the filter type.

The bandpass filter is designed to selectively attenuate frequencies outside the desired range, effectively reducing noise. After using a low-pass filter, we noticed less noise in the output spectrum. As the noise has been filtered, the SNR is higher.

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

**Answer:**
The outputs on Spectrum (BPF) and Spectrum (ED) are shown in Fig. 7 and Fig. 9, respectively.

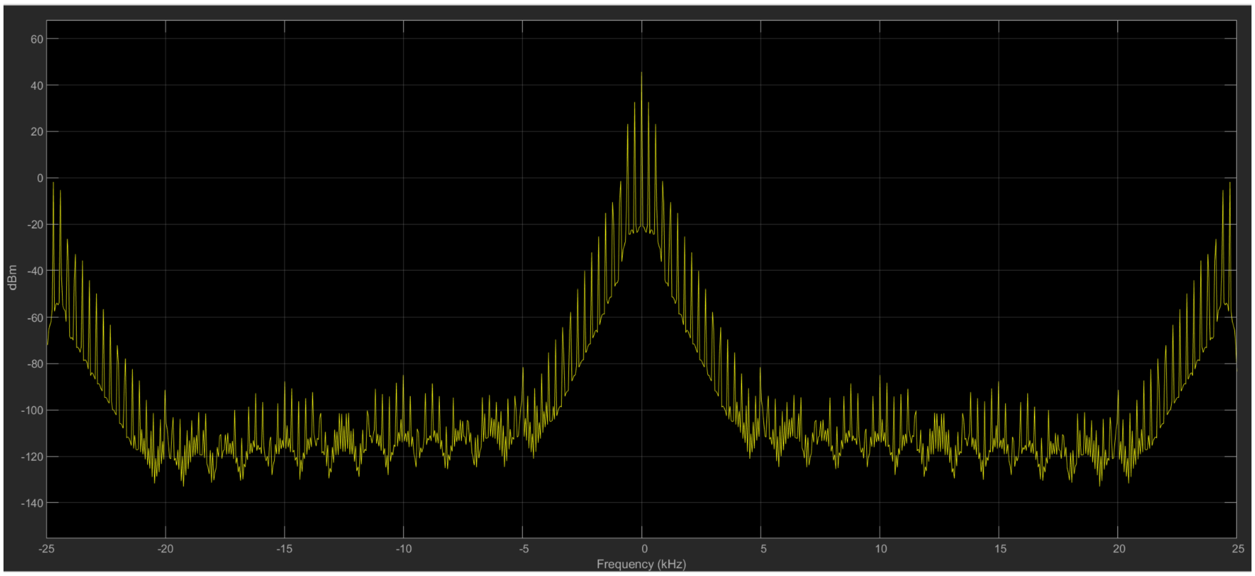



***Fig. 9: output on Spectrum (ED) of DSB-LC AM system***

In general, DSB-LC AM demodulation is the process of extracting the baseband modulating signal from a DSB-LC AM modulated signal contaminated by noise, distortion, and interference. DSB-LC AM modulation is relatively straightforward, requiring only envelope detection and filtering, and the demodulation process does not require any complex algorithm or circuit. However, if the carrier amplitude changes significantly, the quality of the demodulation signal might be affected.

**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 is a feasible DC bias in relation to the amplitude of the source signal so that successful demodulation can be guaranteed.**

**Answer:**

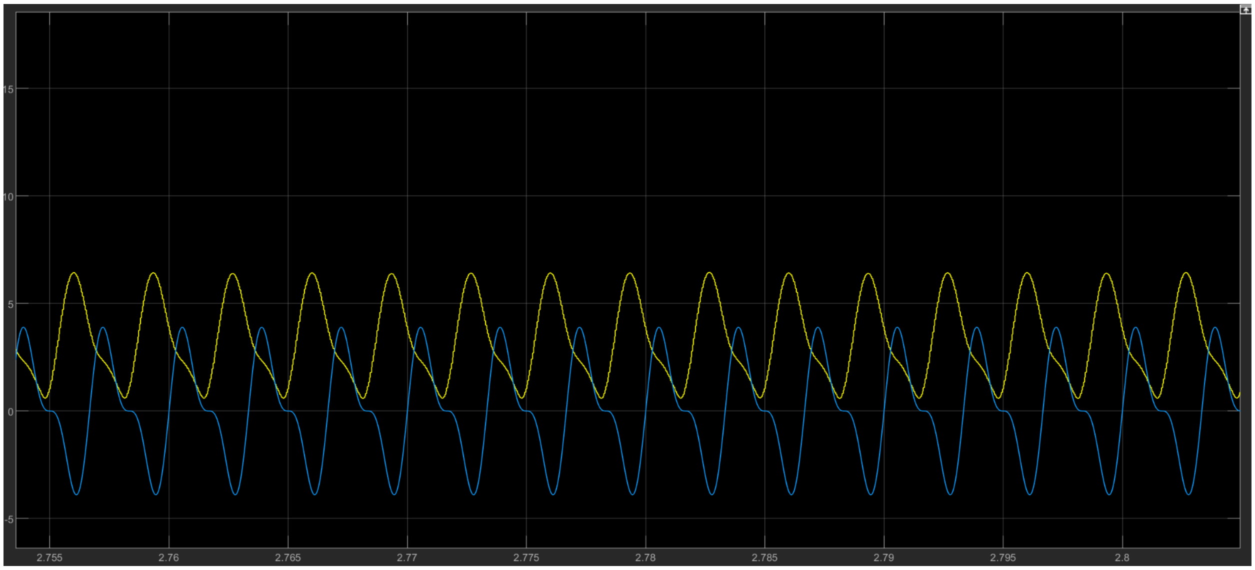



*Fig. 10: output on Scope (ED) of DSB-LC AM system (DC bias = 3)*

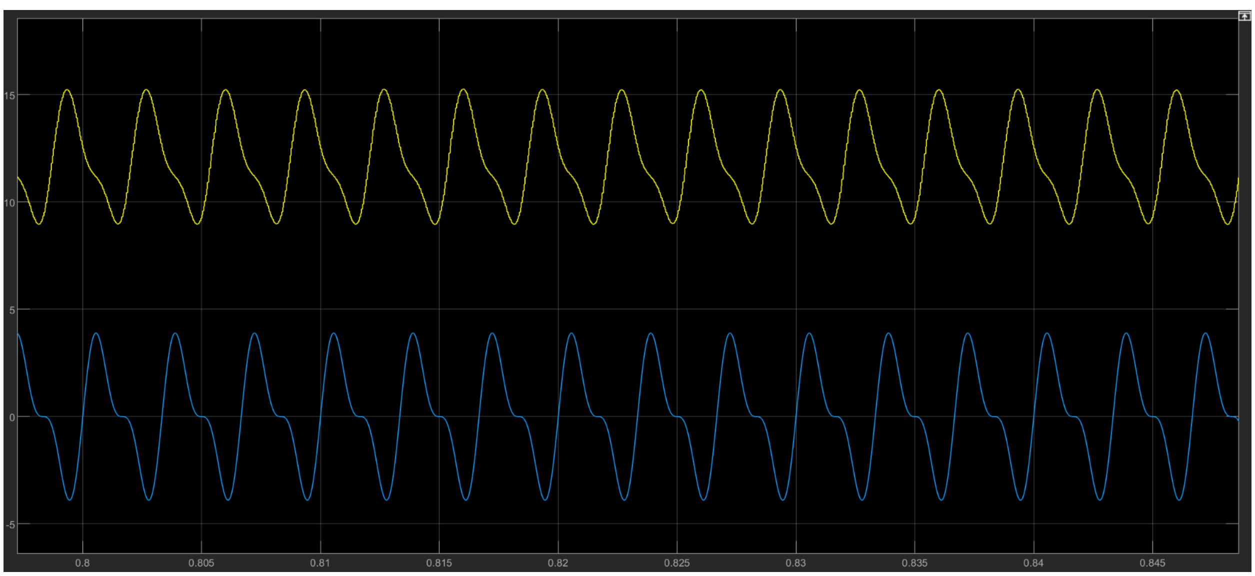



*Fig. 11: output on Scope(ED) of DSB-LC AM system (DC bias = 12)*

We adjusted the DC bias settings to 3 and 12, resulting in the outputs depicted in Figures 10 and 11 on the Scope (ED), respectively. From the outputs, we observed that DC bias will effectively

shift the entire signal up by 3 and 12 units on the amplitude axis, respectively. The outputs indicated that in both cases, the choice of DC Bias values (3 and 12) kept the entire modulated signal above zero.
A feasible DC bias in relation to the amplitude of the source signal is one that ensures the entire modulated signal, after biasing, stays above zero. If the DC bias is too low, it will result in distorted demodulated output due to incorrect envelope detection. An appropriate DC bias ensures that the envelope detector can reliably recover the original modulating signal. Hence it is crucial for demodulation.

**Q7: Repeat Steps 2-3 for DSB-SC AM.**

We constructed the double-sideband suppressed carrier (DSB-SC) to see the difference between it and the large carrier.

**Answer:**

The outputs of the DSB-SC AM system on Scope (Source) and Scope (Mod) are shown in Fig. 12 and Fig. 13, respectively.

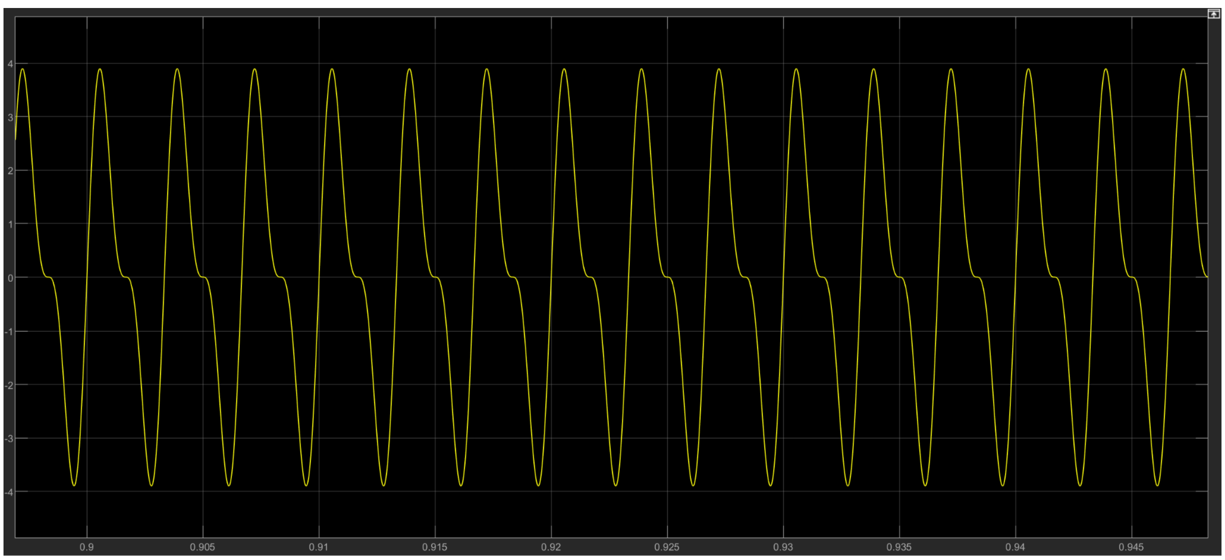



*Fig. 12: output on Scope (Source) of DSB-SC AM system*

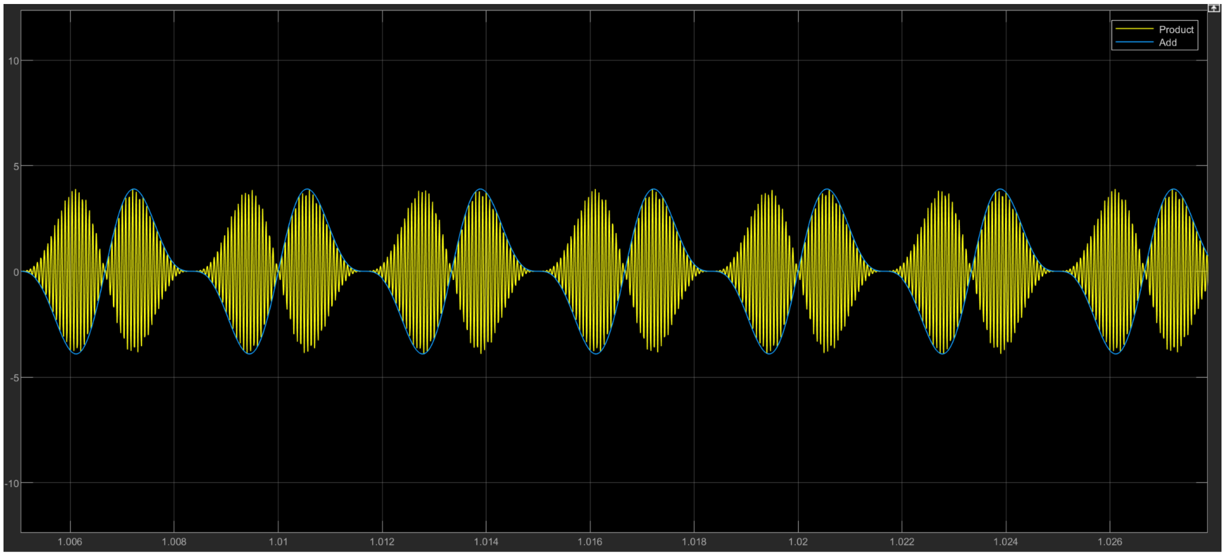



***Fig. 13: output on Scope (Mod) of DSB-SC AM system***

In this DSB-SC AM system, the amplitude of the AM signal will be directly influenced by the amplitudes of the modulating signals (Sine Waves 1, 2, and 3). Observing the outputs, we noticed that the waveform reflects only the variations caused by the modulating signals. From Fig. 13, we can tell that the envelope will be solely influenced by the modulating signals.

Then we observed the outputs of the DSB-SC AM system on Spectrum. The outputs of the DSB-SC AM system on Scope (Source) and Scope (Mod) are shown in Fig. 13 and Fig. 14, respectively.

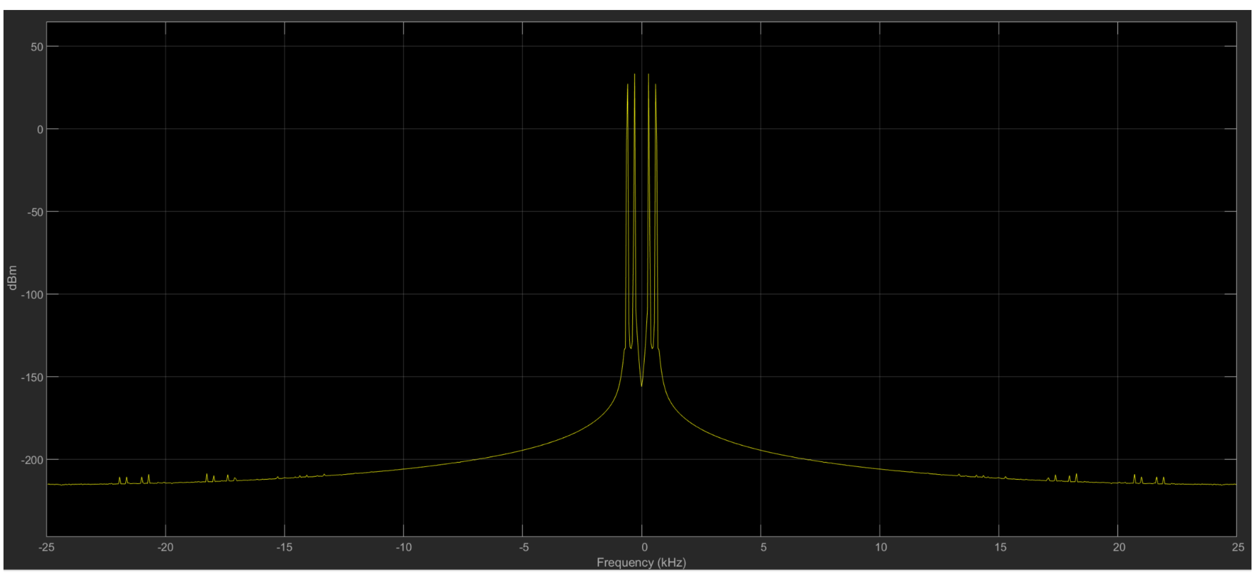



***Fig. 14: output on Spectrum (Source) of DSB-SC AM system***

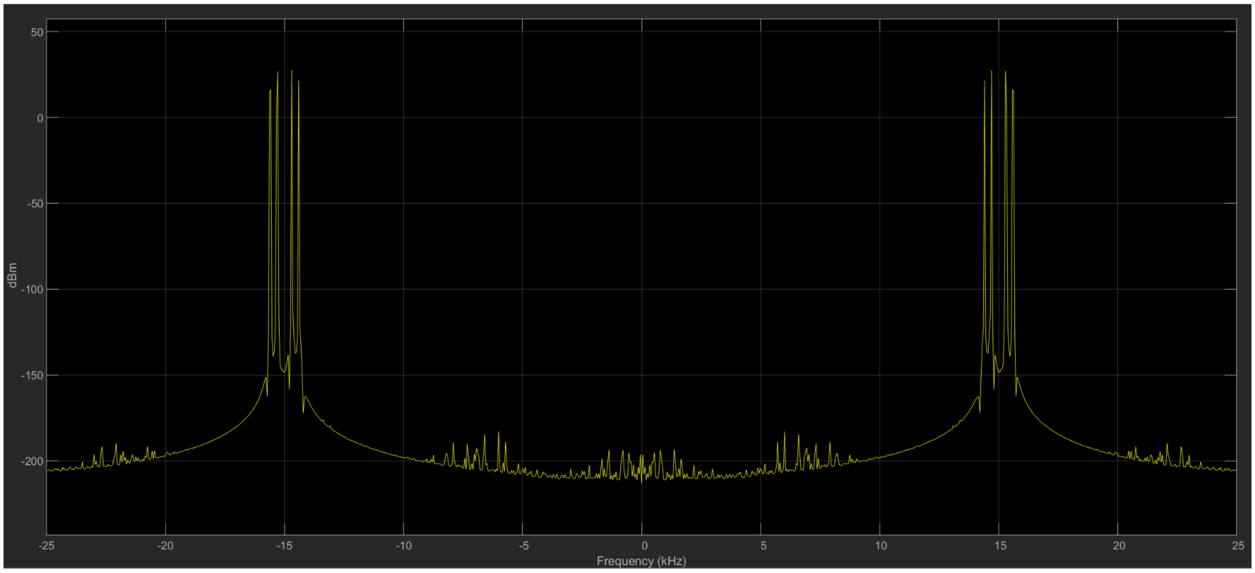



*Fig. 15: output on Spectrum (Mod) of DSB-SC AM system*

The spectrum of the DSB-SC AM signal primarily contains the sidebands (upper and lower) corresponding to the frequency components of the modulating signals with no carrier frequency component. The transmission bandwidth of AM signals is directly related to the maximum frequency component in the modulating signal. For example, if the highest frequency component in the modulating signal is $f_{max}$, then the bandwidth of the DSB-SC AM signal will be $2f_{max}$.

**Q8: 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.**

**Answer:**

Compared to DSB-LC, DSB-SC modulation offers higher power efficiency. In DSB-SC modulation, the carrier signal is completely suppressed and no power is wasted on transmitting the carrier signal. In DSB-LC modulation, both sidebands (upper and lower) and the carrier signal are transmitted. Hence, DSB-SC achieves higher power efficiency than DSB-LC does.

Demodulation of DSB-SC involves using a coherent receiver that regenerates a local carrier signal. The received signal is multiplied by this local carrier, which effectively reconstructs the original modulating signal.

DSB-LC uses a coherent receiver to recover the original modulating signal. Multiplying the received signal by a local carrier, it will extract the sidebands, which are then filtered to recover the modulating signal.

## Part 2: Frequency Modulation (FM)

### Introduction:

The objective of this part is to explore the frequency modulation and demodulation. We used FM modulation and the VCO module to achieve this. The output of the modulation and demodulation signals are observed in the scopes and spectrum analyzers.

### Experiments:

We set up our circuits as shown in Figure 1. The input modulating sine signal is sample-based with 1000 samples per period. Sample time is 1e-6 s. The carrier frequency is 9000 Hz. The sensitivity factor is 3000. The digital filter is a low-pass filter with Fs = 1e6 and Fc = 1e3.

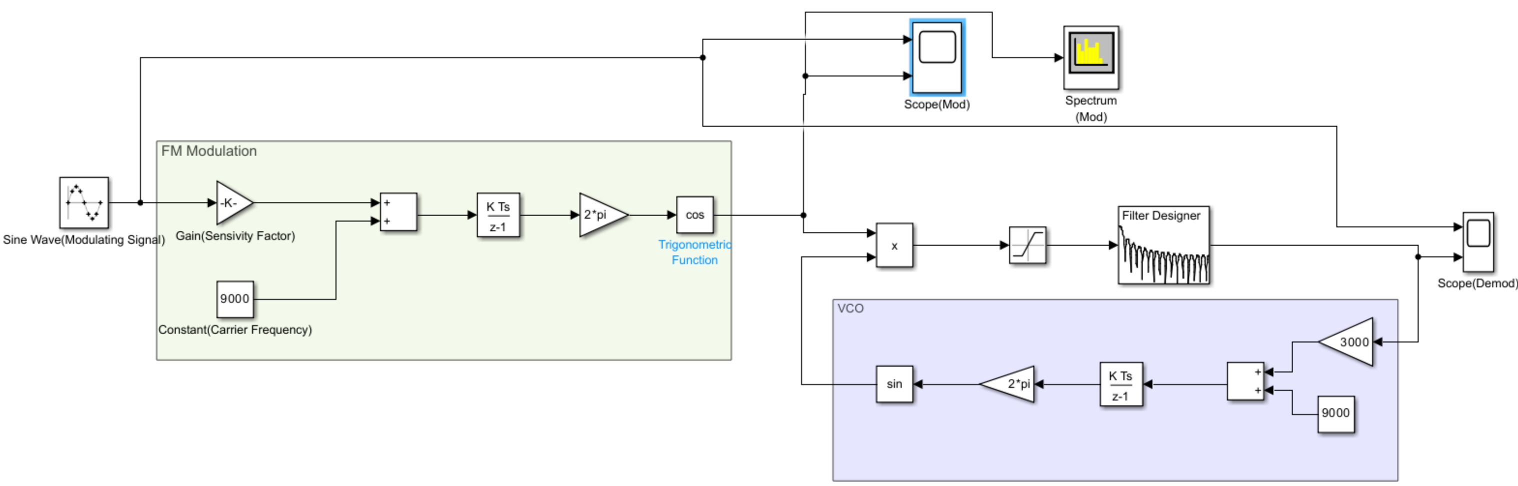



*Fig. 1: the setup of the second part.*

We then observe the Scope(Mod) and get the plot as shown in Figure 2. The yellow one is the modulating signal and the blue one is the modulated signal. The spectrum of the modulated signal is shown in Figure 3. The comparison between the demodulated signal and the modulating signal is shown in Figure 4.

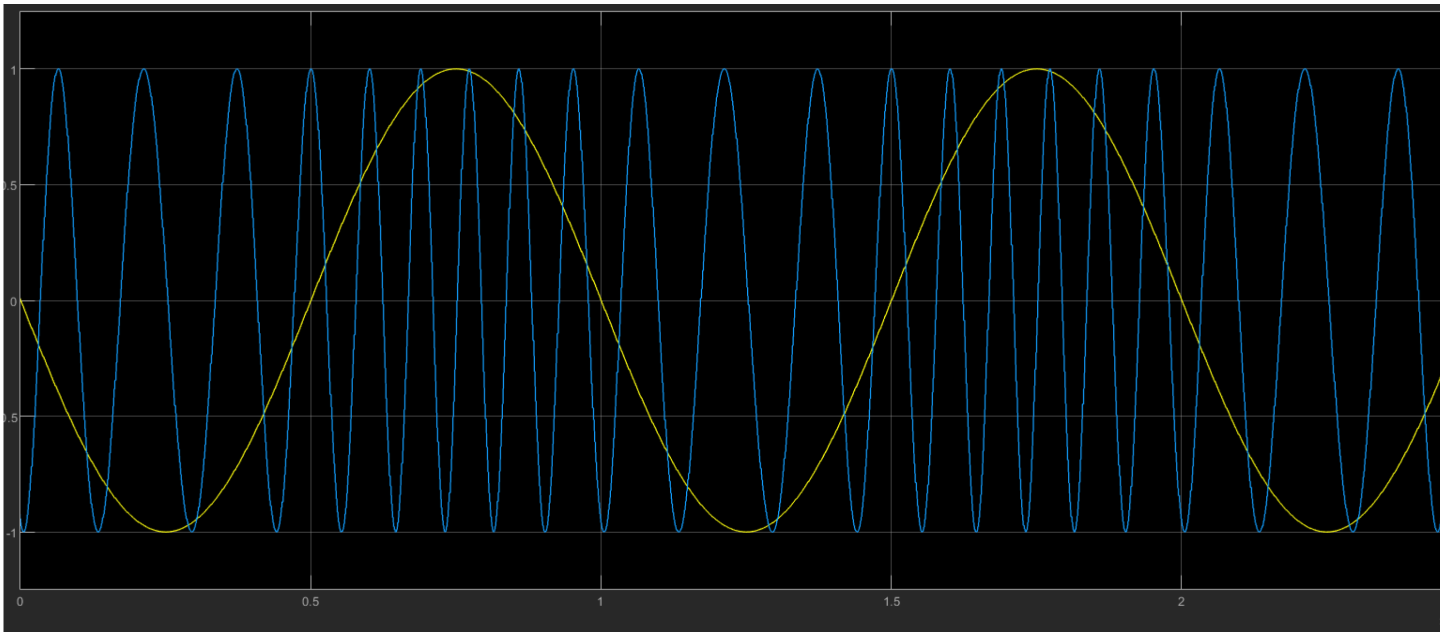



*Fig. 2: Plot on the scope(mod)*

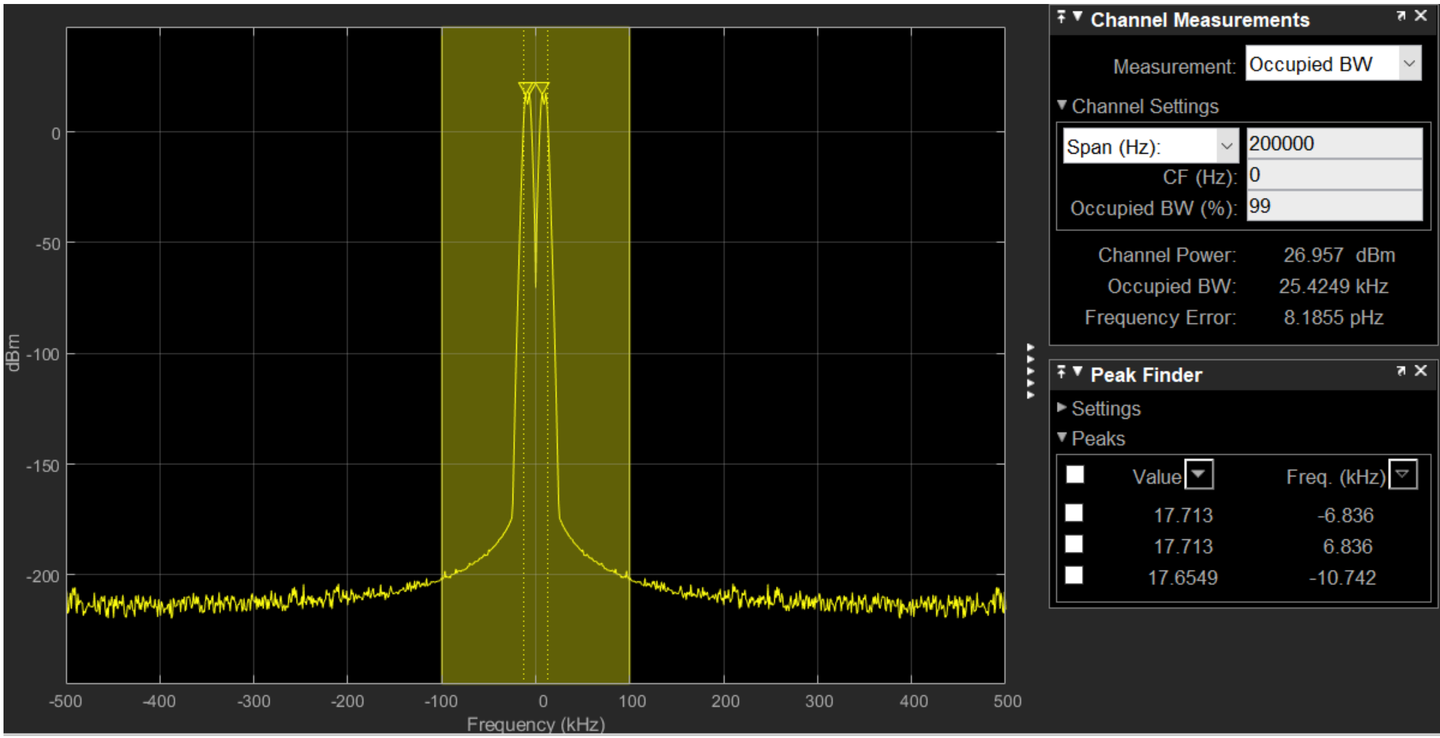



*Fig. 3: Spectrum on the scope(mod)*

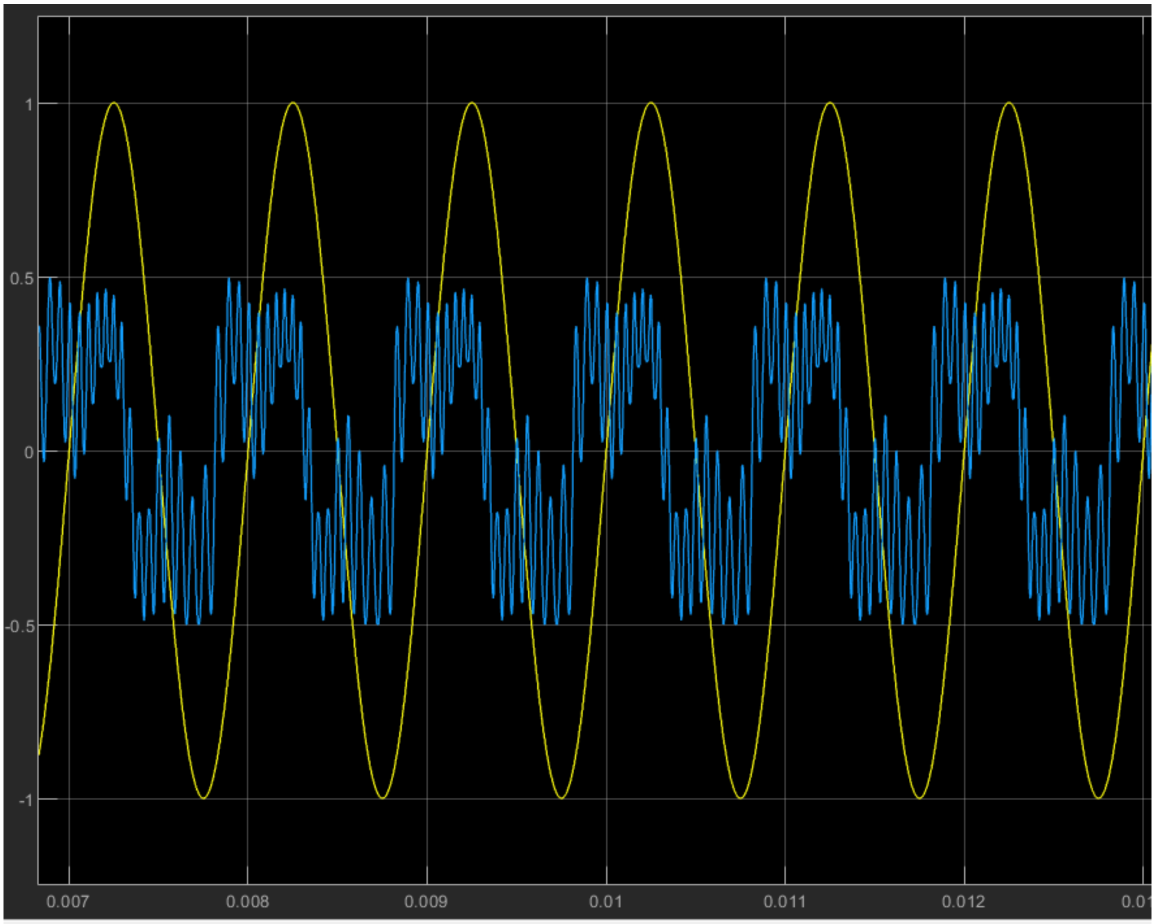



***Fig. 4: Plot on the scope(demod). The blue one is demodulated signal and the yellow one is input signal.***

## Questions:

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

In the FM modulation process, we multiplied the input sine wave with a sensitivity factor with Gain = 3000 and added 9000 to it. The signal before the integrator is $3000 * a(t) + 9000$. The final modulated signal is $cos(2\pi * \int_{-\infty}^{t} (3000a(t) + 9000)\, dt = cos(2\pi * (9000t + 3000 \int_{-\infty}^{t} a(t)dt))$.

In the demodulation process, we used a Phase Locked Loop. The VCO output signal has the same carrier frequency but with a 90-degree phase shift. Hence the output of the VCO is $s(t) = sin(2\pi * (9000t + \int_{-\infty}^{t} 3000b(t)dt))$. After the multiplication, we have a higher frequency component: $0.5sin(4\pi * 9000t + 2\pi(\int_{-\infty}^{t} 3000a(t)dt + \int_{-\infty}^{t} 3000b(t)dt))$ and a lower frequency component: $0.5sin(2\pi(\int_{-\infty}^{t} 3000a(t)dt - \int_{-\infty}^{t} 3000b(t)dt))$ which is also the demodulated signal.

**Answer:**

**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 sum 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**

**Answer:** The output on Scope(Mod) is shown in Figure 2. We can see that the FM signal has the same amplitude as the modulating signal. When the modulating signal has a higher amplitude, the FM signal has a higher frequency. When added another sine wave with an amplitude of 1, the output is shown in Figure 5. We can see the amplitude of the FM signal is still 1. Compared to AM modulation, which is a linear process, FM modulation is not a linear process.

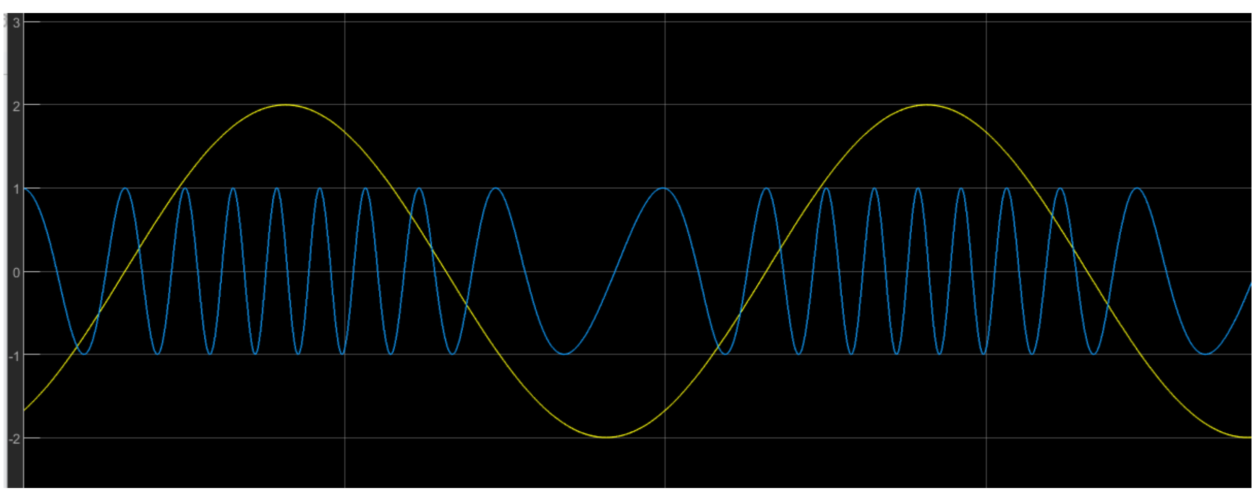



*Fig. 5: Plot on the scope(mod) when input is the summation of two waves.*

**Q3: Vary Gain (Sensitivity Factor) from small (i.e., the modulation index $\beta$ less than 1 radian) to large (i.e., the modulation index $\beta$ greater than 1 radian). Comment on the sensitivity of the carrier to the modulating signal in terms of amplitude and frequency variation.**

**Answer:** When we increase the sensitivity factor to 10000 where the modulation index $\beta$ is greater than 1 radian. We can see the output isn't enveloped properly as shown in Figure 6. The amplitude and frequency aren't affected since they are only related to the carrier frequency and input signal amplitude.

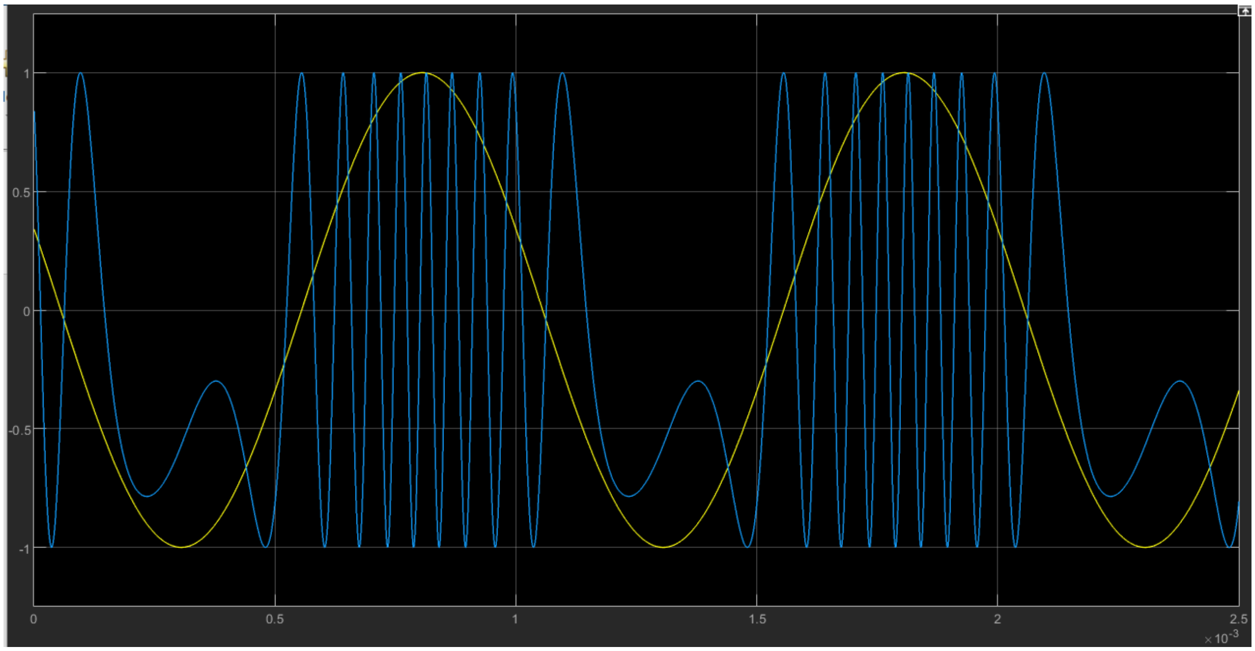



***Fig. 6: Plot on the scope(mod) when the modulation index is greater than 1.***

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

**Answer:**

1)When we increased the amplitude of the sine wave to 3, the spectrum of the modulated signal is shown in Figure 7. Compared to what we got from Figure 3, the energy has changed from 26.957dBm to 26.029dBm, there is a slight decrease.

2)When we increased the frequency of the sine wave, the power changed to 26.952dBm as shown in Figure 8. We can see a higher modulating frequency tends to increase the channel power but the change is negligible.

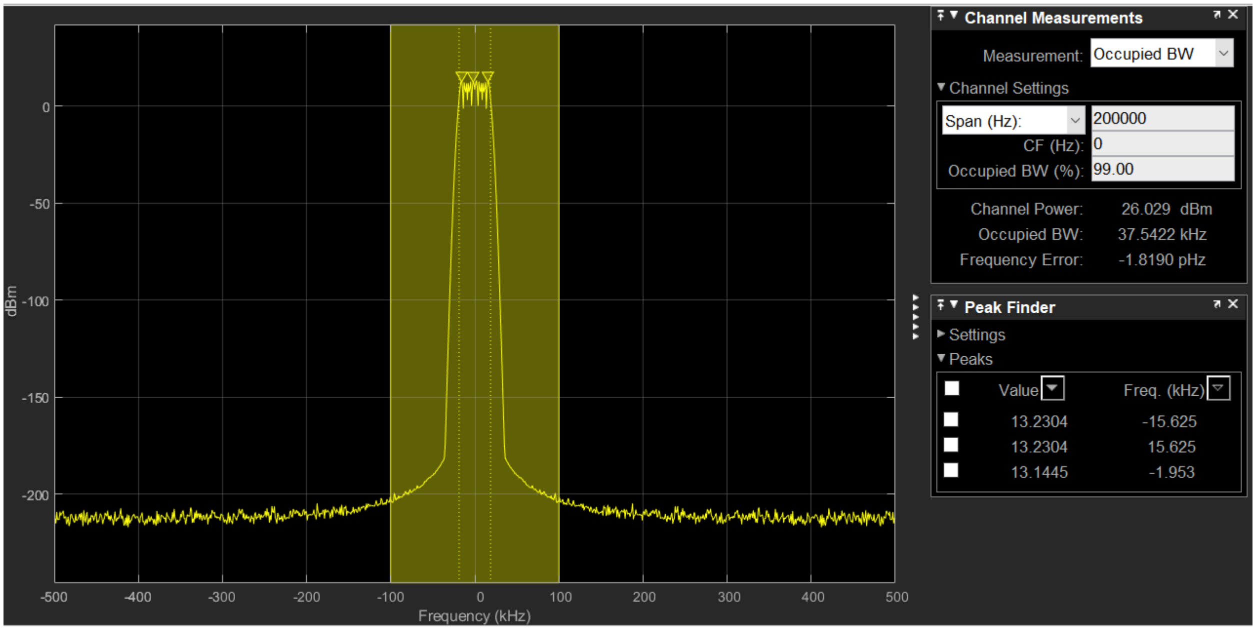



*Fig. 7: Plot on the spectrum when the input amplitude is increased.*

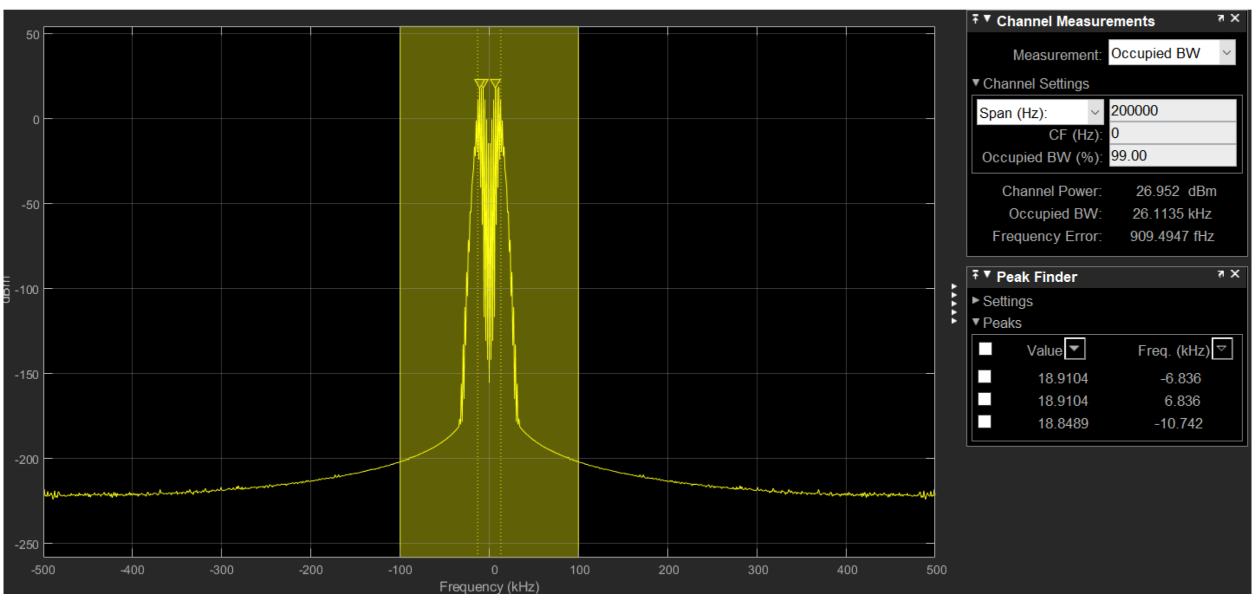



*Fig. 7: Plot on the spectrum when the input frequency is increased.*

3) In AM, the total channel power will increase when we increase the modulating amplitude since we want to change the amplitude and add a gain to it. In FM, power won't be affected since we just redistribute the frequency.

## Part3: Power/Bandwidth Trade-off in FM

### Introduction:

Part 3 of the lab aims to understand the possibility of Power/Bandwidth tradeoff in frequency modulation systems.

### Experiments:

In part 3, we set up the system as shown in Figure 1 by using a sample-based sine wave with 1000 samples per period and 1e-5 sample time. Gaussian noise is of 1e-2 variance and 1e-5 sample time. The analog filter is of 8 filter order and is bandpass with 8000*2*pi lower frequency and 10000*2*pi high frequency. FM demodulation subsystem is shown in Figure 2 with an Analog Filter with 200*2*pi passband edge frequency.

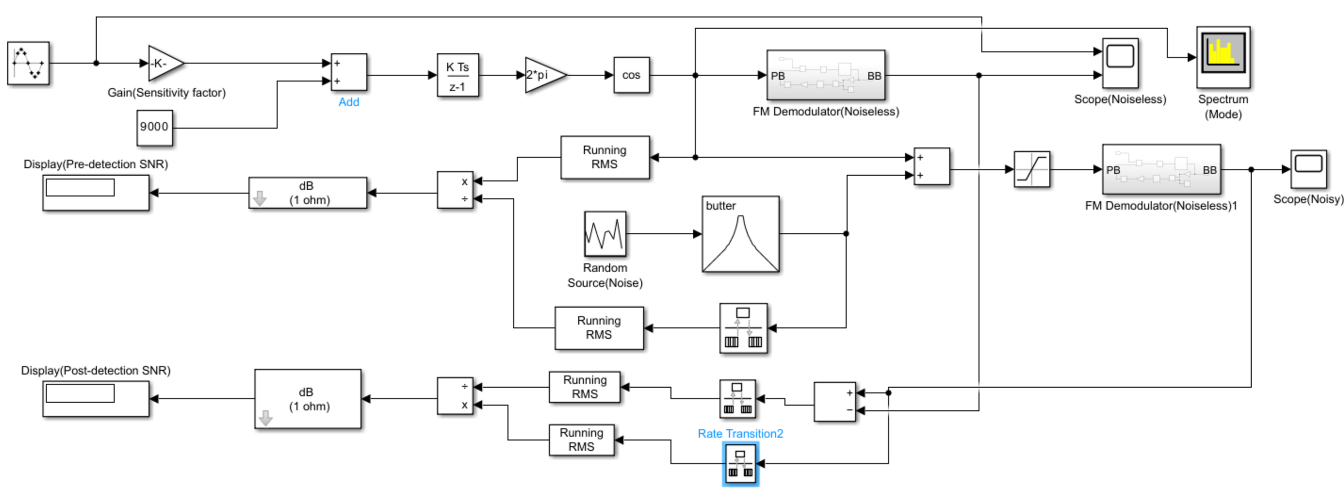



*Fig.1: System in part 3.*

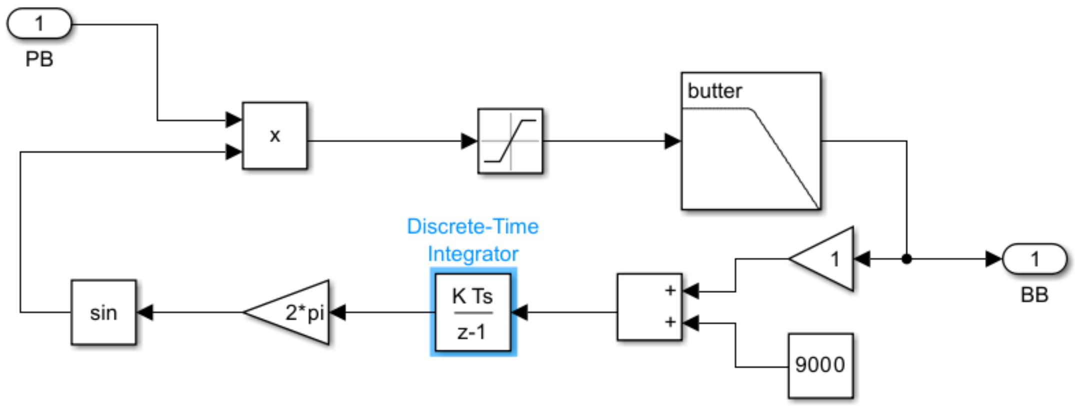
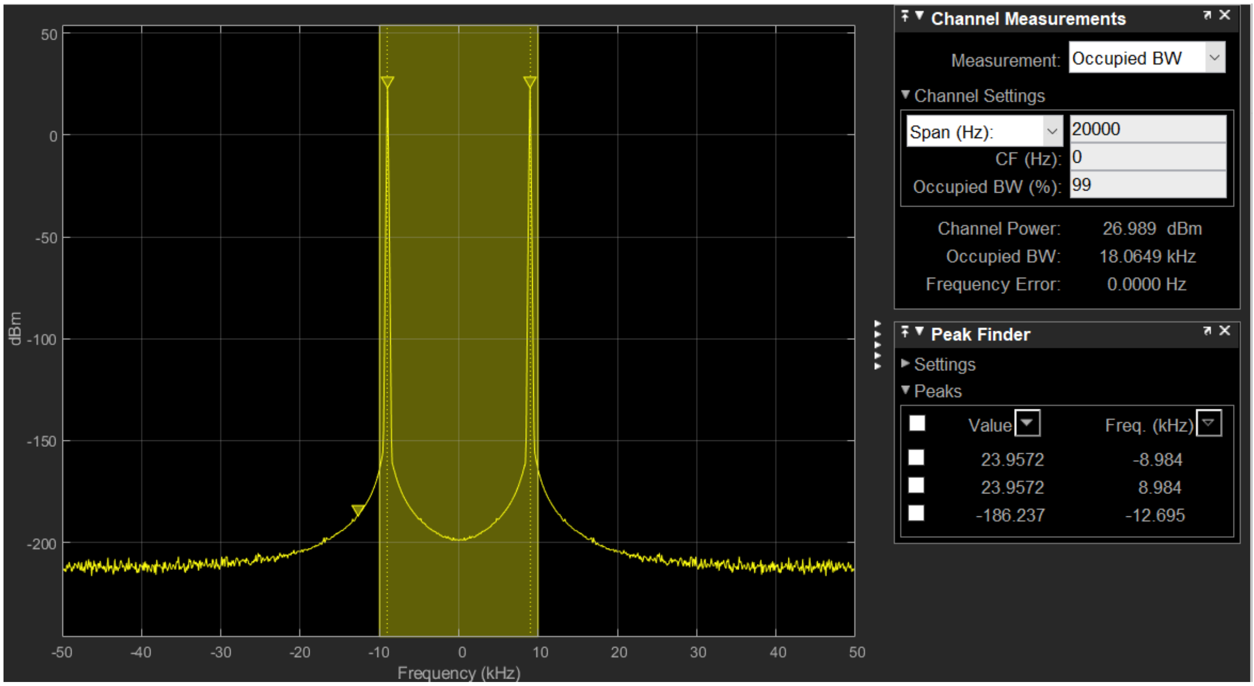


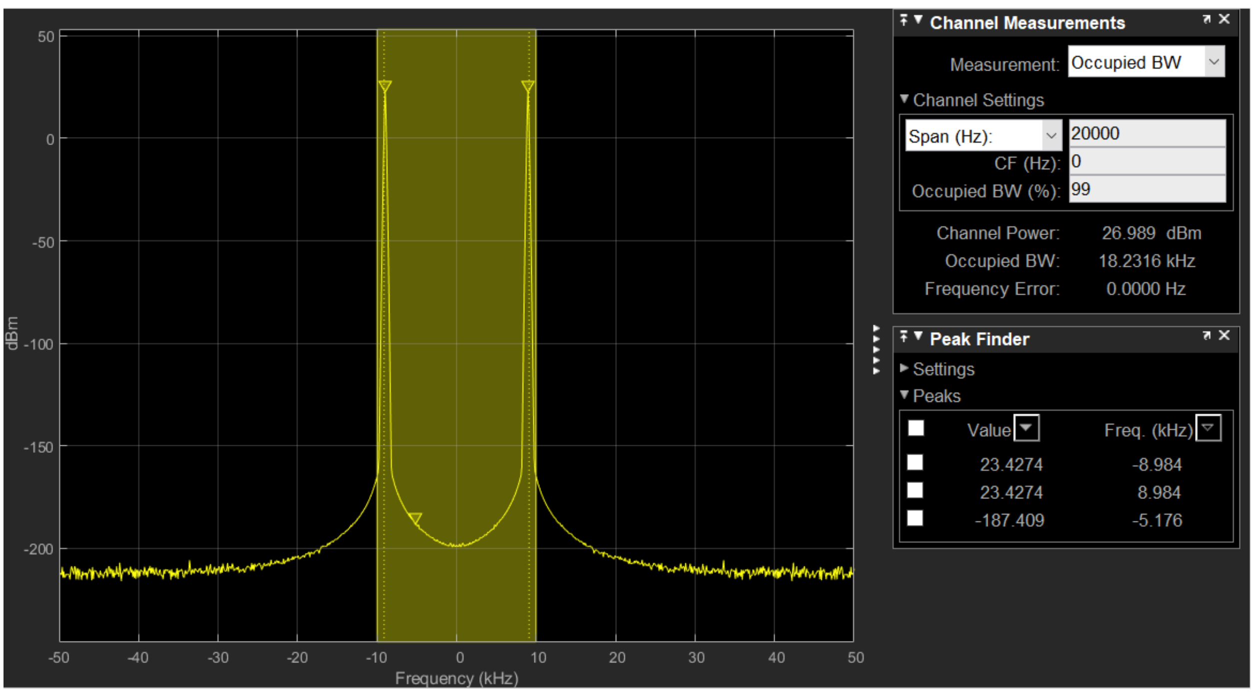

*Fig.2: FM demodulation subsystem*

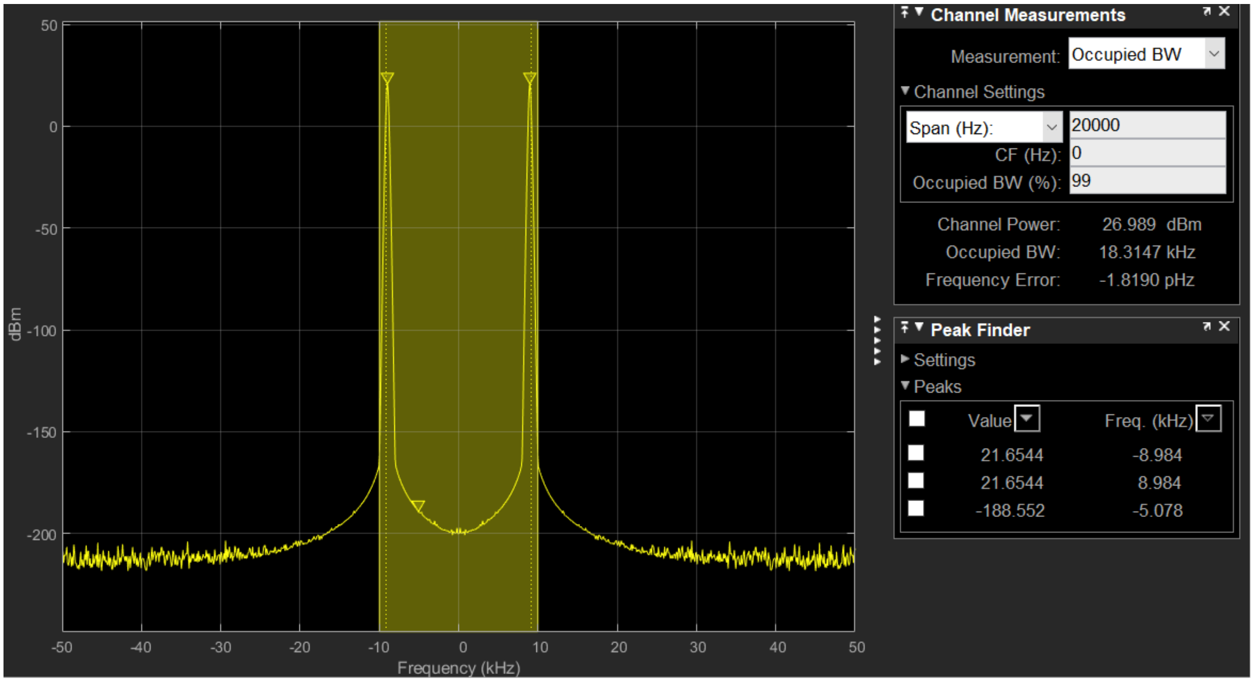
## Questions:

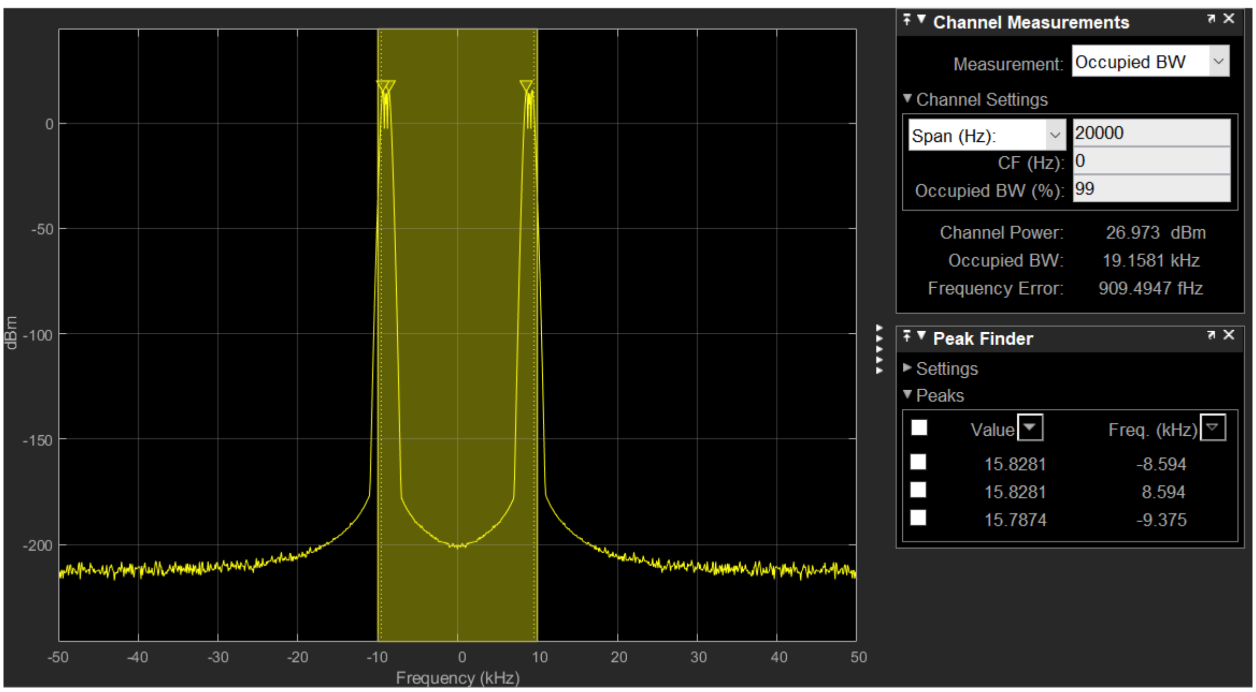
**Q1: Denote the modulating frequency as $fm$. Vary Gain (Sensitivity Factor) $\Delta f$ as $\Delta f =$ $0.1fm$, $0.5fm$, $fm$, ... , $10fm$. Observe the output on Spectrum (Mod) and comment on how the number of significant sideband pairs (i.e., peaks with power above -10 dBm) varies with $\Delta f$.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

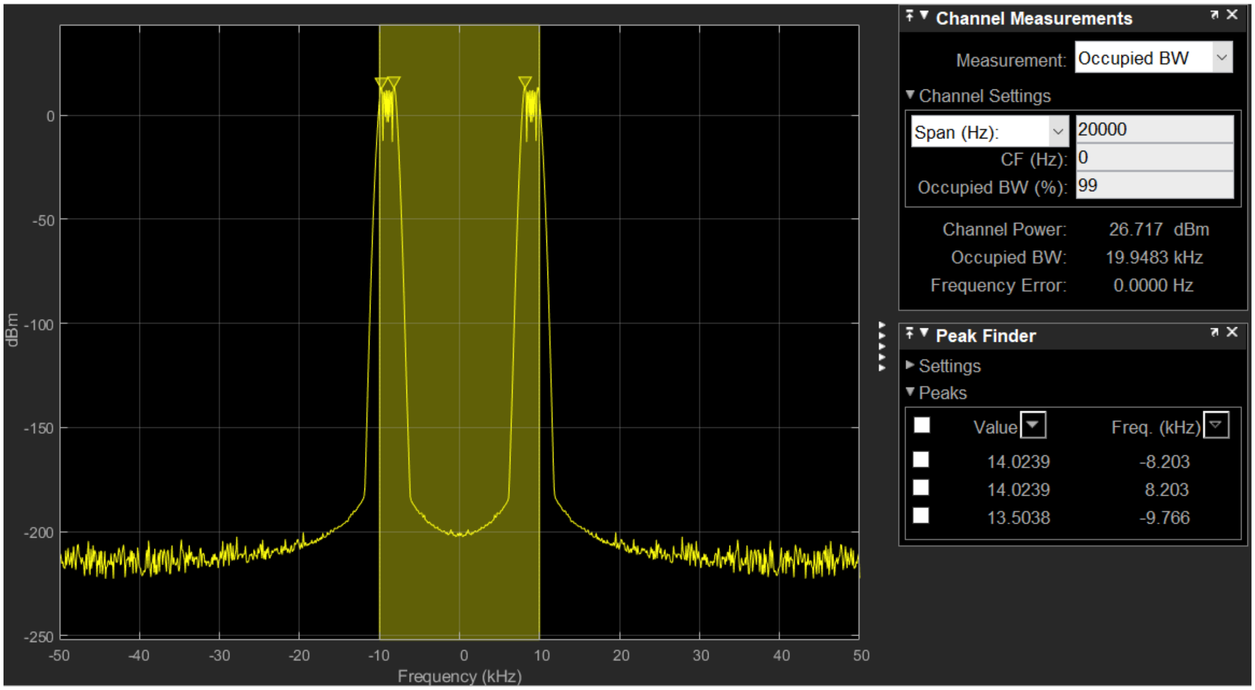
**Answer:** modulating frequency $= 1/0.01 = 100Hz$. We can clearly see that when the gain increases from 0.1fm to 10fm, the number of significant sideband pairs has increased. Number of sidebands depends on the extent of frequency deviation. Larger sensitivity factor result in a wider spread of sidebands.


Channel Measurements
Measurement: Occupied BW
Channel Settings
Span (Hz): 20000
CF (Hz): 0
Occupied BW (%): 99
Channel Power: 26.989 dBm
Occupied BW: 18.0649 kHz
Frequency Error: 0.0000 Hz
Peak Finder
Settings
Peaks
Value
Freq. (kHz)
23.9572 -8.984
23.9572 8.984
-186.237 -12.695
dBm
Frequency (kHz)


Channel Measurements
Measurement: Occupied BW
Channel Settings
Span (Hz): 20000
CF (Hz): 0
Occupied BW (%): 99
Channel Power: 26.989 dBm
Occupied BW: 18.2316 kHz
Frequency Error: 0.0000 Hz
Peak Finder
Settings
Peaks
Value
Freq. (kHz)
23.4274 -8.984
23.4274 8.984
-187.409 -5.176
dBm
Frequency (kHz)


Channel Measurements
Measurement: Occupied BW
Channel Settings
Span (Hz): 20000
CF (Hz): 0
Occupied BW (%): 99
Channel Power: 26.989 dBm
Occupied BW: 18.3147 kHz
Frequency Error: -1.8190 pHz
Peak Finder
Settings
Peaks
Value Freq. (kHz)
21.6544 -8.984
21.6544 8.984
-188.552 -5.078
dBm
Frequency (kHz)


Channel Measurements
Measurement: Occupied BW
Channel Settings
Span (Hz): 20000
CF (Hz): 0
Occupied BW (%): 99
Channel Power: 26.973 dBm
Occupied BW: 19.1581 kHz
Frequency Error: 909.4947 fHz
Peak Finder
Settings
Peaks
Value Freq. (kHz)
15.8281 -8.594
15.8281 8.594
15.7874 -9.375
dBm
Frequency (kHz)




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

**Answer:**

Based on Carson's role $B_{FM} = 2(1 + \beta)W$ and $\Delta f = Kf = Gain.\ \beta = \frac{\Delta f}{W}$.

| $\Delta f$ | Actual transmission bandwidth as shown in the spectrum. | Bandwidth predicted by Carson's role | percentage |
|---|---|---|---|
| **0.1*fm*=10Hz** | **18.0649Khz** | **2(1+0.1)*100=220Hz** | **1.217%** |
| **0.5*fm*=50Hz** | **18.2316Khz** | **2(1+0.5)*100=300Hz** | **1.645%** |
| ***fm*=100Hz** | **18.3147Khz** | **2(1+1)*100=400Hz** | **2.184%** |
| **5*fm*=500Hz** | **19.1581Khz** | **2(1+5)*100=1200Hz** | **6.263%** |
| **10*fm*=1000Hz** | **19.9483Khz** | **2(1+10)*100=2200Hz** | **11.028%** |