BIRZEIT UNIVERSITY

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Electrical and Computer Engineering Department

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COMMUNICATION LABORATORY

Frequency Modulation

Report No.1

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Abstract

This experiment aims to transform the theoretical knowledge of Frequency Modulation (FM) into a practical application. It covers the most vital communication basics, including, how to perform the FM modulation methods in both time and frequency (spectrum) domains of sinusoidal and square message signals. In addition, to understand the characteristic of the FM modulator sensitivity, and learn how to determine the zero carrier crossings. Finally, it represents the demodulation techniques of the FM signal by examining the characteristics of the two receiver loop filters when the gain of the loop filter is varied between the two loop filters, and the effect and the usage of pre-emphasis.

Table of Contents

Table of Figures

List of Tables

Theory

1. Angle Modulation

Firstly, angle modulation is a type of continuous-wave modulation in that the carrier signal c(t) varies according to the input message signal. This kind of modulation is divided into two types according to the effect at the frequency or the phase of the carrier signal. The following equation shows the standard formula of the angle modulation:

$$\boldsymbol{s(t) = Ac\cos(\theta_i(t))}$$

Where, **Ac** is the amplitude of the modulated signal which is the same as the carrier amplitude (in this modulation, the amplitude of the carrier is not effected by the input message signal). Also, the $\boldsymbol{\theta_i(t)}$ is the angle of the modulated signal.

As mentioned, there are two types of angle modulation as follows:

- ***Phase Modulation:*** the process of varying the phase of the carrier with respect to the message signal.
- ***Frequency Modulation:*** the process of varying the frequency of the carrier with respect to the message signal.

2. Frequency Modulation (FM)

Frequency modulation (FM) is a type of angle modulation in which the frequency of a sinusoidal carrier wave deviates from a center frequency by an amount proportional to the instantaneous value of the original message signal. In FM, the center frequency is the carrier frequency. If the modulating signal $\boldsymbol{m(t) = A_m\cos(2\pi f_m t)}$ and the carrier signal $\boldsymbol{c(t) = A_c\cos(2\pi f_c t)}$ **then**

$$\boldsymbol{s(t) = A_c cos[2\pi f_c + \beta sin(2\pi f_m t)]}$$

Where $\boldsymbol{\beta}$ **is the modulation index** such that**:** $= \frac{\Delta f}{f_m} = \frac{kf\,Am}{fm}$ **.** The difference between FM modulated frequency (instantaneous frequency) and normal carrier frequency is termed as Frequency Deviation, and it is denoted by $\boldsymbol{\Delta f}$**, which is equal to** $\boldsymbol{\Delta f = kf * Am}$**.**

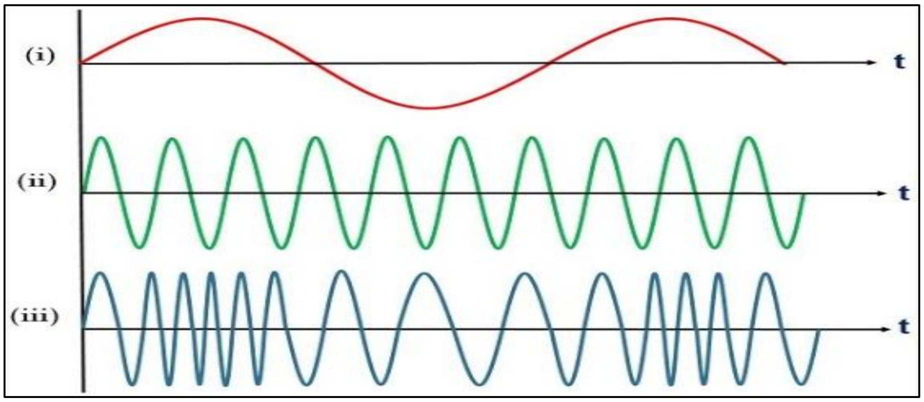

Figure 1 Message signal, carrier signal, and FM modulated signal in time domain.

Now, we can divide the Frequency Modulation (FM) into two types depending on the value of the **modulation index $\boldsymbol{\beta}$** as the following:

2.1 Narrowband FM (NBFM)

It occurs when the modulation index of the FM modulation is too small compared with the wideband, usually the **modulation index $\boldsymbol{\beta \ll 1}$** , so it will has a small bandwidth compared to the wide one, and the spectrum will consist of the carrier, upper and lower sideband only.

$$\boldsymbol{s(t)_{NBFM} = A_c \cos(2\pi f_c t) - Acsin(2\pi f_c) 2\pi k_f \int m(t)dt}$$

2.2 Wideband FM (WBFM)

In this kind, the modulation index $\boldsymbol{\beta}$ is very large compared to the narrow, **modulation index $\boldsymbol{\beta \gg 1}$.** In addition, the spectrum will consist of a carrier and an infinite number of sidebands that are located around.

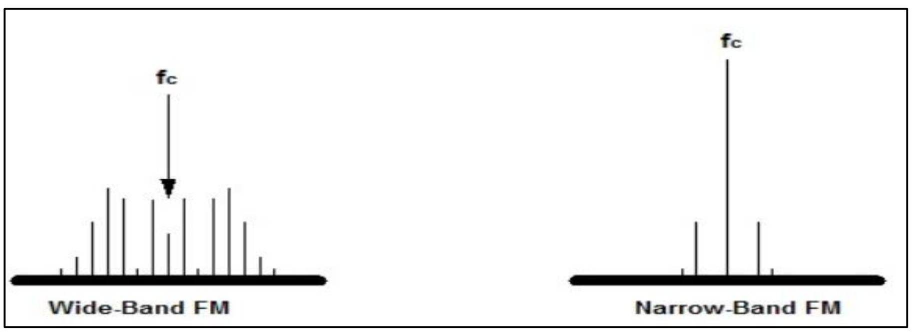

Figure 2 Comparison between NBFM and WBFM spectrum.

3. Frequency Demodulation

Frequency demodulation is the operation that performs the inverse of the frequency modulation in order to retrieve the original message signal. After the signal has been received, filtered, and amplified, we can detect the message from the carrier. There are two techniques used to demodulate the FM signal, which are using **High Pass Filter**, and **Phase Lock Loop (PLL)**.

3.1 Demodulation using High Pass Filter

The first method to demodulate the FM signal is using high pass filter. The filter converts the frequency modulation to amplitude modulation, which allows to use of the envelope-detector circuitry designed for use with amplitude modulation. An RC high-pass filter with a cutoff frequency near the carrier signal can be used to generate the waveform.

3.2 Demodulation using Phase-Locked Loop (PLL)

A phase-locked loop (PLL) is a high performance FM demodulation method that locks onto the intensity of an incoming waveform using a phase detector, a low-pass filter and a voltage-controlled oscillator (VCO) in a negative-feedback system as shown in the following figure:

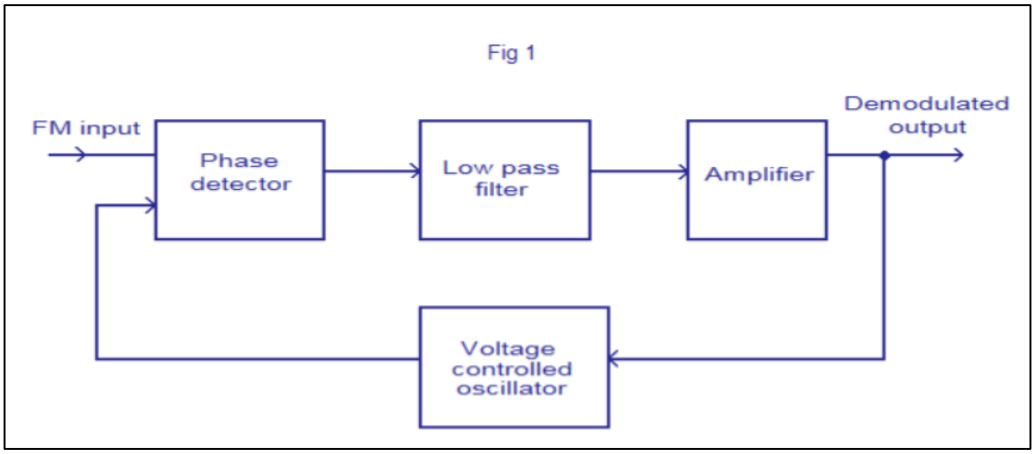

Figure 3 FM signal demodulation using Phase-Locked Loop (PLL) block diagram.

The phase detector generates a signal proportional to the phase difference between the incoming waveform and the VCO output, which is then smoothed by the loop filter and serves as the VCO's control signal.

Procedure and Data Analysis

Part 1: Modulation

The first part of the experiment aims to study and analyze the behavior of frequency modulation (FM), which will be divided into two sections. The first section will focus on modulation in the time domain, while the second section will explore the frequency domain.

Section 1: Time Domain

1.1 Displaying the FM signal in the time domain

Firstly, this part aims to display and simulate the FM signal in the time domain. The sinusoidal message signal with amplitude Vss=20 Volts, and message frequency Fm = 1kHz was generated using the function generator. The following figure shows the frequency modulation circuit.

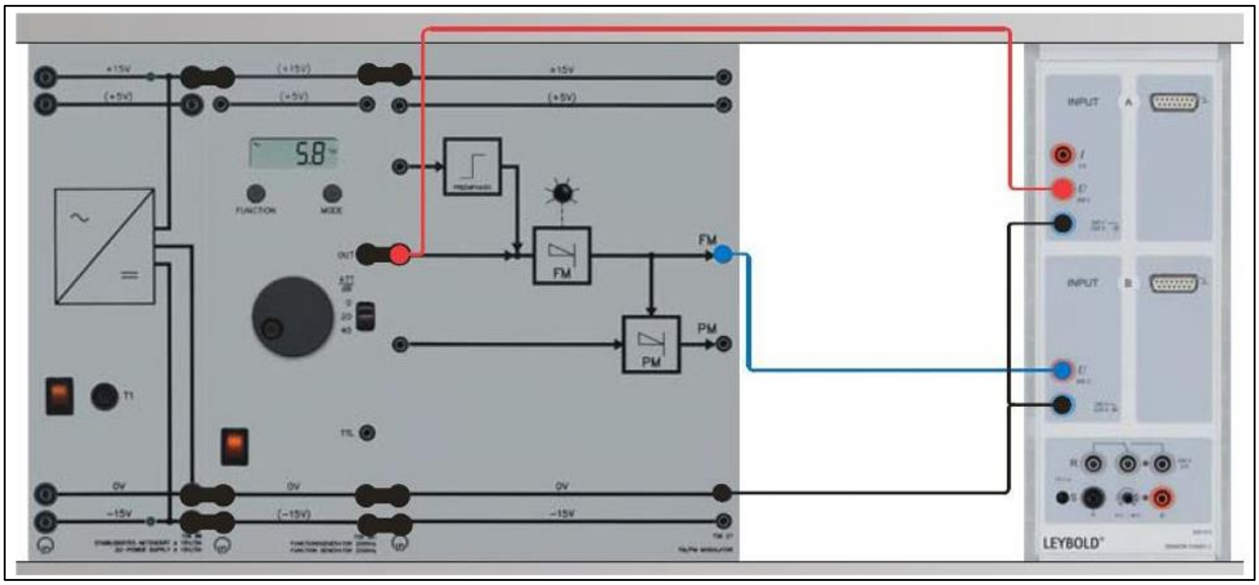

Figure 4 FM Modulation Circuit.

The following figure *(Figure 5)* shows the result of connecting the previous circuit of the frequency modulation (FM). It is noticed that the modulated signal s(t) frequency is changing with respect with the value of the amplitude modulation.

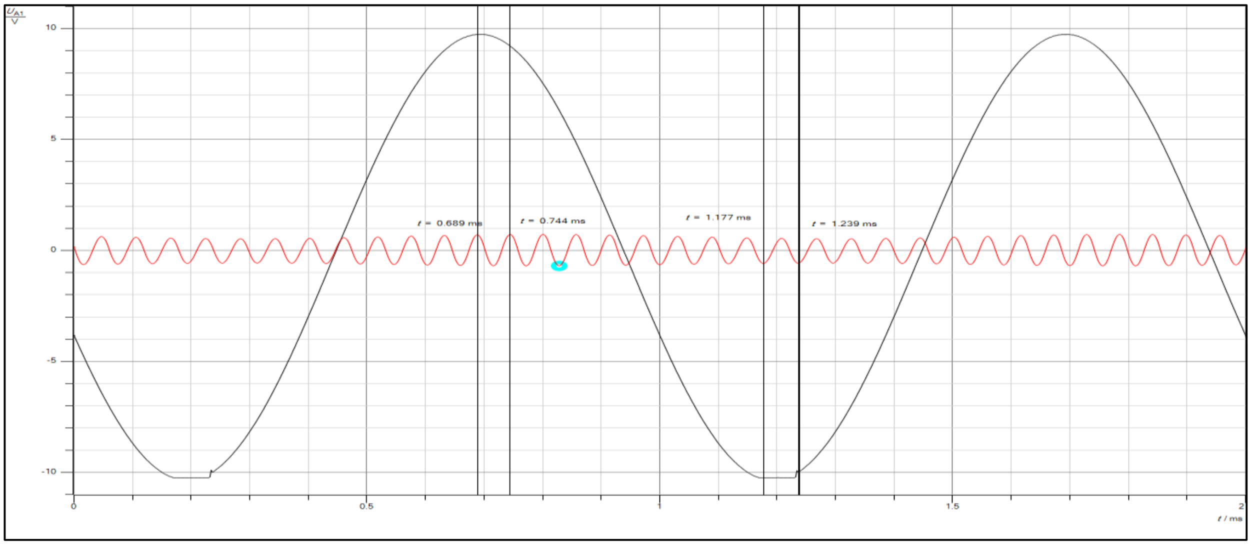

Figure 5 The message signal m(t), and the FM modulated signal s(t) in time domain.

The above result, which is the effect of changing the message amplitude on the modulated signal frequency happened because as the message amplitude increases, the frequency of the modulated signal of FM also increases, and the modulation index will also increase resulting in a wide range of frequency deviation according to the following equation:

$$\boldsymbol{\beta = \frac{\Delta f}{f_m} = \frac{kf\ Am}{fm}}$$

In contrast, when decreasing the amplitude of the original message signal m(t), the modulation index will decrease, and the frequency deviation will also decrease causing narrow frequency deviations, which leads to a decrease in the frequency of the modulated signal of FM. As a result, the change in the amplitude of the message signal will lead to changes on the frequency of FM signal.

Section 2: Frequency Domain (Spectrum)

Now, in this section, the ***Cassy lab*** was set in FFT mode in order to find the spectrum of the FM-modulated signal. The interval was adjusted and observed the x-range became ready for the next steps.

2.1 Setting the carrier frequency to exactly 20 kHz

The next step was setting the amplitude of the message signal to 0 (Vss = 0V). The result of the modulated signal will be representing only the carrier signal c(t) only; this can be proved using the FM modulation equation as the following:

$$s(t) = A_c cos[2\pi f_c + \beta sin(2\pi f_m t)] \ \textit{Where} \ \ \beta = \frac{\Delta f}{f_m} = \frac{kf\ Am}{fm}$$

Now, when setting $Am = 0$ → this means the value of $\beta = 0$.

Consequently, $s(t) = A_c cos[2\pi f_c + \beta sin(2\pi f_m t)] \rightarrow A_c cos[2\pi f_c + 0 * sin(2\pi f_m t)]$

This means the FM-modulated signal will be equal to the carrier signal c(t) as follows:

$$\therefore\ s(t) = A_c cos(2\pi f_c) \ \equiv \textit{Carrier Signal}$$

The next step was to observe the carrier impulse and adjusted it to be **20 kHz** in the frequency domain by using the FFT property in the ***Cassy lab*** as shown in the following figure:

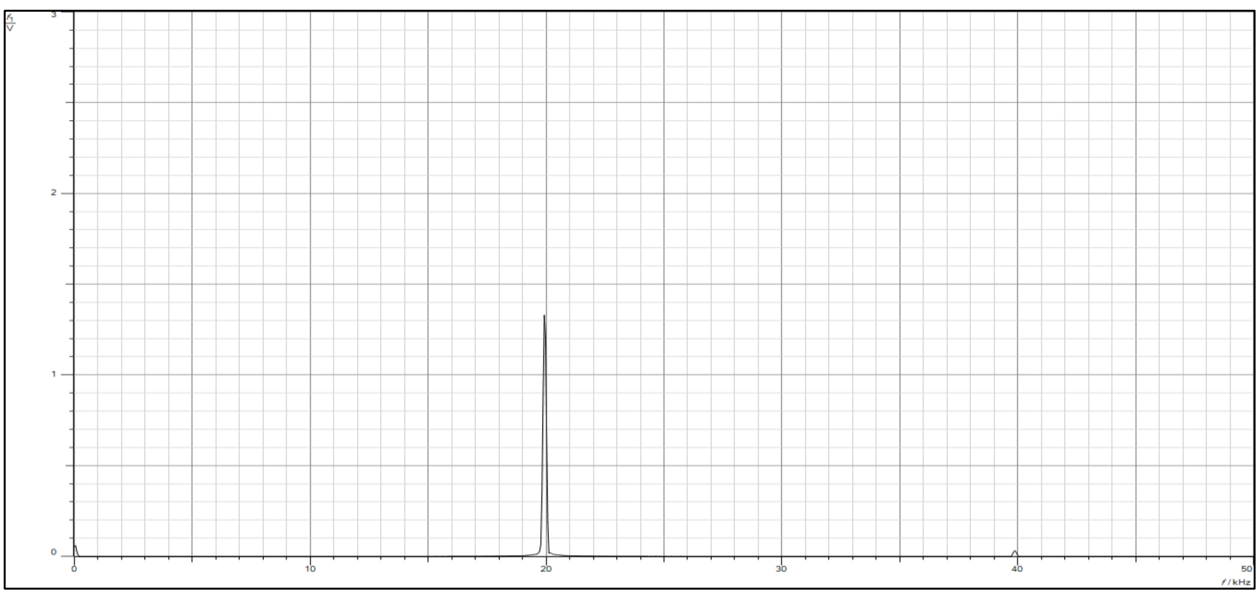

Figure 6 Adjusting the Frequency carrier to 20 kHz.

2.2 The Characteristic of the FM Modulator

The main aim of this part is to find and calculate the value of the FM modulator sensitivity constant in Hz/V unit. It is known that the instantaneous frequency equation is as the following:

$$\boldsymbol{f_i}(\mathbf{t}) = \boldsymbol{f_c} + \boldsymbol{k_f}\mathbf{m}(\mathbf{t}) \rightarrow \text{as a result, the } K_f \text{ can be obtained as } \boldsymbol{k_f} = \frac{\boldsymbol{f_i}(\mathbf{t}) - \boldsymbol{f_c}}{\boldsymbol{m}(\boldsymbol{t})}$$

As the message signal is set to be a constant value that means there will **not be any variation in the amplitude over time**, which leads to **no variation in the frequency**.

To determine the value of the modulator sensitivity constant, a DC-signal message signal starting from **-10V to 10V** using a 20 kHz carrier signal, the carrier frequency can be determined from the spectrum, and the operation will be repeated by incrementing the DC-Voltage value by 2V in each step and measuring the carrier frequency. The results of this part were obtained and recorded in the following table in order to calculate the value of the modulator sensitivity constant:

Table 1 Measuring the carrier frequency value with respect of changing message value.

Message Voltage	Carrier Frequency	Message Voltage	Carrier Frequency
-10	**19.23**	**2**	**20.12**
-8	**19.37**	**4**	**20.26**
-6	**19.53**	**6**	**20.41**
-4	**19.68**	**8**	**20.56**
-2	**19.82**	**10**	**20.72**
0	**19.97**		

✓ The final step is determining the FM modulator sensitivity constant $\boldsymbol{k_f}$ using the equation:

$$\boldsymbol{k_f} = \frac{\mathbf{20.72 - 19.23}}{\mathbf{10 - \ -10}} = \frac{\mathbf{1.49}}{\mathbf{20}} = \mathbf{74.5}\ \boldsymbol{Hz/Volt}.$$

2.2.1 Determining of the frequency deviation for a 10V message signal

As mentioned before, the frequency deviation $\Delta \boldsymbol{f}$ used to calculate the value of the FM modulation index $\boldsymbol{\beta} = \frac{\Delta f}{f_m}$, which $\Delta \boldsymbol{f} = \boldsymbol{Kf} * \boldsymbol{Am}$. As a result, the value of the deviation depends on the **amplitude voltage** value and the **FM modulator sensitivity**.

To determine the frequency deviation for the 10V message signal, it can be easily done by using the value of Kf that was found before as shown:

$$\Delta \boldsymbol{f} = \boldsymbol{Kf} * \boldsymbol{Am} = \mathbf{74.5} * \mathbf{10} = \mathbf{745}\ \textbf{Hz.}$$

2.3 Displaying the FM signal spectrum

The objective of this part is to display the FM signal spectrum for different input message frequencies, including square and sinusoidal message signals in different frequencies and duty cycles, and to compare and analyze the changes in the spectrum results.

2.3.1 Sinusoidal Message signal

Using the same circuit connection, using a sinusoidal input message signal with **VSS=20V** and message frequency **fm=300 Hz** and making the DC offset equal to zero (DC=0). The FM spectrum of the modulated signal was obtained as the following:

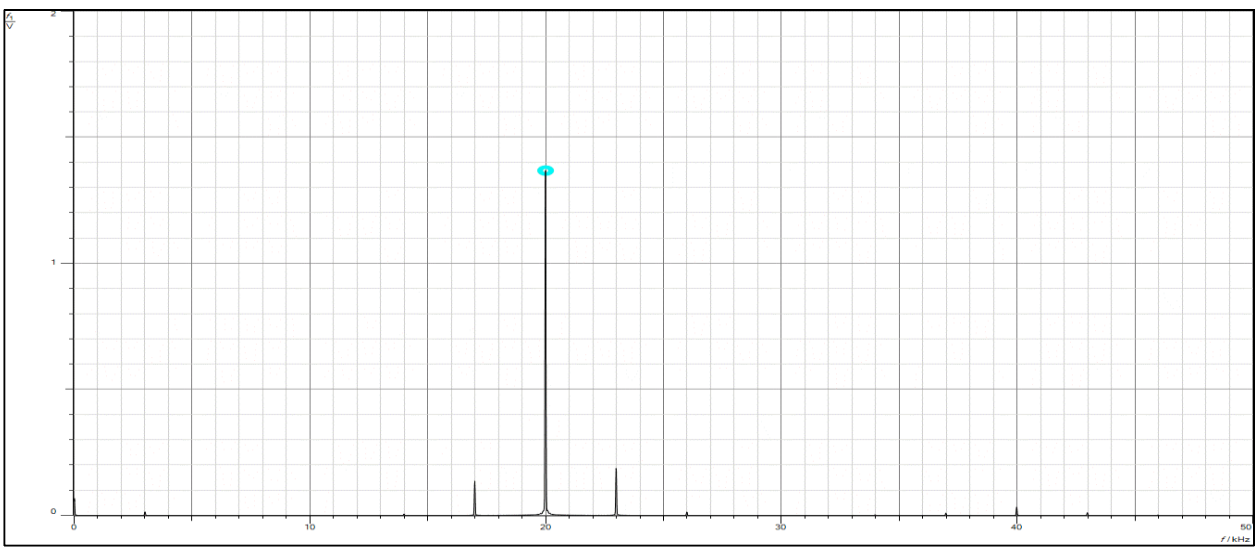

Figure 7 The spectrum of the FM modulated signal with fm=300 Hz sinusoidal message signal.

When repeating the same steps with different message frequency value (fm=200 Hz) and keeping the value of VSS=20V. The spectrum of the modulated signal in this case was as shown in the following figure:

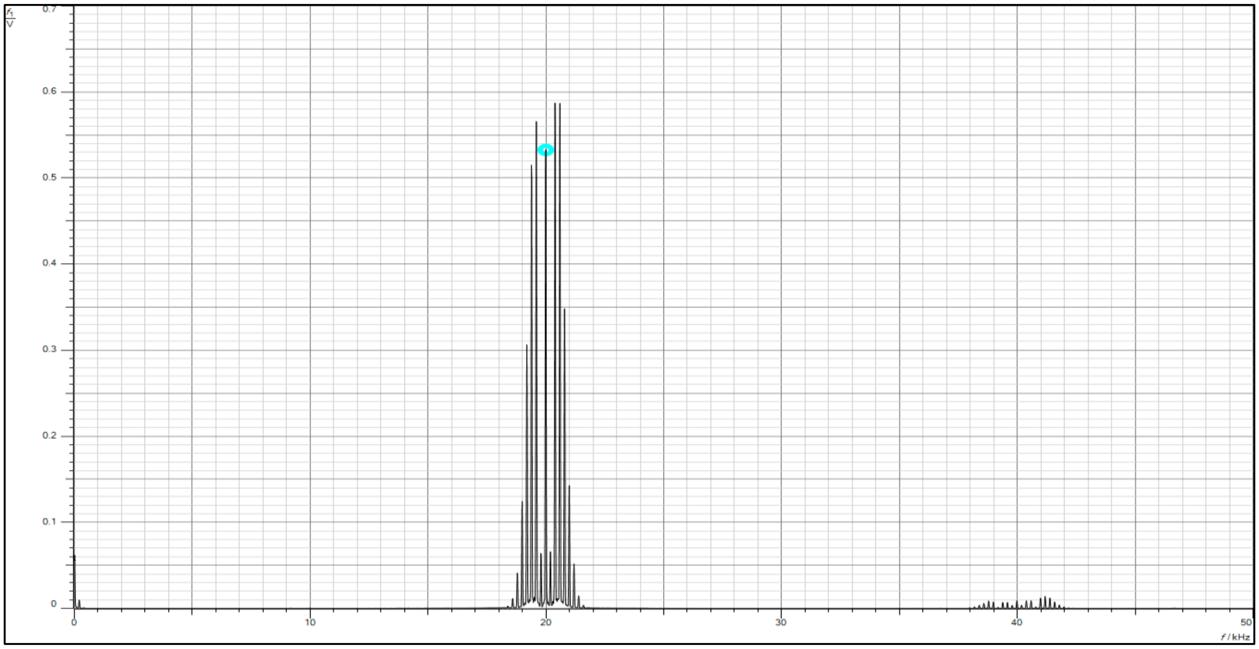

Figure 8 The spectrum of the FM modulated signal when changing the frequency to fm=200 Hz.

To compare the changes between the two message frequency, in the first case when the fm=300 Hz, the message signal has a higher frequency than when fm=200 Hz. This means that for the same amplitude of message signal, the modulation index $\boldsymbol{\beta}$ will be lower when fm=300 Hz compared to when fm=200 Hz because the inversely proportional to the value of fm depends on the following equation: $\boldsymbol{\beta = \frac{\Delta f}{f_m} = \frac{kf\ Am}{fm}}$ **.**

As a result, in FM modulation, when the modulation index β is small (fm =300Hz), this leads to have a **narrow bandwidth signal ($\boldsymbol{\beta \ll 1}$),** similar to the amplitude modulated (AM) spectrum signal which contains the **carrier, and two sidebands only**.

In contrast, when the modulation index (β) is high (fm=200 Hz and $\boldsymbol{\beta \gg 1}$), the spectrum will have a **wider bandwidth**.

2.3.2 Square Message signal

In this part, the square message signal was used as an input for the FM modulation operation, using VSS = 20V, duty cycle 50%, and frequency fm=200Hz. The FM-modulated signal of the square wave in time and frequency domains are shown in the following figures:

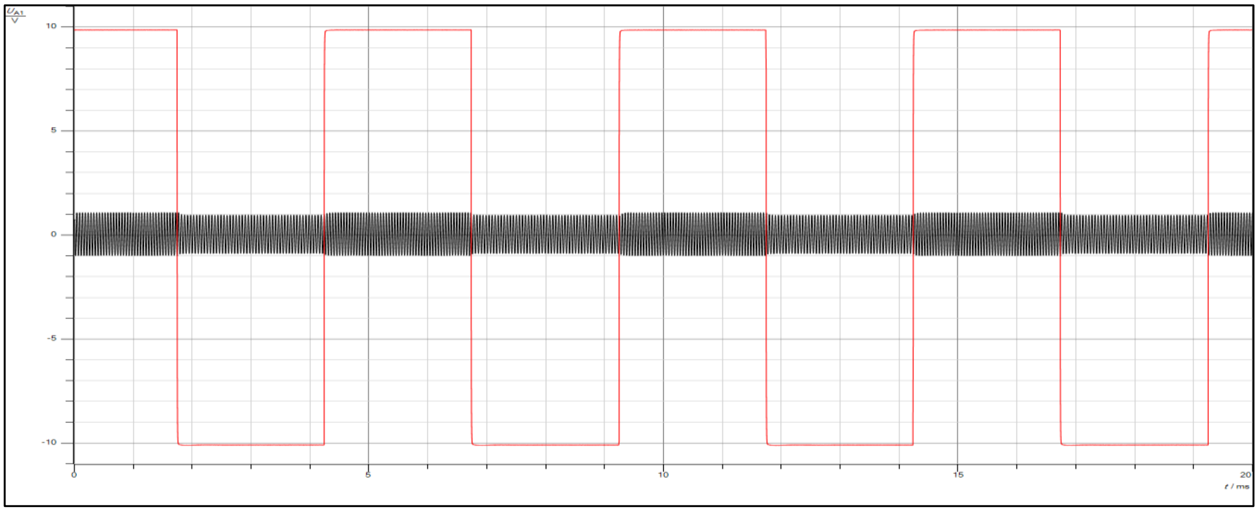

Figure 9 FM modulated signal for the square wave in time domain.

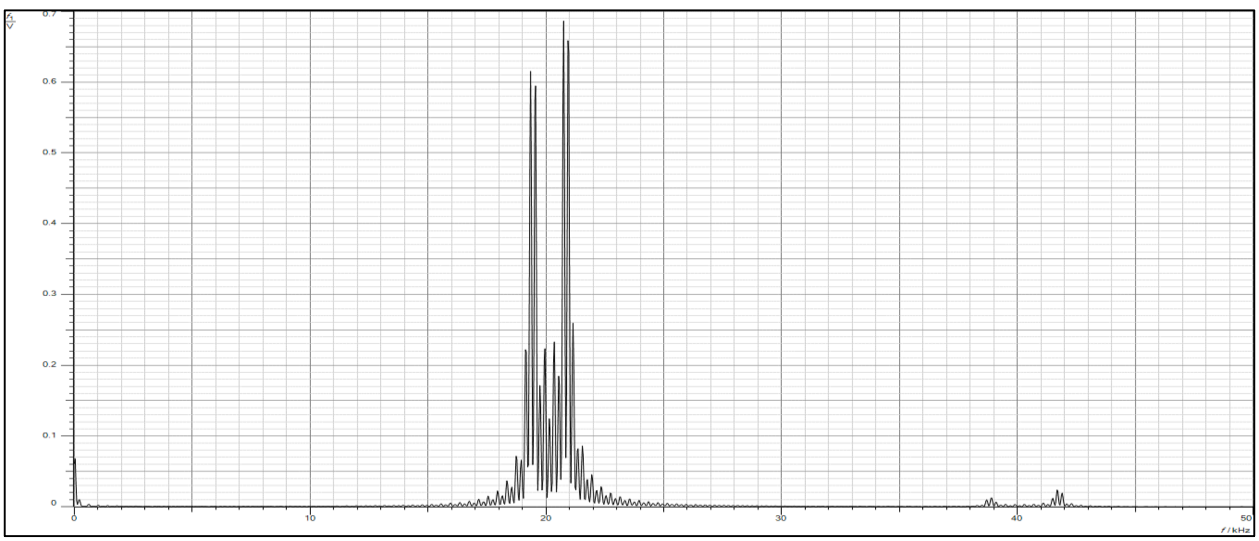

Figure 10 FM modulated signal for the square wave in frequency domain.

The difference between the spectrums of the message types is that when the input message is square, it has a wider range of spectrums in each sideband compared with the sinusoidal one when the message frequency is equal **(fm=200 Hz).** In addition, it is noticed that the value of the spectrum at 20 kHz in the sinusoidal message is higher than the square one.

2.4 Determining the zero carrier crossings

The zero carrier crossings happens when the carrier frequency spectrum becomes zero at a certain value of **modulation index** ($\boldsymbol{\beta}$) when varying the value of the message frequency fm **(while keeping the Am the same)** or the message amplitude Am **(while keeping the value of the frequency constant)**. In this part, two values of modulation index ($\boldsymbol{\beta}$) ***at β=2.4048*** and ***β=5.5201*** will be used in calculations.

✓ **Message signal with constant frequency of 100 Hz:**

1] $\boldsymbol{\beta} = \frac{\Delta \boldsymbol{f}}{\boldsymbol{f_m}} = \frac{\boldsymbol{kf\ Am}}{\boldsymbol{fm}} = \mathbf{2.4048} = \frac{\mathbf{74.5} * \boldsymbol{Am}}{\mathbf{100}} \rightarrow \boldsymbol{Am} = \mathbf{3.2279} * \mathbf{2} = \mathbf{6.4558}\,\boldsymbol{V}.$

2] $\boldsymbol{\beta} = \frac{\Delta \boldsymbol{f}}{\boldsymbol{f_m}} = \frac{\boldsymbol{kf\ Am}}{\boldsymbol{fm}} = \mathbf{5.5201} = \frac{\mathbf{74.5} * \boldsymbol{Am}}{\mathbf{100}} \rightarrow \boldsymbol{Am} = \mathbf{7.4095} * \mathbf{2} = \mathbf{14.819}\,\boldsymbol{V}.$

Note: *The value of the Kf = 74.5 obtained from the section 2.2 (The Characteristic of the FM Modulator)*

Table 2 Amplitude values results in zero carrier crossing.

Modulation index ($\boldsymbol{\beta}$)	**2.4048**	**5.5201**
Amplitude (V)	**6.4558**	**14.819**

✓ **Message signal with a constant amplitude of 10V:**

1] $\boldsymbol{\beta} = \frac{\Delta \boldsymbol{f}}{\boldsymbol{f_m}} = \frac{\boldsymbol{kf\ Am}}{\boldsymbol{fm}} = \mathbf{2.4048} = \frac{\mathbf{74.5} * \mathbf{10}}{\boldsymbol{fm}} \rightarrow \boldsymbol{fm} = \mathbf{309.79}\,\boldsymbol{Hz}.$

2] $\boldsymbol{\beta} = \frac{\Delta \boldsymbol{f}}{\boldsymbol{f_m}} = \frac{\boldsymbol{kf\ Am}}{\boldsymbol{fm}} = \mathbf{5.5201} = \frac{\mathbf{74.5} * \mathbf{10}}{\boldsymbol{fm}} \rightarrow \boldsymbol{fm} = \mathbf{134.96}\,\boldsymbol{Hz}.$

Table 3 Frequency values results in zero carrier crossing.

Modulation index ($\boldsymbol{\beta}$)	**2.4048**	**5.5201**
Frequency (Hz)	**309.79**	**134.96**

2.4.1 Varying the message amplitude while keeping the frequency constant

Now, in this part, the sinusoidal signal with VSS= 0V and fm=100 Hz was generated. And then slowly, the amplitude of the message signal increased. The following figure shows the spectrum of the modulated signal when the amplitude equals to Vss=6.5V:

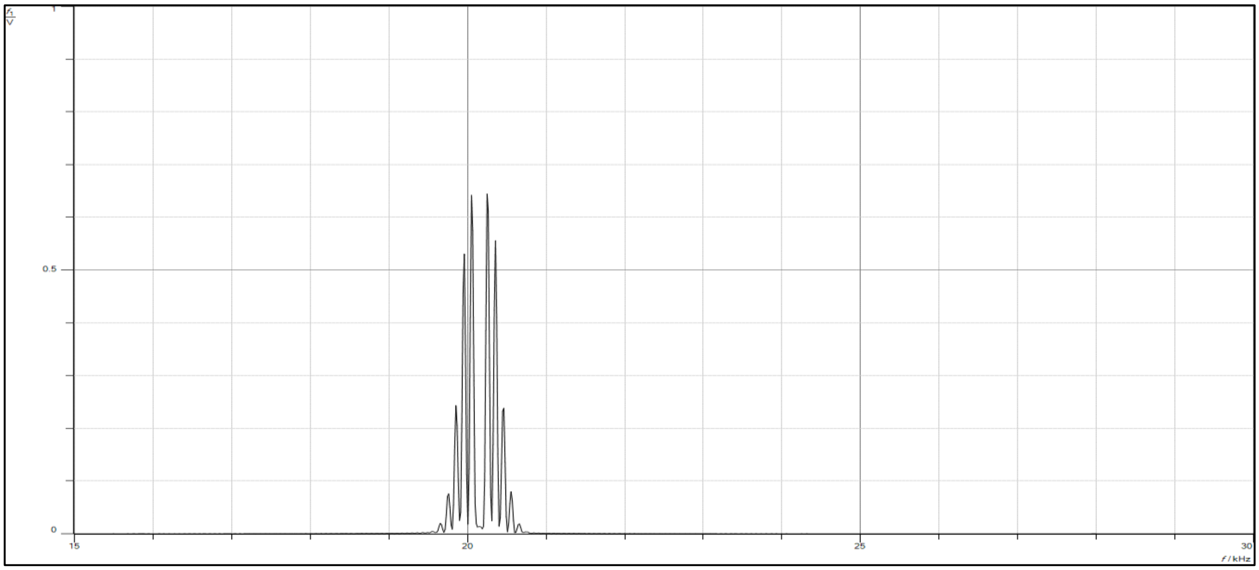

Figure 11 Modulated Signal spectrum when increasing Am =6.5 V and keeping fm=100 Hz.

While keeping the frequency, and increasing the amplitude up to 15V, the result of the spectrum is as the following:

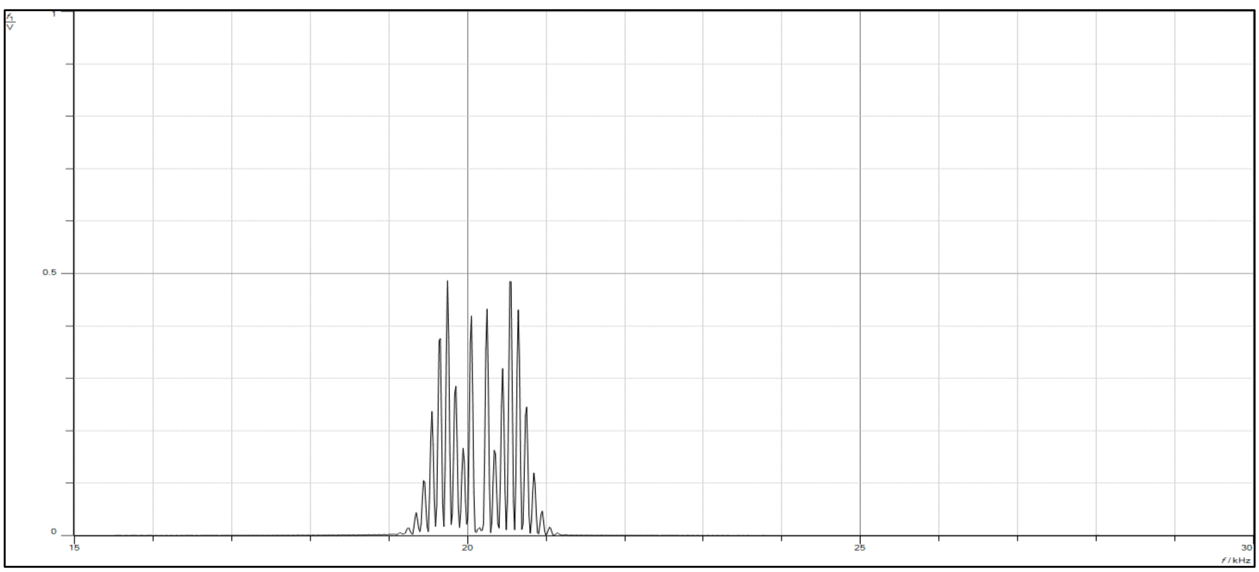

Figure 12 Modulated Signal spectrum when increasing Am =15 V and keeping fm=100 Hz.

It is noticed that, by increasing the value of the amplitude of the sinusoidal message and keeping the frequency the same, the value of the carrier impulse is decaying more and more.

2.4.2 Varying the message frequency while keeping the amplitude constant

By repeating the same steps, keeping the Am to 10V, and starting with fm=1kHz. Slowly reducing the frequency of the message, the carrier impulse will eventually will be disappeared. The following spectrum shows the FM modulated signal when fm is decreased to 134.6 Hz:

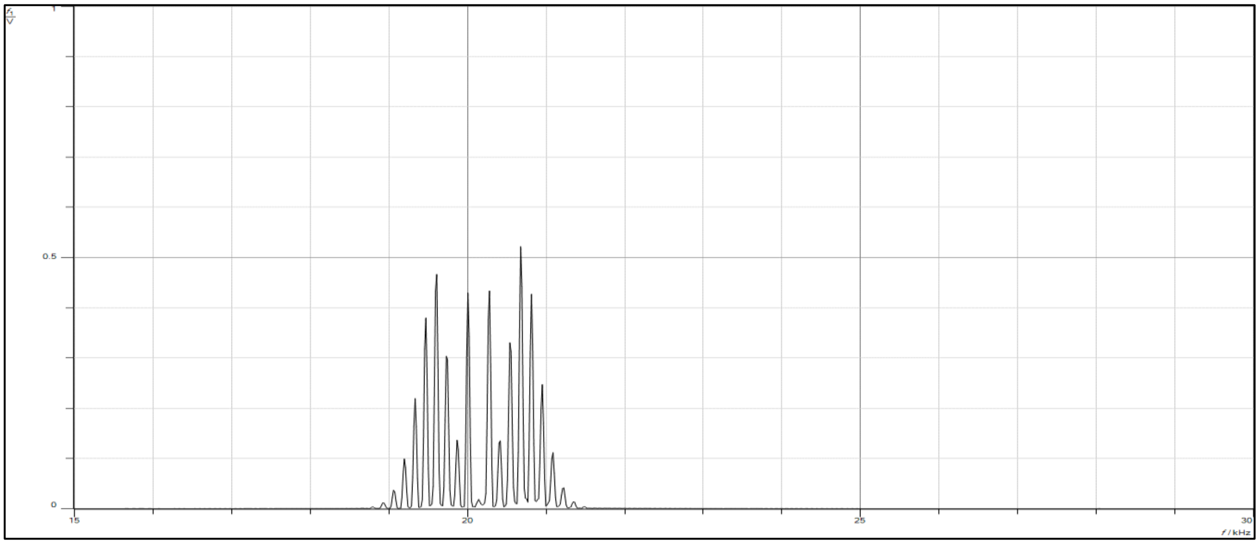

Figure 13 Modulated Signal spectrum when decreasing the fm to 134.6 Hz Am =15 V and keeping the Am = 10V.

To sum up, both situations will end to disappearing the impulse of the carrier signal, either by **increasing** the amplitude while keeping the frequency value constant, or **decaying** the frequency while keeping the amplitude is constant.

Part 2: Demodulation

The main objectives of this part are to retrieve the original signal m(t) from the FM-modulated signal in the time domain. In addition, to study the effect of the two low pass filters with and without pre-emphasis.

Section 1: Time domain FM demodulated signal

In this section, it was required to connect the circuit shown in the next figure. Using VSS=10V and fm = 500 Hz for the sinusoidal input message signal m(t).

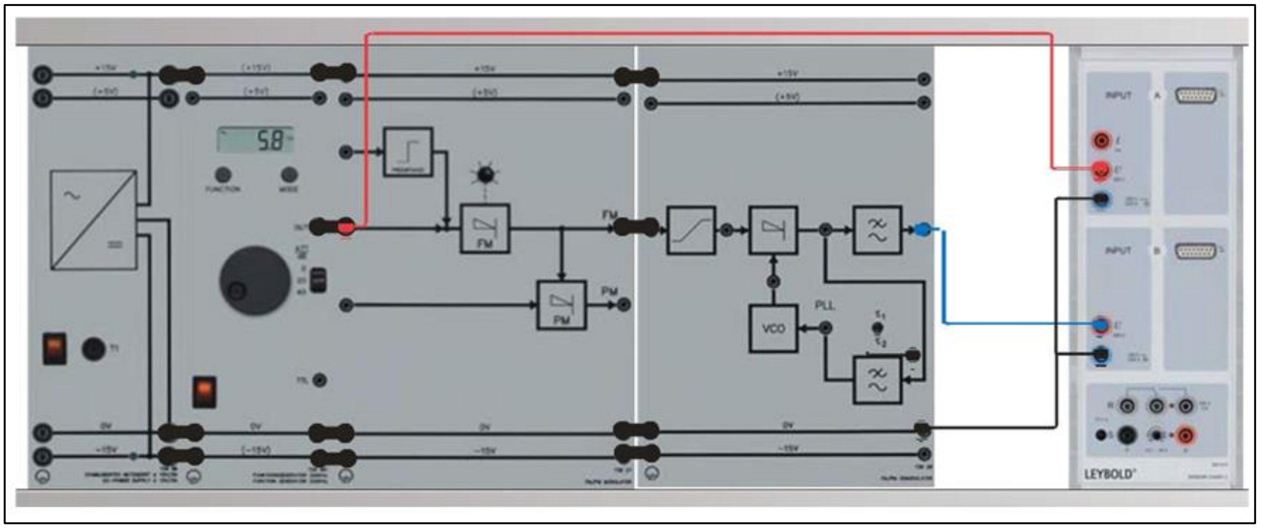

Figure 14 FM Demodulation Circuit.

The FM demodulation option is done using the circuit of PLL in order to retrieve the original message signal. The following figure shows the original message signal(in red) and the demodulated signal (the black) from the phase-locked loop circuit.

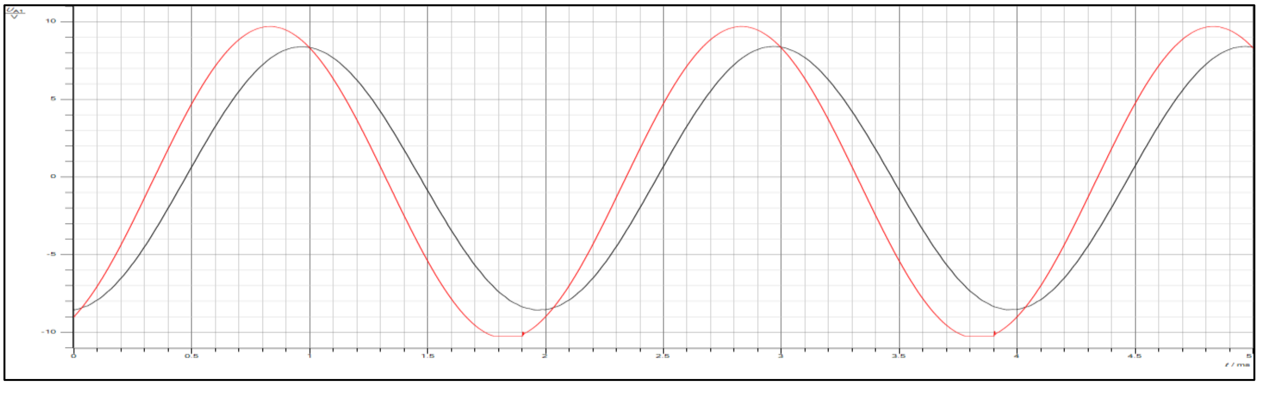

Figure 15 The original and demodulated signal in time domain.

Section 2: Studying the effect of the receiver loop filter

In experiment's receiver is designed to use two receiver loop filters, each one is representing a low-pass filter with a special gain-bandwidth characteristics. The main purpose of this section is compare the original message signal with the demodulated one by varying the gain of the loop filter between the two receiving filters.

2.1 Studying Loop filters τ1 and τ2 without pre-emphasis

The objective of this part is to study the two loop filters without the pre-emphasis by determining the gain between the message signal and the demodulated signal, and recording the results in the following table. The used sinusoidal modulating signal m(t) is with VSS=4V and starting frequency fm=500Hz.

Table 4 The gain of t1 and t2 filters without pre-emphasis.

Without the Pre-emphasis					
Message frequency (Hz)	**500**	**1000**	**2000**	**3000**	**4000**
Ad using τ1 filter	0.273	0.521	1.143	1.992	3.074
Ad using τ2 filter	1.180	1.178	1.243	1.632	2.465

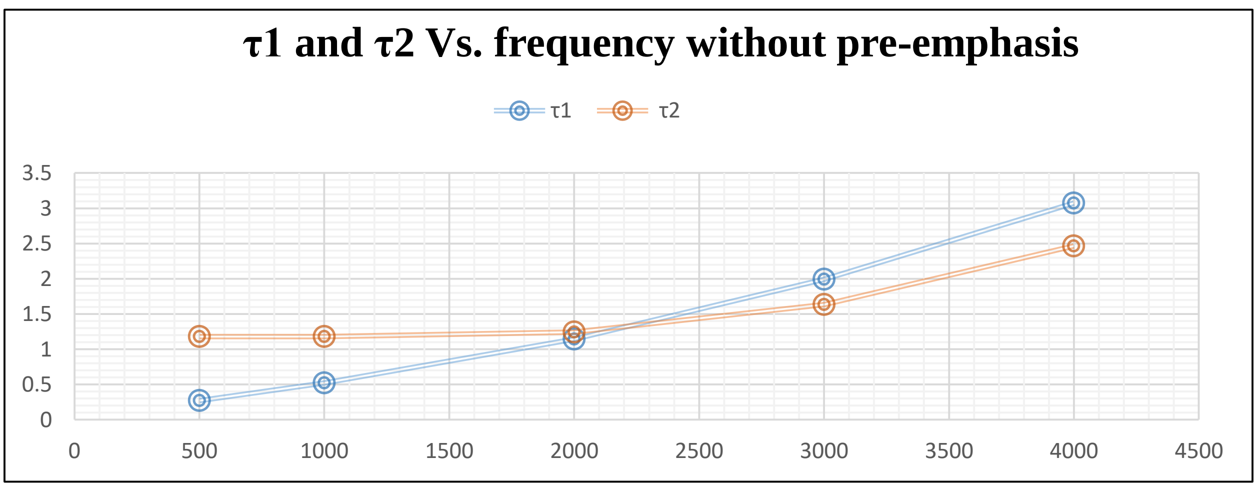

Figure 16 The plot of gain of τ1 and τ2 without pre-emphasis.

From the previous plot, it is noticed that as the input frequency of the message signal increase, the gain of the τ1 is getting higher than the τ2.

2.2 Studying Loop filters τ1 and τ2 with pre-emphasis

The purpose of adding the pre-emphasis block to the demodulation circuit is to improve the quality of the demodulated signal. In this part, the same steps was applied, and results of the gain for both filters were recorded in the following table:

Table 5 The gain of t1 and t2 filters with pre-emphasis.

With the Pre-emphasis					
Message frequency (Hz)	**500**	**1000**	**2000**	**3000**	**4000**
Ad using τ1 filter	0.207	0.248	0.3901	0.626	0.967
Ad using τ2 filter	0.895	0.561	0.424	0.511	0.772

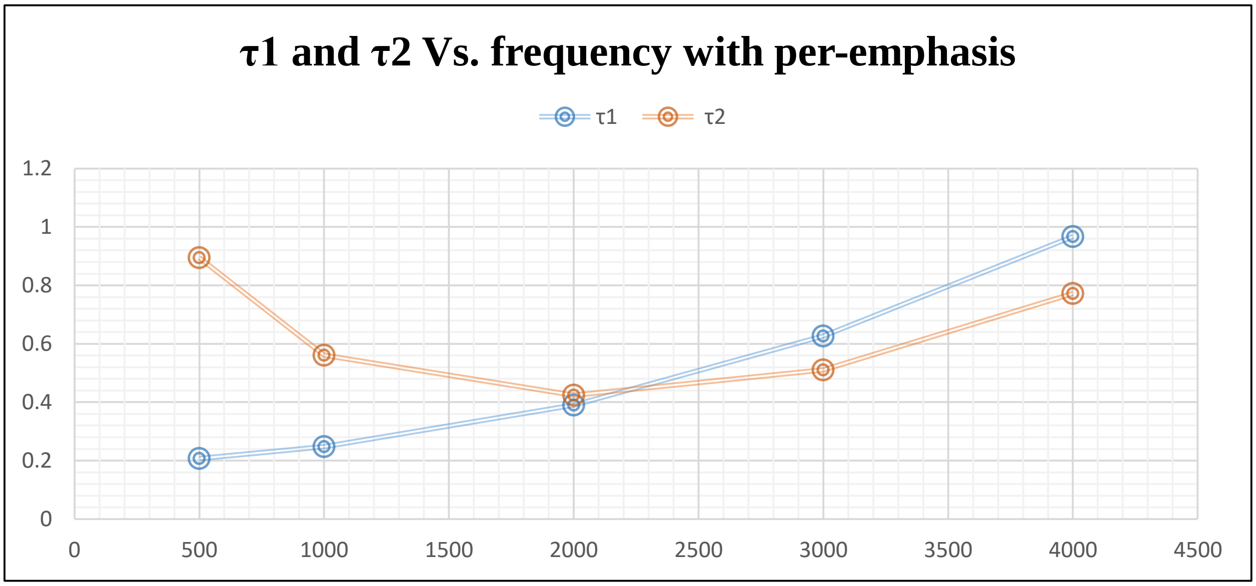

Figure 17 The plot of gain of τ1 and τ2 with pre-emphasis.

From the previous plots, it is noticed that adding the pre-emphasis block to the modulation operation caused to reduce the value of the gain compared with results of gain without pre-emphasis for both filters. The following figures show the gain with and without pre-emphasis for both filters τ1 and τ2:

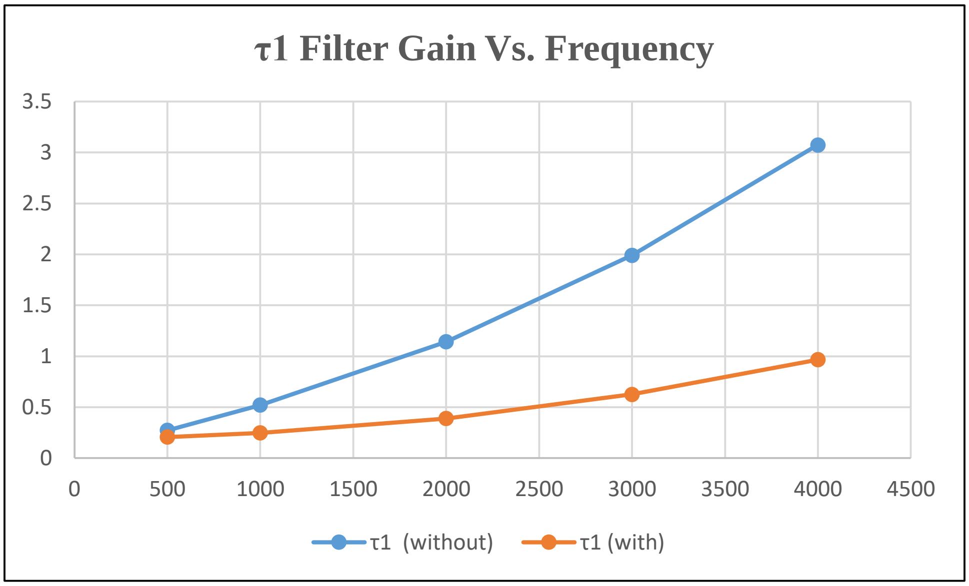

Figure 18 τ1 filter gain without and without pre-emphasis.

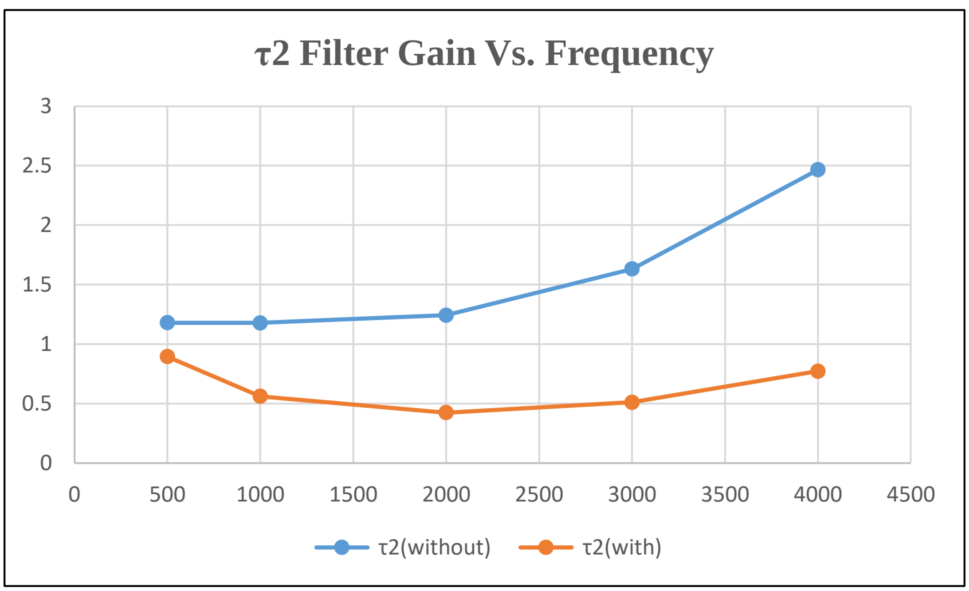

Figure 19 τ2 filter gain without and without pre-emphasis.

Conclusion

In conclusion, the concepts of frequency modulation and demodulation in the time and frequency domain were covered and discussed clearly. Moreover, the experiment examined the FM modulator sensitivity and examined how to determine the zero carrier crossing. Finally, it covered the demodulation techniques of the FM modulated signal and compared the characteristics of the two receiver loop filters when the gain of the loop filter is varied between the two loop filters, and the effect and the usage of pre-emphasis.

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Appendixes

Assume the following cases:

$\beta = \frac{k_f A_m}{f_m}$

1. A message with a constant frequency of 100Hz.

   Calculate the first three values of the message amplitude that will result in zero carrier crossing. Fill them in the following table.

   6.4558 14.819

Modulation index (β)	2.4048	5.5201	~~8.6537~~
Amplitude (V)	3.2279	7.4095	

2. A message with a constant amplitude of 10V

   Calculate the first three values of the message frequency that will result in zero carrier crossing. Fill them in the following table.

Modulation index (β)	2.4048	5.5201	~~8.6537~~
Frequency (Hz)	309.79	134.96	

2.4.1: Varying the message amplitude while keeping the frequency constant

Use a sinusoidal signal with V_{SS} = 0V and fm = 100Hz of the function generator as the modulating signal m(t). Slowly Increase the amplitude of the message. Plot the modulated signal spectrum using the Cassy Lab then **take a picture** of the impulses. (Adjust the x-axis range to be suitable for the plot) Observe the decay of the carrier impulse. Record the values of the amplitudes when the carrier impulse disappears.

1st carrier decay at amplitude = ____________ → 6.5 عمليا أول

2nd carrier decay at amplitude = ____________ → 15 عمليا التانية

3rd ~~carrier decay at amplitude =~~ ____________

Compare the theoretical values that were found before. What can you conclude?

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2.4.2: Varying the message frequency while keeping the amplitude constant.

Use a sinusoidal signal with V_{SS} = 20V and fm = 1kHz of the function generator as the modulating signal m(t). Slowly reduce the frequency of the message. Plot the modulated signal spectrum using the Cassy Lab then **take a picture** of the impulses. (Adjust the x-axis range to be suitable for the plot) Observe the decay of the carrier impulse. Record the values of the amplitudes when the carrier impulse disappears.

1st carrier decay at frequency = ____________

2nd carrier decay at frequency = ____________ → $\boxed{134.6}$

3rd ~~carrier decay at frequency =~~ ____________

2.1: Studying Loop filters τ_1 and τ_2 without pre-emphasis

In this section set the Cassy Lab in FFT mode. To do this go to:

Settings > Calculator > FFT > choose input channel (FFT of)

Finally, adjust the Interval and observe the x-axis range

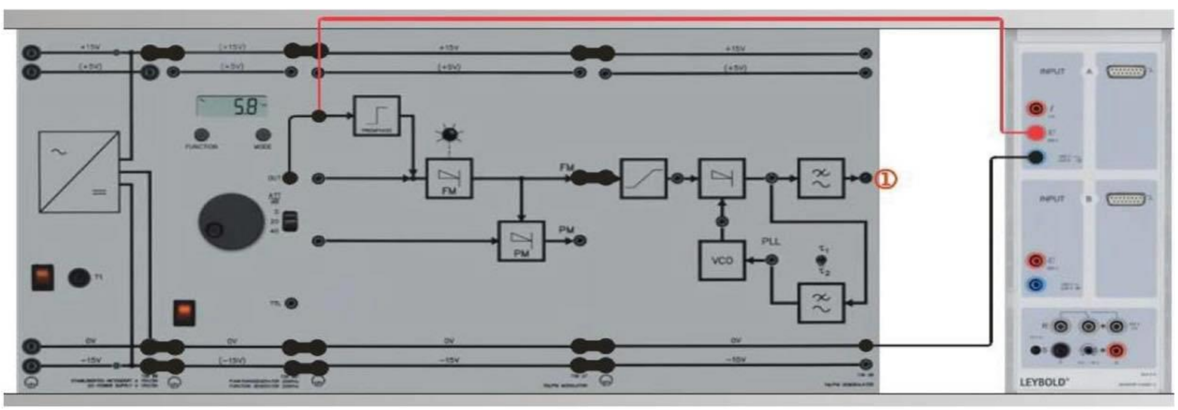
Use a sinusoidal modulating signal m(t) with V_{SS} = 4V and starting with fm = 500Hz. Determine the amplitude of the demodulated signal using the spectrum for each loop filter. **Record the values into the table.** Plot Ad/Am versus fm on the chart below.

Without the Pre-emphasis						
Message Frequency (Hz)	500	1000	2000	3000	4000	~~5000~~
A_d using τ_1 filter	2.42/8.84	2.57/4.93	2.55/2.23	2.53/1.27	2.49/0.81	
A_d using τ_2 filter	2.42/2.05	2.57/2.18	2.55/2.05	2.53/1.55	2.49/1.01	

2.2: Studying Loop filters τ_1 and τ_2 with pre-emphasis

Pre-emphasis is the process of amplifying its input signal if it is at a specific range of frequency (Usually high frequency).

Assemble the components as shown.



Use a sinusoidal modulating signal m(t) with V_{SS} = 4V and starting with fm = 500Hz. Determine the amplitude of the demodulated signal using the spectrum for each loop filter. **Record the values into the table**. Plot Ad/Am versus fm on the chart below.

With the Pre-emphasis						
Message Frequency (Hz)	500	1000	2000	3000	4000	~~5000~~
A_d using τ_1 filter	2.39/11.5	2.51/10.10	2.45/6.28	2.41/3.85	2.37/2.45	
A_d using τ_2 filter	2.34/2.67	2.51/4.47	2.45/5.77	2.07/4.05	2.37/3.07	