Lab assignment

Modulation lab

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EEE202

Digital and Analogue Communications

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Introduction

Modulation has become an essential part of modern communication systems. Signal Modulation can be defined as the process in which a sinusoidal signal, known as the carrier, is mixed with another electrical signal, formally known as the message or baseband signal, to produce a new signal. This experiment aims to investigate three different methods of signal modulation and thoroughly analyze the outcome of each respectively. Detailed introduction and explanation for each section is provided. It should be mentioned that the simulations in this experiment were created by Matlab Simulink.

Section 1: Amplitude modulation (AM)

The first section of this experiment analyzes the Amplitude Modulation (AM). By applying this method of modulation, the message, which is the electrical signal representing the input of the system, is used to modify the amplitude of a sinusoid, referred to as the carrier, which has a considerably higher frequency than the message's frequency.

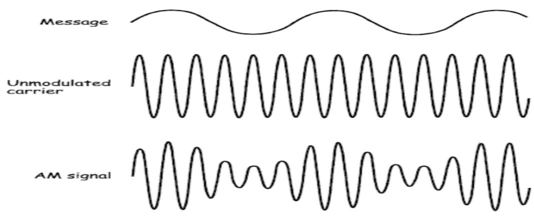

Figure 1: AM modulation

As displayed in the above figure (Figure 1), after Amplitude Modulation, the amplitude of the carrier signal has been amplified to values both above and below its amplitude in the unmodulated state. If the positive and negative peaks of the AM signal were to be tracked by dots, a dotted line, referred to as the signal's envelope, would be obtained (Figure 2). It can be observed that both the upper and lower envelope have the same shape as the primary signal (message), with the lower envelope displaying the inverted image of the signal.

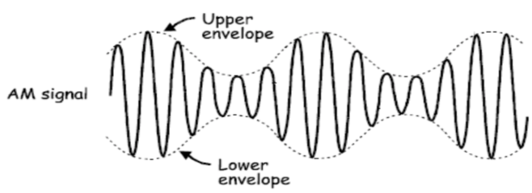

Figure 2: AM signal with envelopes

Furthermore, based on the telecommunications theory, the mathematical model for defining AM signals is as follows:

$$AM = (DC + \text{message}) \times \text{ the carrier} \tag{1}$$

Assuming that the sinusoidal carrier wave $c(t)$ and message wave $m(t)$ are defined respectively as follows

$$c(t) = A_c cos(2\pi f_c t)$$
$$m(t) = A_m cos(2\pi f_m t)$$

The modulated signal $s(t)$ would consequently be defined via the following equation

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

Where μ is known as the modulation index and can be found by the following equation

$$\mu = \frac{A_m}{A_C} \tag{2}$$

Hence, the resulting AM signal consists of three sinewaves:

1. At the carrier frequency (f_c)
2. At frequency equal to the sum of the carrier and message frequencies ($f_c + W$)
3. At frequency equal to the difference of the carrier and message frequencies ($f_c - W$)

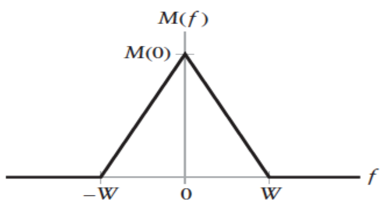

Figure 3: Message signal's spectrum

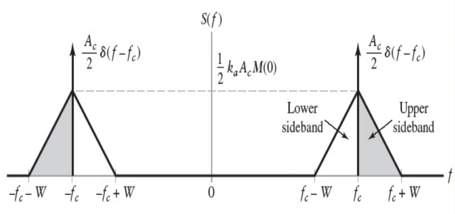

Figure 4: AM modulated wave spectrum

The latter two sine-waves are referred to as the side-bands. Hence, AM is also known as double-side-band, full carrier (DSBFC).

Section 2: DSBSC modulation

This section of the experiment aims to investigate DSBSC modulation, which is fairly similar to the previously examined AM modulation. To elaborate on the similarity of these two modulations, it can be stated that in DSBSC compared to AM, a message signal is used to vary the amplitude of a sine-wave, known as the carrier, which would produce a frequency considerably higher than message's frequency. The following figure displays the effect of DSBSC modulation on the sinusoidal carrier signal and the subsequent DSBSC signal (Figure 5).

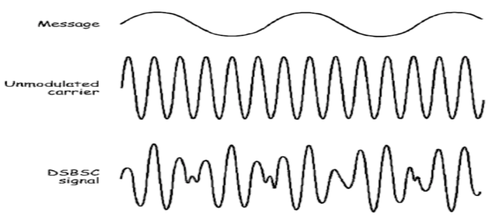

Figure 5: DSBSC Modulation

As illustrated in the above figure, the obtained output is significantly different than the output corresponding to AM modulation (Figure 1). Accordingly, if the signal's envelopes were to be drawn, the following figure (Figure 6) would be obtained. By slight comparison between the envelopes in the current and previous section, it can be noticed that in DSBSC modulation, the upper and lower envelopes do not have the same shape as the message, which differs from the outcome of AM modulation .

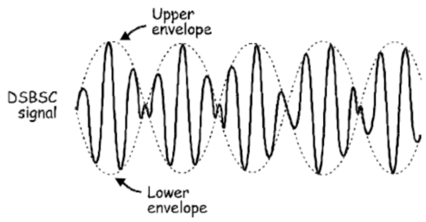

Figure 6: DSBSC Modulation with upper and lower envelopes

However, as displayed in the figure below (Figure 7), if the alternating halves of the envelopes were to be examined, it would be concluded that they form the same shape as the message.

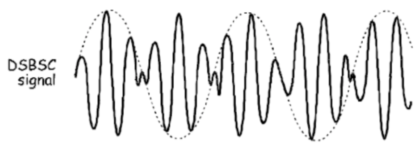

Figure 7: DSBSC Modulation

The mathematical model for defining DSBSC signals is as follows:

$$AM = \text{message} \times \text{ the carrier} \tag{3}$$

Assuming that the sinusoidal carrier wave $c(t)$ and message wave $m(t)$ are defined respectively as follows

$$c(t) = A_c cos(2\pi f_c t)$$
$$m(t) = A_m cos(2\pi f_m t)$$

The modulated signal $s(t)$ would consequently be defined via the following equation

$$s(t) = A_c m(t) cos(2\pi f_c t)$$

By applying fourier transform on s(t), we would get

$$S(f) = \frac{A_c}{2}[M(f - f_c) + M(f + f_c)]$$

Hence, as suggested by the equation above, the DSBSC signal would consists of two sine-waves, rather than three:

1. At frequency equal to the sum of the carrier and message frequencies $(f_c + W)$
2. At frequency equal to the difference of the carrier and message frequencies $(f_c - W)$

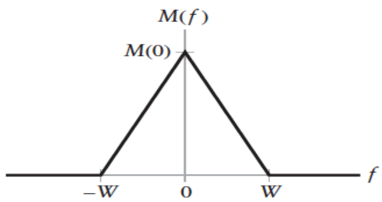

Figure 8: Message signal's spectrum

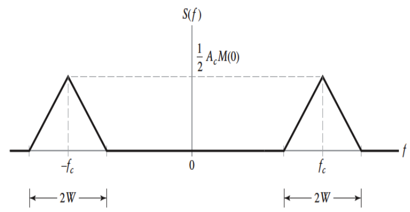

Figure 9: DSBSC modulated wave spectrum

Therefore, the DSBSC signal does not include a sine-wave at the carrier frequency (f_c). Consequently, DSBSC, which is the abbreviation for doube-sideband suppressed carrier, is chosen due to the presence of the mentioned two side-bands ($f_c + W$ and $f_c - W$), without impluses at f_c and $-f_c$ (check Figure 9). The absence of the carrier wave in DSBSC would result in less power consumption compared to AM, which is fairly beneficial.

Section 3: Frequency modulation (FM)

The last section of this experiment analyzes the Frequency Modulation (FM). In FM, the message's amplitude is use to modify the frequency of the carrier signal, rather than its amplitude. Since electrical noise is known to change the amplitude of the transmitting signal, employing FM would mean less vulnerability to electrical noise.

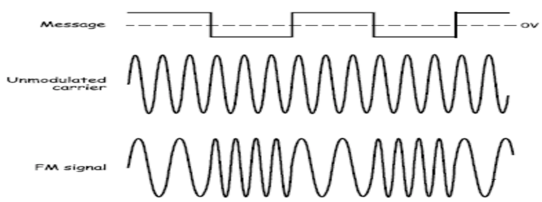

Figure 10: FM Modulation

The above figure (Figure 10) displays an instance of FM modulation. As illustrated in this figure, the upper and lower envelopes are flat due to no change in the amplitude of the carrier signal when using FM modulation. Moreover, it can be also be noticed that the obtained FM signal has a higher frequency (smaller wavelength) at points where the message's amplitude is greater and contains lower frequencies (larger wavelength) where the amplitude of the message is smaller.
For FM, assuming that the sinusoidal carrier wave $c(t)$ and message wave $m(t)$ are defined respectively as follows

$$c(t) = A_c cos(2\pi f_c t) \text{ and } m(t) = A_m cos(2\pi f_m t)$$

The modulated signal $s(t)$ would consequently be

$$s(t) = A_c cos(2\pi f_c t + \beta sin(\omega_m t))$$

Where β is the modulation index and is calculated as follows:

$$\beta = \frac{\Delta f \text{ (frequency deviation)}}{f_m \text{ (message's frequency)}} \tag{4}$$

Assuming $\beta << 1$ (narrowband fm), then

$$s(t) = A_c cos(w_c) - \beta A_c sin(w_c) sin(w_m t) \tag{5}$$

Assuming $\beta >> 1$ (broadband fm), then

$$s(t) = A_c \sum_{-\infty}^{\infty} J_n(\beta) cos(w_c t + w_m t) \tag{6}$$

Applying Fourier transform would give

$$S(f) = \frac{A_c}{2} \sum_{-\infty}^{\infty} J_n(\beta)[\delta(f - f_c - nf_m) + \delta(f + f_c + nf_m)] \tag{7}$$

Experiment Procedure and Results

Section 1: Amplitude modulation (AM)

Procedure

As the initial step of conducting this section of the experiment, the following block diagram (Figure 11) is constructed in the Matlab Simulink.

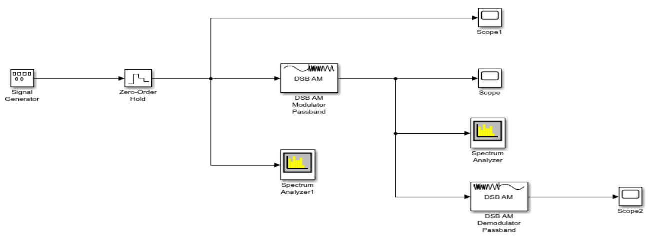

Figure 11: AM Modulation block diagram

The parameters to be set in the given block diagram are as follows:

1 **The carrier** A carrier frequency of $100kHz$ with amplitude of 1 is applied to the DSB AM Modulator and Demodulator Passband blocks. The cut-off frequency in these blocks should be set to $f_c + f_m = 110kHz$.

2 **The message** In this section of the experiment, two message signals are to be produced and examined. The frequency is set to $10kHz$ in both cases. As for the amplitude of each message signal, it is required that the modulation index in each case be 0.5 and 1 respectively. Based on equation 2, since the amplitude of the carrier wave (A_C) was set to be 1, the modulation index would be equal to the amplitude of the message wave. Accordingly, the amplitude in the Signal Generator block would be set to 0.5 and 1 respectively.

3 **Sampling rate** The sampling time is set in the Zero-Order Hold block's settings. According to the Nyquist Theorem, the sampling rate (f_s) must be at least twice the highest frequency ($2f_{max}$).

$$f_s \geq 2 \times (f_c + f_m) = 220kHz$$

As a binary value was preferred for better results, $f_s = 1024kHz$ was assumed for this experiment. Subsequently, the sampling time would be obtained by the following equation:

$$T_s = \frac{1}{f_s} = \frac{1}{1024000} s \tag{8}$$

4 **Simulation time** Each cycle of the modulating signal requires $\frac{1}{f_m}$ seconds of simulation time to be simulated. Hence, for 10 cycles to be seen, the corresponding simulation would be as follows

$$\text{Simulation time} = \frac{1}{10kHz} \times 10 = \frac{10}{10000} = 0.001s$$

5 **FFT size for the spectrum scope** As there exists 10 cycles of the modulating signal, the expected frequency resolution (f_r) would be as calculated as follows:

$$f_r = \frac{f_m}{\#\text{ of cycles}} = \frac{10kHz}{10} = 1kHz \tag{9}$$

Consequently, the FFT size for the spectrum scope (M), referred to as the window length in Simulink, should meet the following criterion:

$$M \geq \frac{f_s}{f_r} = \frac{1024kHz}{1kHz} = 1024 \tag{10}$$

Hence, the minimum FFT size would be 1024.

Results

The obtained results are as follows (Figures 12-21):

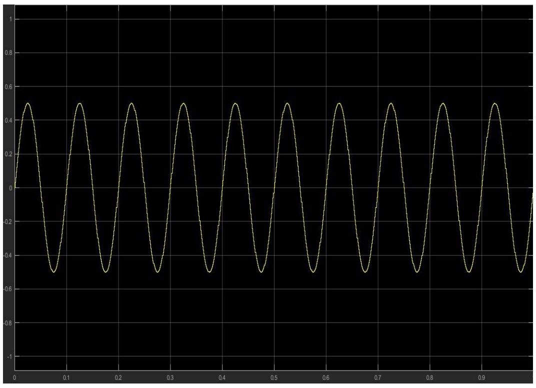

Figure 12: Modulating Signal on Scope1 ($\mu = 0.5$)

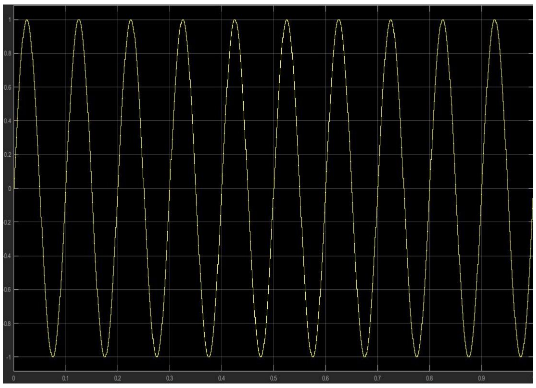

Figure 13: Modulating Signal on Scope1 ($\mu = 1$)

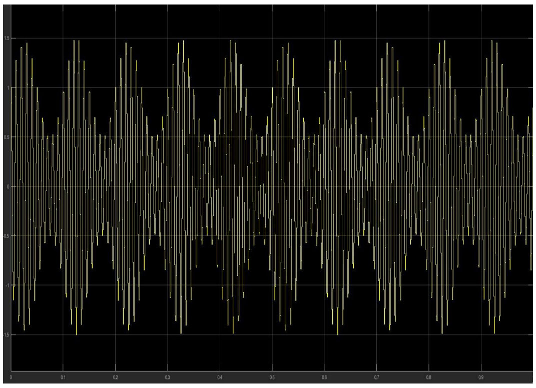

Figure 14: Modulated Signal on Scope ($\mu = 0.5$)

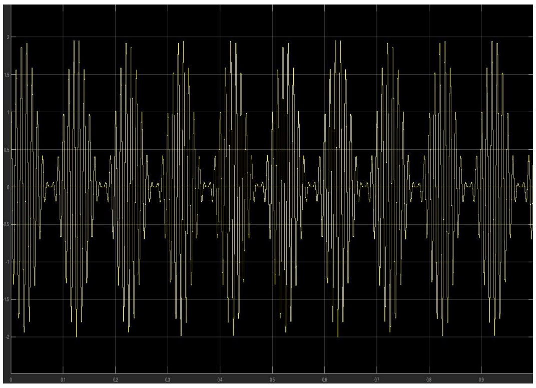

Figure 15: Modulated Signal on Scope ($\mu = 1$)

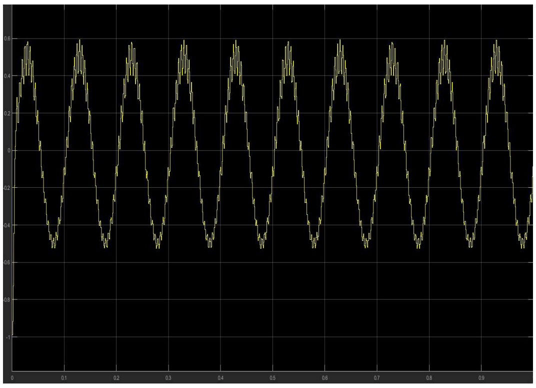

Figure 16: Demodulated Signal on Scope2($\mu = 0.5$)

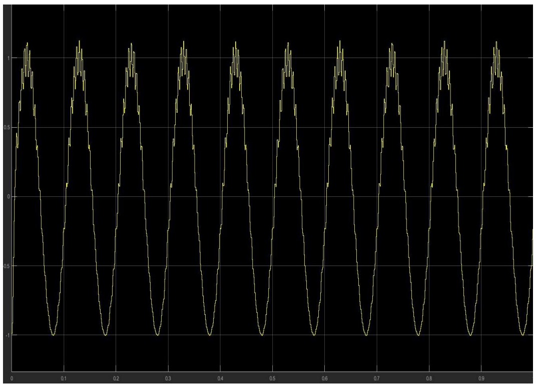

Figure 17: Demodulated Signal on Scope2 ($\mu = 1$)

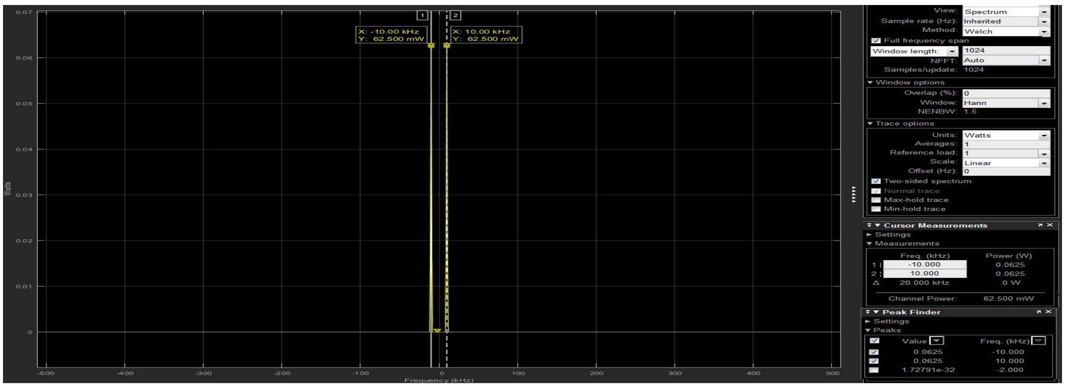

Figure 18: Modulating signal's spectrum($\mu = 0.5$)

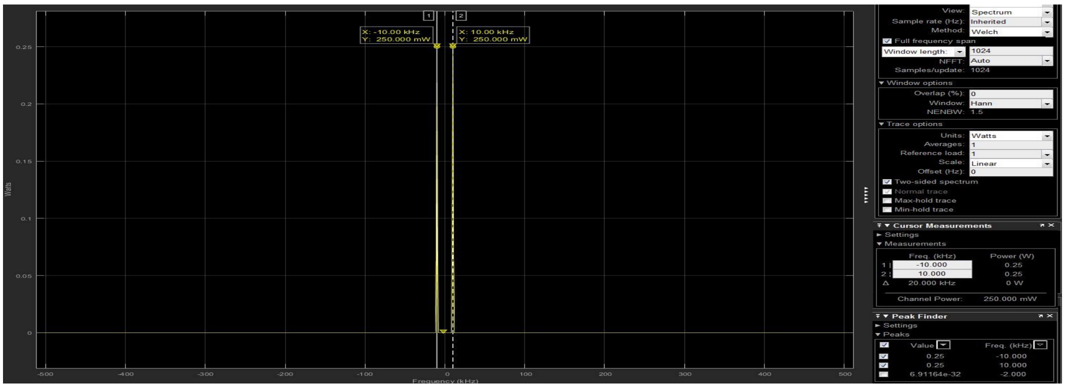

Figure 19: Modulating signal's spectrum ($\mu = 1$)

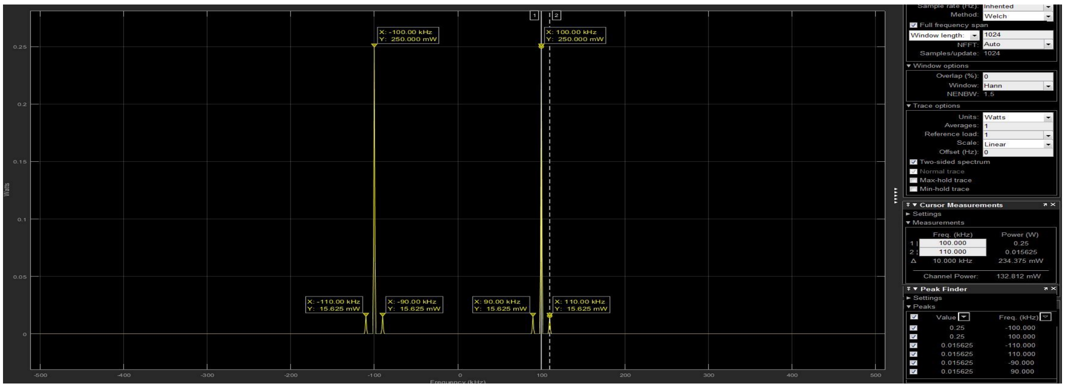

Figure 20: Modulated signal's spectrum($\mu = 0.5$)

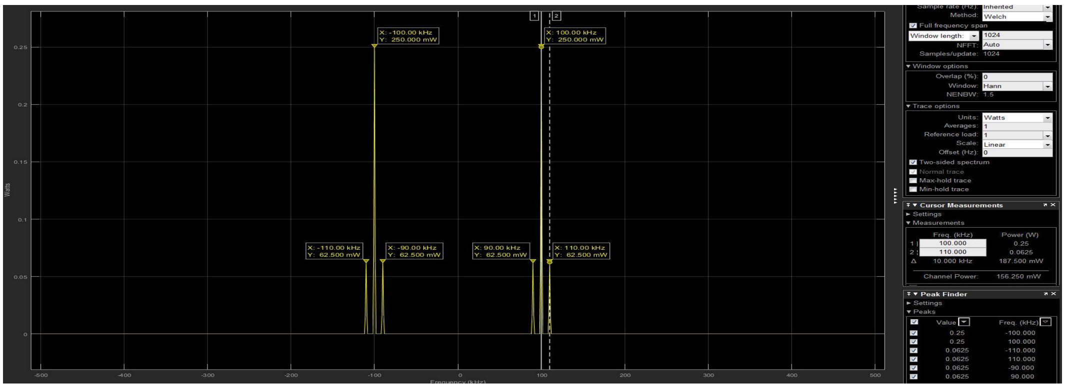

Figure 21: Modulated signal's spectrum ($\mu = 1$)

Scopes 1 and 2 display the modulating signal and the demodulated signal respectively. By comparing the two it can be noticed that the demodulated signal resembles the modulating signal wave. This suggests that although the demodulated does not represent a perfect reconstruction of the modulating signal, as distortations in the waveform can be noticed, the modulation is still successful.

The carrier power (P_c) and the power of each sideband (P_s) can be obtained from the following equations respectively:

$$P_c = \frac{A_c^2}{2} \text{ and } P_s = \frac{A_m^2}{4} \tag{11}$$

Therefore, when modulation index = 0.5, we have that

$$P_c = \tfrac{1}{2} \text{ and } P_s = \tfrac{0.5^2}{4} = \tfrac{1}{16}, \text{ giving } P_c = 8 \times P_s$$

And for modulation index = 1 (Maximum modulation)

$$P_c = \tfrac{1}{2} \text{ and } P_s = \tfrac{1}{4}, \text{ giving } P_C = 2 \times P_s$$

The above results are clearly illustrated in Figures 20 and 21, where the following values are mentioned:

When $\mu = 0.5$, then $P_c = 250mW$ and $P_s = 15.625 \times 2 = 31.25mW$, which supports $P_c = 8 \times P_s$.

And When $\mu = 1$, then $P_c = 250mV$ and $P_s = 62.5 \times 2 = 125mW$, which supports $P_c = 2 \times P_s$.

It should be noted that each sideband frequency consists of a lower and an upper sideband. The multiplication by 2 is due to this reason.

Section 2: DSBSC modulation

Procedure

First, similar to the previous section, the block diagram of the modulation method which in this section is DSBSC is assembled (Figure 22).

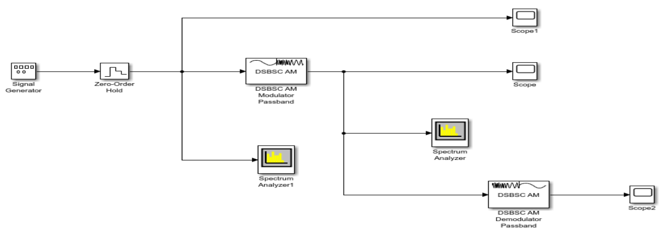

Figure 22: DSBSC Modulation block diagram

The same parameters as the first section are used to prepare the block diagram for simulation (check procedure part of Section 1). The concluding values from Section A are provided respectively in the table below.

A_c	A_m	μ	f_c	f_m	f_s	f_r	T_s
1	1	1	$100kHz$	$10kHz$	$1024kHz$	$1kHz$	$\frac{1}{1024000}$s

Simulation time	min FFT size	Cut-off frequency
0.001s	1024	$110kHz$

Results

The obtained results are as follows (Figures 23-27):

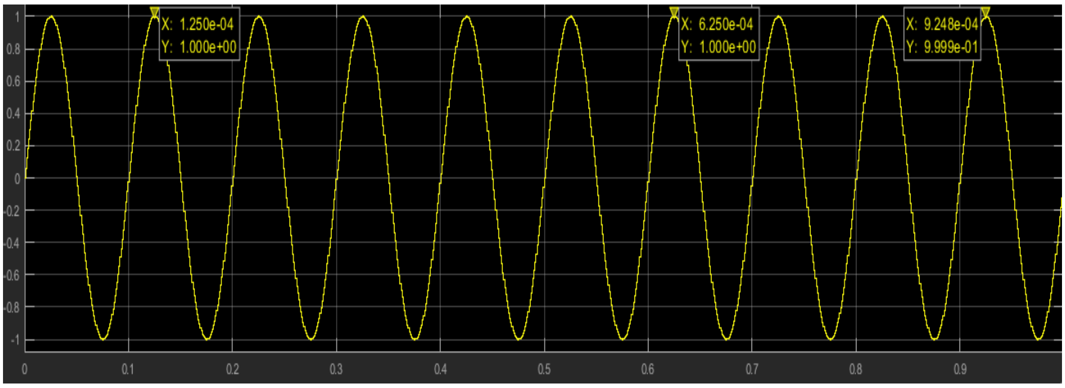

Figure 23: Modulating Signal on Scope1

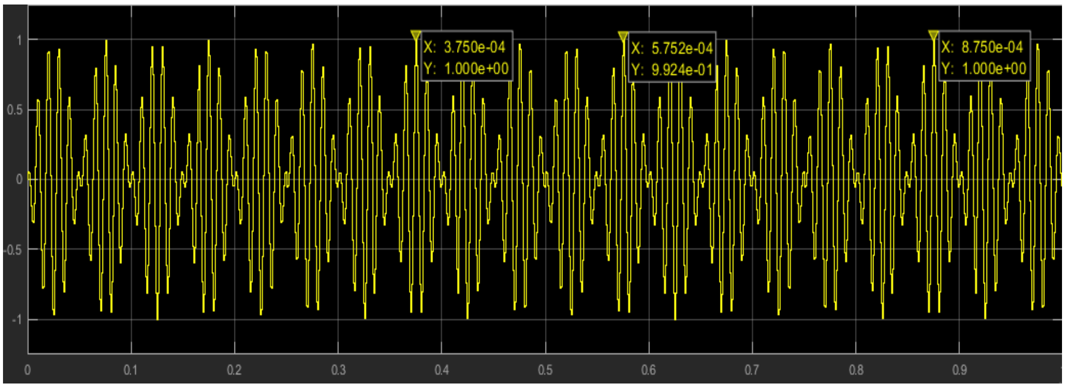

Figure 24: Modulating Signal on Scope1

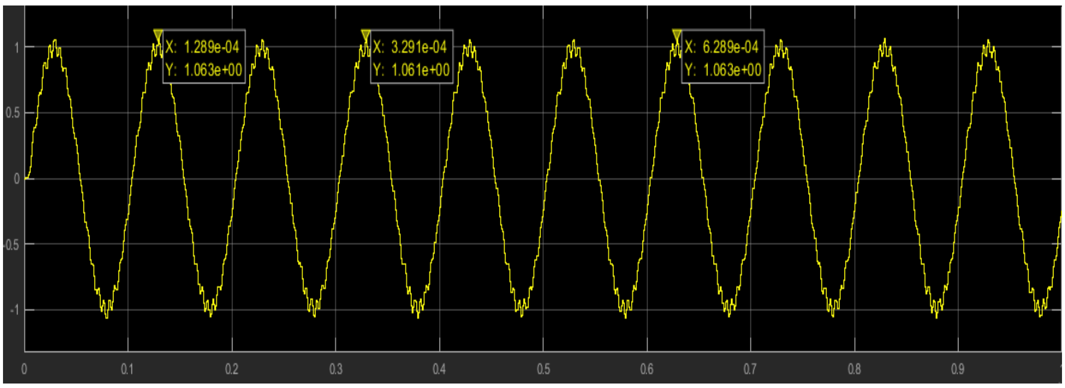

Figure 25: Demodulated Signal on Scope2

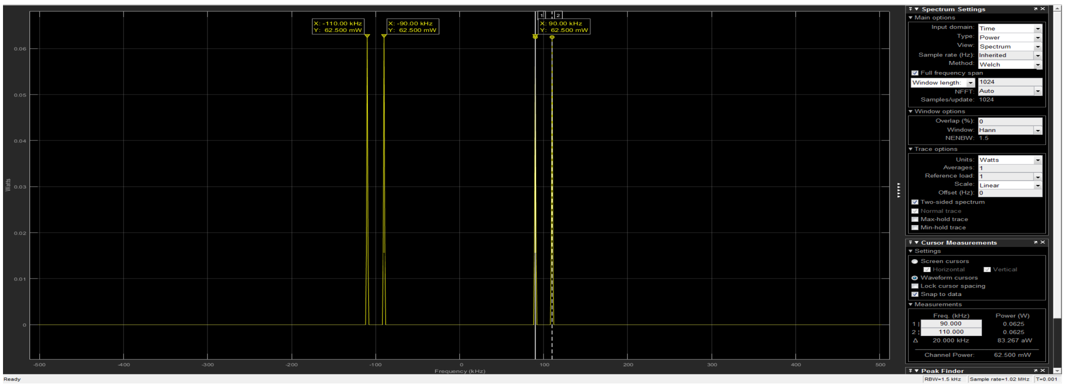

Figure 26: Modulating Signal's spectrum

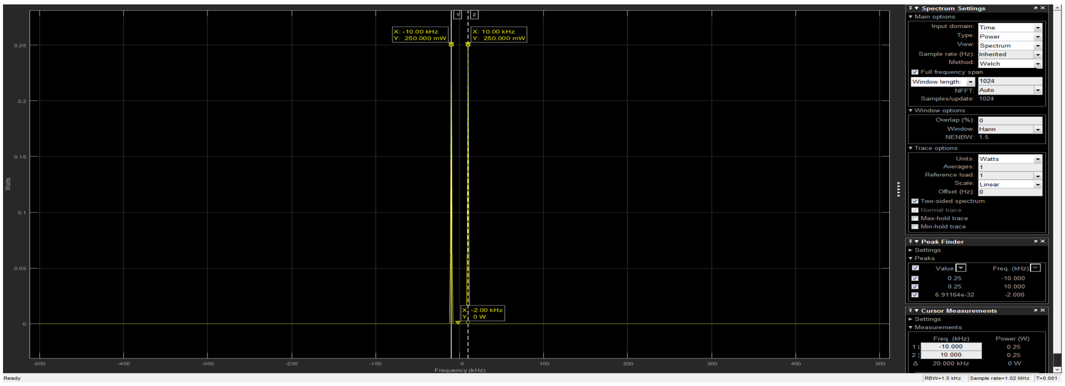

Figure 27: Modulated Signal's spectrum

By comparing Scopes 1 and 2, it can be noticed that similar to the previous section, the demodulated signal (displayed in Scope 2) resembles the modulating signal wave (Displayed in Scope 1) likewise. In comparison with AM modulation, distortions can also be seen in the demodulated sign. However, it can also be noticed that the distortions in the demodulated signal have decreased significantly.
Comparison between Scopes in AM and DSBSC signal highlights lower frequency per cycle of the modulated signal, which is the same frequency as the modulating signal per cycle in DSBSC. This is a logical outcome as the modulated signal in DSBSC does not contain the carrier frequency.
In addition, DSBSC has a much higher power efficiency compared to AM.

$$\text{Power Efficiency} = \frac{\text{Power of Sidebands}}{\text{Total Power}} \tag{12}$$

Where total power is the sum of the power of sidebands and the carrier.
By assuming modulation index of 1 (100% modulation) for both AM and DSBSC, we would get

$$\text{Power Efficiency in AM}= \frac{\frac{1}{4}}{\frac{1}{4}+\frac{1}{2}} = \frac{1}{3} \approx 33\%$$

$$\text{Power Efficiency in DSBSC}= \frac{\frac{1}{8}}{\frac{1}{8}+0} = 1 = 100\%$$

The high power efficiency in DSBSC modulation makes it the more dominant method of modulation in the field of transmission compared to AM.

Section 3: Frequency modulation (FM)

Procedure

Similar to the previous sections, the first step of analyzing the modulation method is to build the corresponding block diagram (Figure 28)

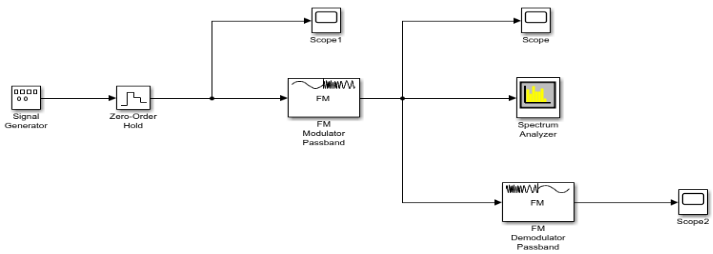

Figure 28: FM Modulation block diagram

The parameters for the given block diagram are set respectively as below:

1. **The carrier** A carrier wave with frequency of $100kHz$ and amplitude of 1 is supplied to both the FM Modulator and Demodulator Passband blocks. In addition, based on the equation 4, the frequency deviation (Δf) would be equal to the multiplication product of the modulation index (β) and the modulating signal frequency (f_m). Hence, as the modulation indexes of 0.5 and 10 are to be analyzed respectively, the frequency deviation in the two mentioned blocks would be set to $0.5 \times 1kHz = 500Hz$ and $10 \times 1kHz = 10kHz$ for narrowband and broadband FM respectively.

2. **The message** A sinusoidal wave and a squarewave, with amplitude of 1 and frequency of $1kHz$ are supplied to the Signal Generator block respectively.

3. **Sampling rate** The sampling rate (f_s) is determined by the following:

   if $\beta << 1$, then $f_s \geq 2(f_c + f_m) = 202kHz$

   if $\beta >> 1$, then $f_s \geq 2(f_c + \Delta f) = 2(f_c + \beta f_m) = 220kHz$

Consequently, a sampling rate of 409600Hz was assumed. Therefore, the sampling time T_s would be $\frac{1}{f_s} = \frac{1}{409600}s$.

4. **Simulation time** As mentioned in Section A, the time required to simulate 10 cycles of the modulating signal is $\frac{10}{f_m}$. Therefore the simulation time for this section would be set to $\frac{10}{1kHz} = 0.01$ seconds.

5. **FFT size for spectrum scope** By equation 9, the expected frequency resolution f_r would be $\frac{1kHz}{10} = 0.1kHz$ for displaying 10 cycles of the modulating signal. Therefore, as discussed in Equation 10, the FFT size for the spectrum scope has to meet the following condition:

$$M \geq \frac{f_s}{f_r} = \frac{409600}{100Hz} = 4096 \tag{13}$$

   Conclusively, the minimum FFT size would be 4096.

Results

The results for the sinewave modulating signal are as follows (Figures 29-36):

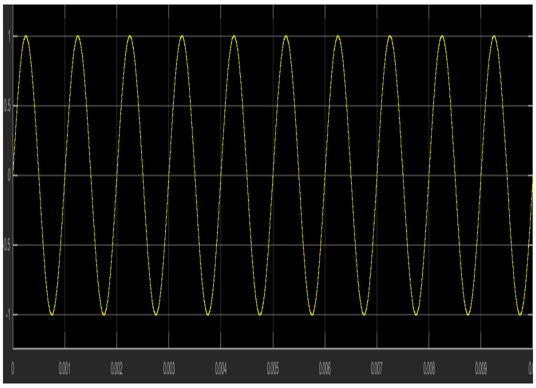

Figure 29: Modulating Signal on Scope1 ($\mu = 0.5$)

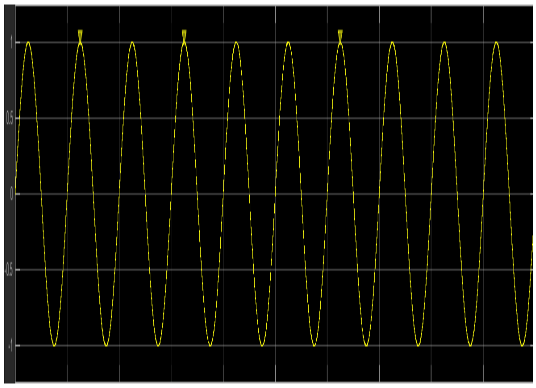

Figure 30: Modulating Signal on Scope1 ($\mu = 10$)

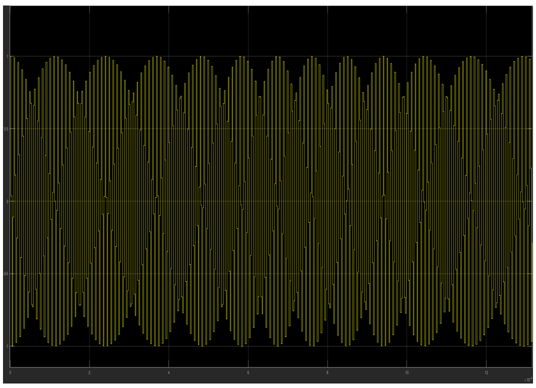

Figure 31: Modulated Signal on Scope ($\mu = 0.5$)

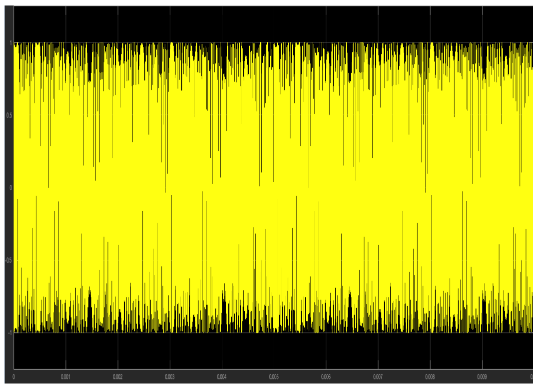

Figure 32: Modulated Signal on Scope ($\mu = 10$)

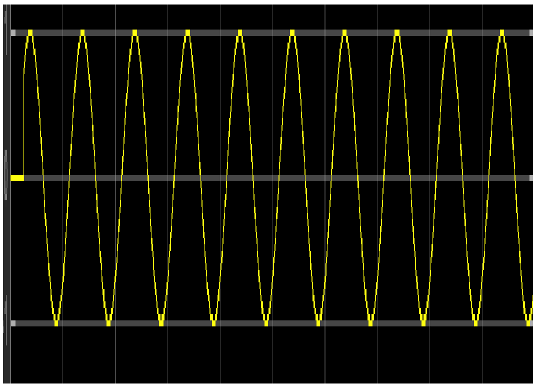

Figure 33: Demodulated Signal on Scope ($\mu = 0.5$)

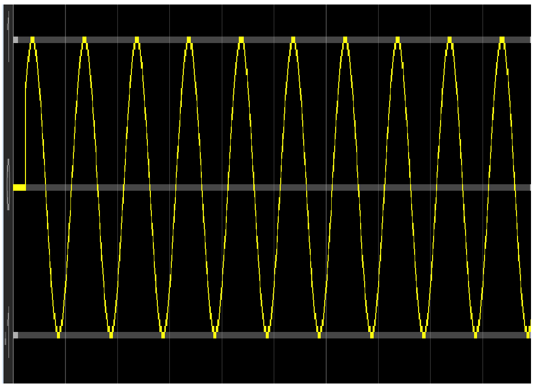

Figure 34: Demodulated Signal on Scope ($\mu = 10$)

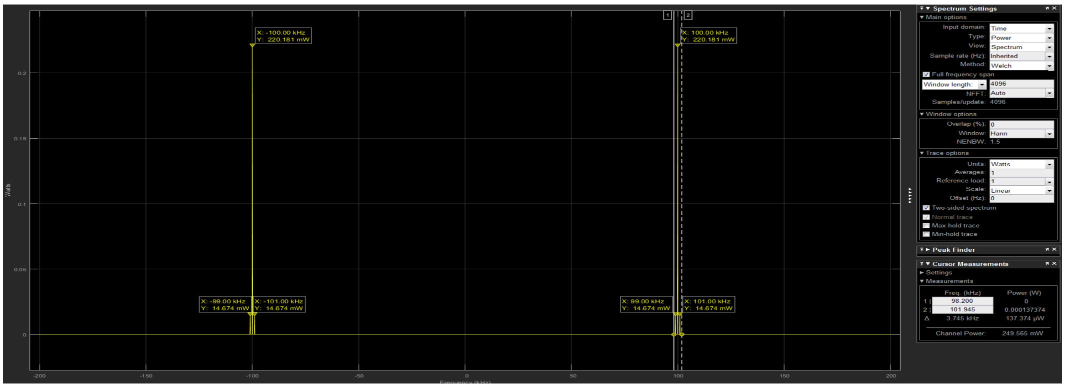

Figure 35: Modulated signal's spectrum ($\mu = 0.5$)

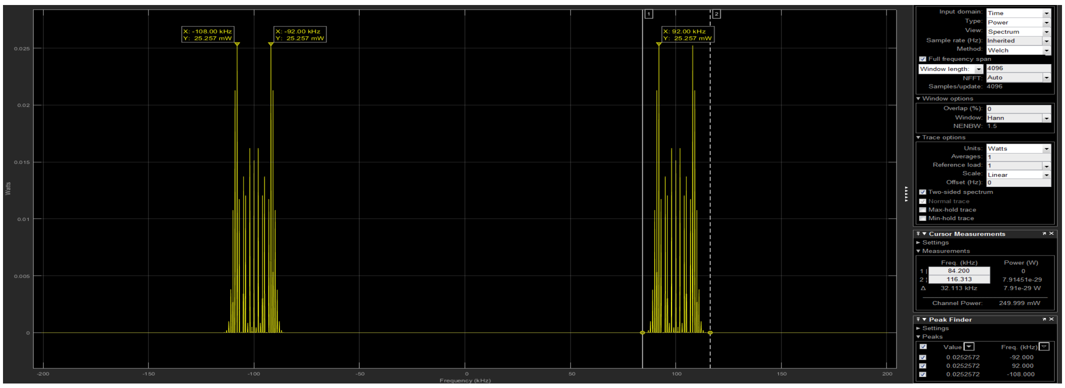

Figure 36: Modulated signal's spectrum ($\mu = 10$)

The results for the squarewave message wave are as follows (Figures 37-44):

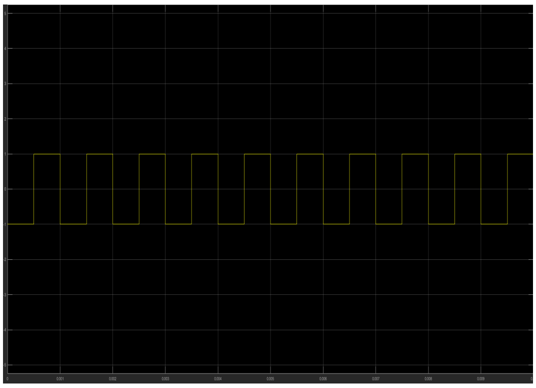

Figure 37: Modulating Signal on Scope1 ($\mu = 0.5$)

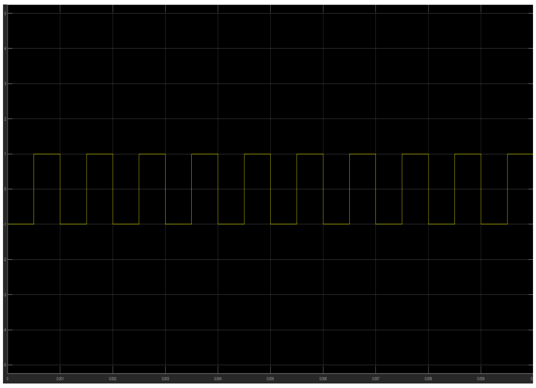

Figure 38: Modulating Signal on Scope1 ($\mu = 10$)

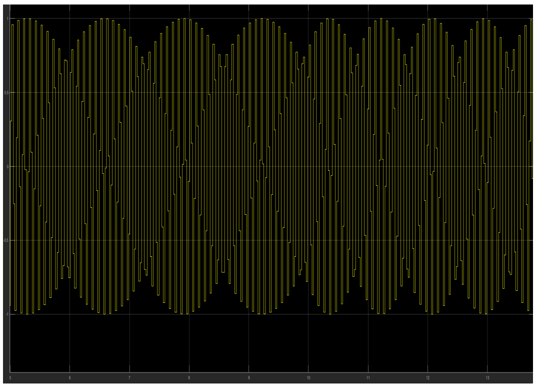

Figure 39: Modulated Signal on Scope ($\mu = 0.5$)

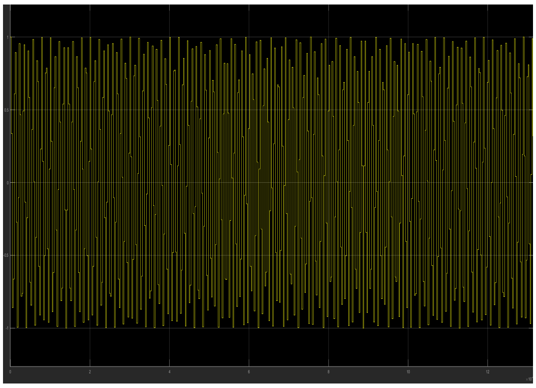

Figure 40: Modulated Signal on Scope ($\mu = 10$)

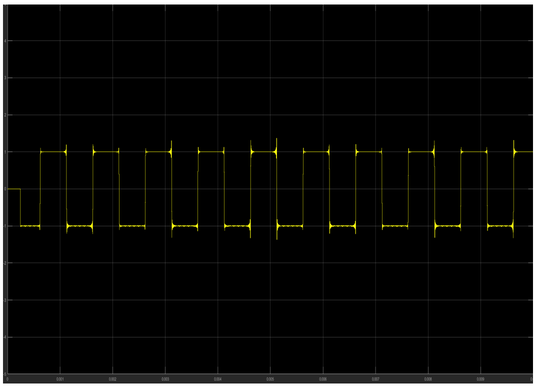

Figure 41: Demodulated Signal on Scope ($\mu = 0.5$)

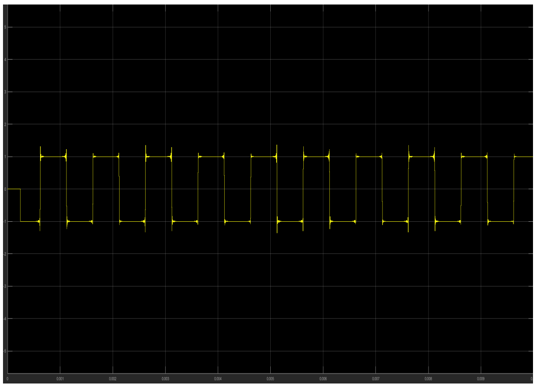

Figure 42: Demodulated Signal on Scope ($\mu = 10$)

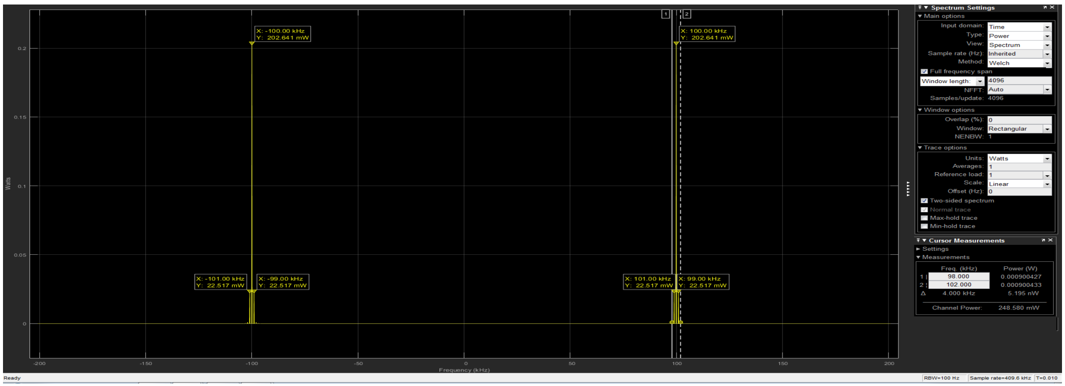

Figure 43: Modulated signal's spectrum ($\mu = 0.5$)

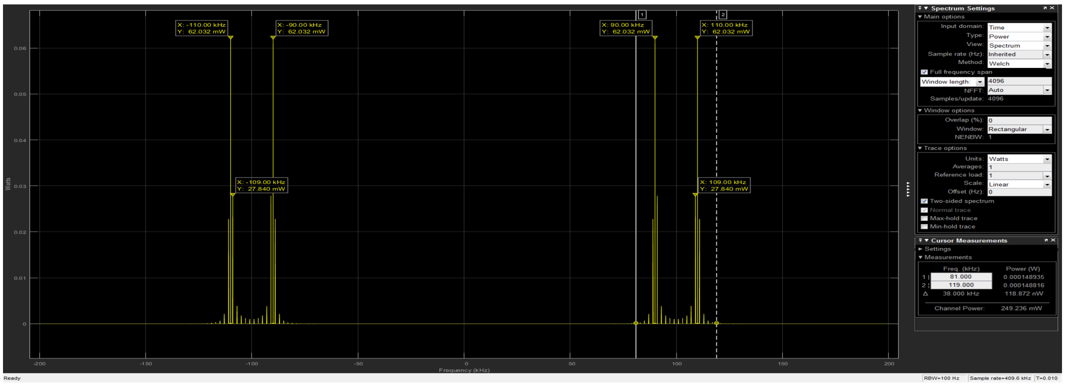

Figure 44: Modulated signal's spectrum ($\mu = 10$)

Comparison of Scopes 1 and 2 shows that the demodulated signal has significant resemblance to the modulating signal. This resemblance is slightly higher than the ones in the previous two sections as there is less distortion in the demodulated signal. Slight delay in the demodulated signal can also be noticed.

In this experiment, two sinusoidal signals and two squarewave signals with modulation indexes of 0.5 and 10 are respectively produced and analyzed. The modulation of these signals would illustrate narrowband FM (when $\beta = 0.5$)and broadband FM (when $\beta = 10$). By investigating the figures (Figures 35, 36, 43, and 44), it can be noticed that the number of lower/upper sideband pairs along with the carrier are considerably less in narrowband FM. This is due to its small modulation index(β), as smaller β results in lower frequency deviation (Equation 4). Subsequently, presence of more lower/upper sideband pairs would result in higher power regarding sidebands, which according to equation 9 would lead to higher power efficiency. Hence, broadband FM is significantly more power efficient compared to narrowband FM.

Another comparison to be made between narrowband and broadband FM is regarding the bandwidth. As the name suggests, narrowband FM has a much smaller bandwidth compared broadband FM.

When $\beta << 1$, then bandwidth $B = 2f_m = 2kHz$

When $\beta >> 1$, then bandwidth $B = 2\delta f = 2\beta f_m = 20kHz$

The last comparison to be made between narrowband and broadband FM would be based on B_T, where $B_T = 2n_{max}f_m$, where n_{max} is the largest value that satisfies $|J_n(\beta)| > 0.01$.

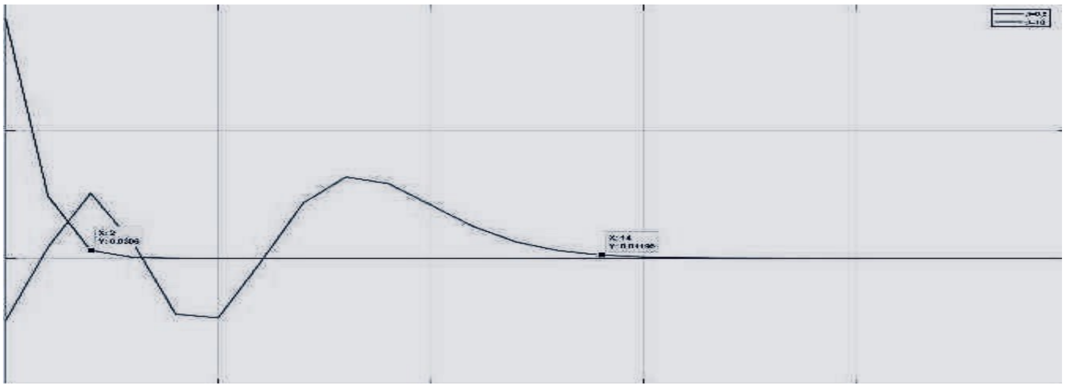

Figure 45: $J_n(\beta)$ graph

According the above figure (Figure 45), we have that

$n_{max} = 2$ in narrowband FM, giving $B_T = 4kHz$

$n_{max} = 14$ in broadband FM, giving $B_T = 28kHz$

Conclusion

In this experiment, three main methods of signal modulation were discussed and analyzed. Amplitude Modulation (AM) was found out to be a breakthrough for signal transmission as it allowed propagation over long distances and simple to set up. However, DSBSC modulation soon replaced AM as it allows for less power consumption and efficiency. The mentioned two methods amplify the carrier wave and thus make it vulnerable to noise. Frequency Modulation (FM) was invented as a method to modify the carrier wave's frequency rather than its amplitude. Due to this configuration, FM has significantly less amount of noise in its demodulated signal. Moreover, two types of frequency modulation were analyzed; narrowband and broadband. It was discovered that narrowband has lower bandwidth with less power efficiency that allows less noise and better sensitivity and thus, is not suitable for transferring large data. It conclusion, it is believed that this experiment allowed for better learning and stimulated students' interest in this subject.