Modulation

MODULATION

- Defined as

  " The process by which some characteristics of a signal called carrier varied in accordance with the instantaneous value of another signal called modulating signal "

- The information bearing signal is called modulating signal
- The signal resulting from process of modulation is known as modulated signal

TYPES OF MODULATION

- **Continuous wave Modulation** : carrier is continuous in nature (usually sinusoidal) (AM,FM,PM)

- **Pulse Modulation** :Carrier is pulse type waveform

TYPES OF MODULATION

- Sine wave (carrier) described by 3 parameters:
  amplitude, frequency and phase.
- Let carrier signal be:

$$v(t) = A \sin(\omega t + \varphi)$$

So can have

- – **Amplitude modulation (AM)**
- – **Frequency modulation (FM)**
- – **Phase modulation (PM)**

Frequency and phase combined are known as Angle Modulation

AMPLITUDE MODULATION

Let the modulating signal be,

$$m\,(t) = A_m \cos(2\pi f_m t)$$

and the carrier signal be,

$$c\,(t) = A_c \cos(2\pi f_c t)$$

Where,

A_m and A_c are the amplitude of the modulating signal and the carrier signal respectively.

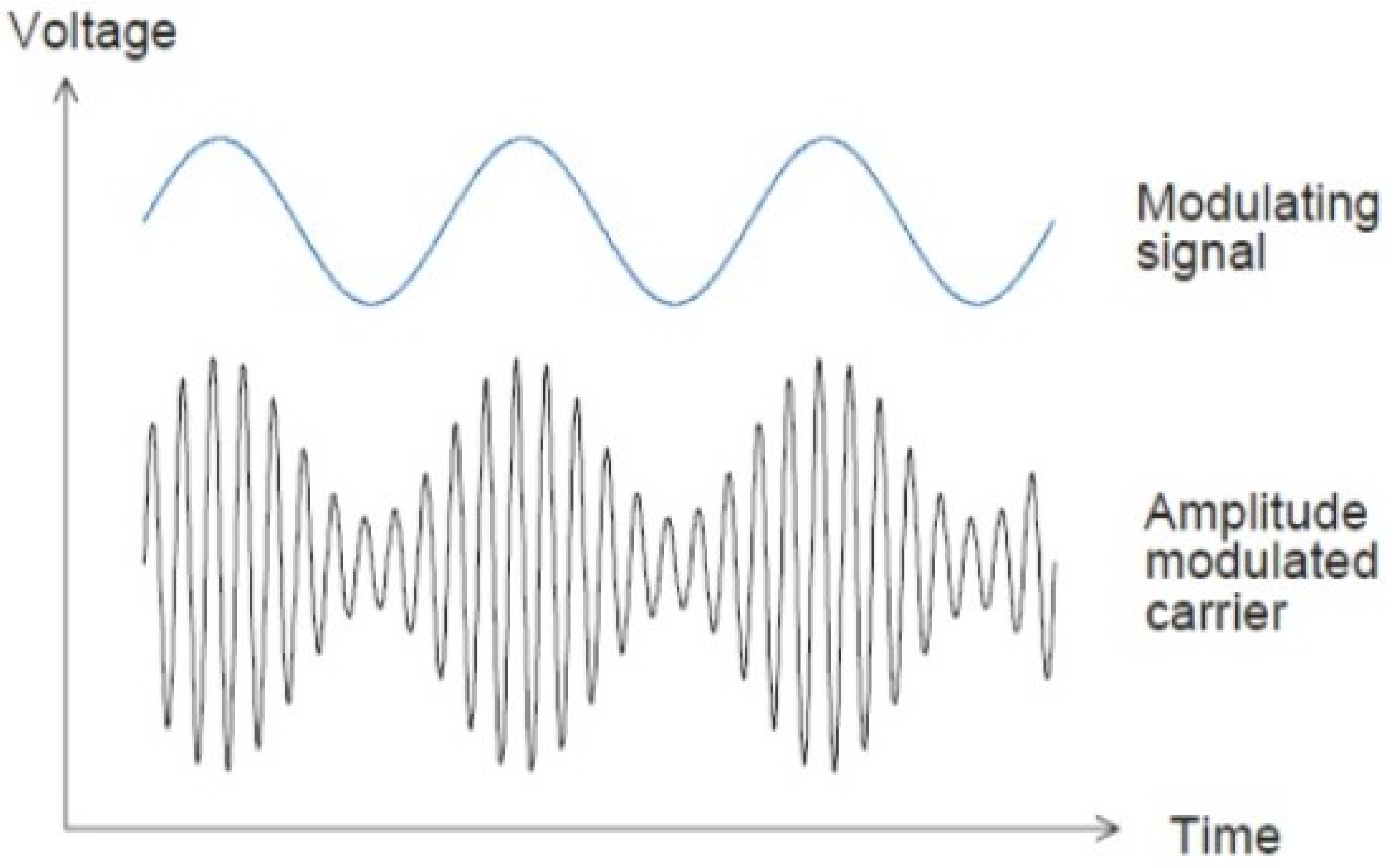
f_m and f_c are the frequency of the modulating signal and the carrier signal respectively.

Then, the equation of Amplitude Modulated wave will be

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

(Equation 1)

AMPLITUDE MODULATION



AMPLITUDE MODULATION

Modulation Index

A carrier wave, after being modulated, if the modulated level is calculated, then such an attempt is called as **Modulation Index** or **Modulation Depth**. It states the level of modulation that a carrier wave undergoes.

Rearrange the Equation 1 as below.

$$s(t) = A_c \left[1 + \left(\frac{A_m}{A_c}\right)\cos(2\pi f_m t)\right]\cos(2\pi f_c t)$$

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

Where, μ is Modulation index and it is equal to the ratio of A_m and A_c. Mathematically, we can write it as

$$\mu = \frac{A_m}{A_c}$$ (Equation 3)

Hence, we can calculate the value of modulation index by using the above formula, when the amplitudes of the message and carrier signals are known.

AMPLITUDE MODULATION

Let $A_{\max}$ and $A_{\min}$ be the maximum and minimum amplitudes of the modulated wave.

We will get the maximum amplitude of the modulated wave, when $\cos(2\pi f_m t)$ is 1.

$$\Rightarrow A_{\max} = A_c + A_m \qquad \text{(Equation 4)}$$

We will get the minimum amplitude of the modulated wave, when $\cos(2\pi f_m t)$ is -1.

$$\Rightarrow A_{\min} = A_c - A_m \qquad \text{(Equation 5)}$$

Add Equation 4 and Equation 5.

$$A_{\max} + A_{\min} = A_c + A_m + A_c - A_m = 2A_c$$

$$\Rightarrow A_c = \frac{A_{\max} + A_{\min}}{2} \qquad \text{(Equation 6)}$$

Subtract Equation 5 from Equation 4.

$$A_{\max} - A_{\min} = A_c + A_m - (A_c - A_m) = 2A_m$$

$$\Rightarrow A_m = \frac{A_{\max} - A_{\min}}{2} \qquad \text{(Equation 7)}$$

AMPLITUDE MODULATION

The ratio of Equation 7 and Equation 6 will be as follows.

$$\frac{A_m}{A_c} = \frac{(A_{max} - A_{min})/2}{(A_{max} + A_{min})/2}$$

$$\Rightarrow \mu = \frac{A_{\max} - A_{\min}}{A_{\max} + A_{\min}} \qquad \text{(Equation 8)}$$

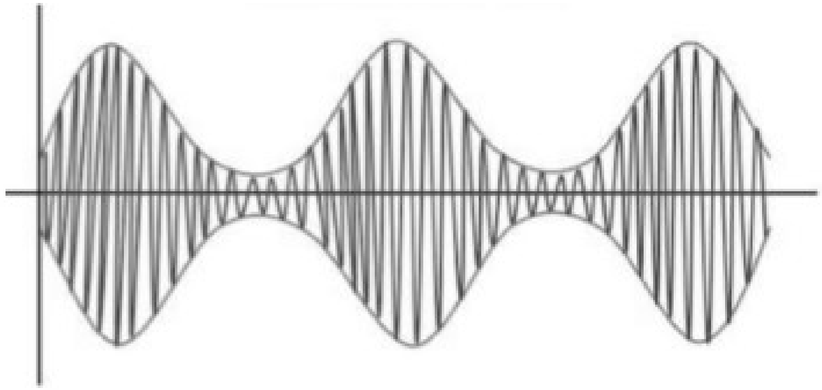
Therefore, Equation 3 and Equation 8 are the two formulas for Modulation index. The modulation index or modulation depth is often denoted in percentage called as Percentage of Modulation. We will get the **percentage of modulation**, just by multiplying the modulation index value with 100.

For a perfect modulation, the value of modulation index should be 1, which implies the percentage of modulation should be 100%.

VARYRING MODULATION INDEX

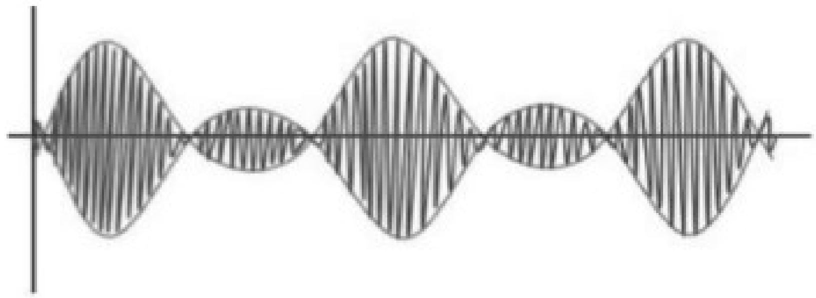
For instance, if this value is less than 1, i.e., the modulation index is 0.5, then the modulated output would look like the following figure. It is called as **Under-modulation**. Such a wave is called as an **under-modulated wave**.

Under-Modulated wave



If the value of the modulation index is greater than 1, i.e., 1.5 or so, then the wave will be an **over-modulated wave**. It would look like the following figure.

Over-Modulated wave



Bandwidth of AM Wave

Bandwidth (BW) is the difference between the highest and lowest frequencies of the signal. Mathematically, we can write it as

$$BW = f_{max} - f_{min}$$

Consider the following equation of amplitude modulated wave.

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

$$\Rightarrow s(t) = A_c\cos(2\pi f_c t) + A_c\mu\cos(2\pi f_c t)\cos(2\pi f_m t)$$

$$\Rightarrow s(t) = A_c\cos(2\pi f_c t) + \frac{A_c\mu}{2}\cos[2\pi(f_c + f_m)t] + \frac{A_c\mu}{2}\cos[2\pi(f_c - f_m)t]$$

Hence, the amplitude modulated wave has three frequencies. Those are carrier frequency f_c, upper sideband frequency $f_c + f_m$ and lower sideband frequency $f_c - f_m$

Here,

$$f_{max} = f_c + f_m \text{ and } f_{min} = f_c - f_m$$

Substitute, f_{max} and f_{min} values in bandwidth formula.

$$BW = f_c + f_m - (f_c - f_m)$$

$$\Rightarrow BW = 2f_m$$

Thus, it can be said that the bandwidth required for amplitude modulated wave is twice the frequency of the modulating signal.

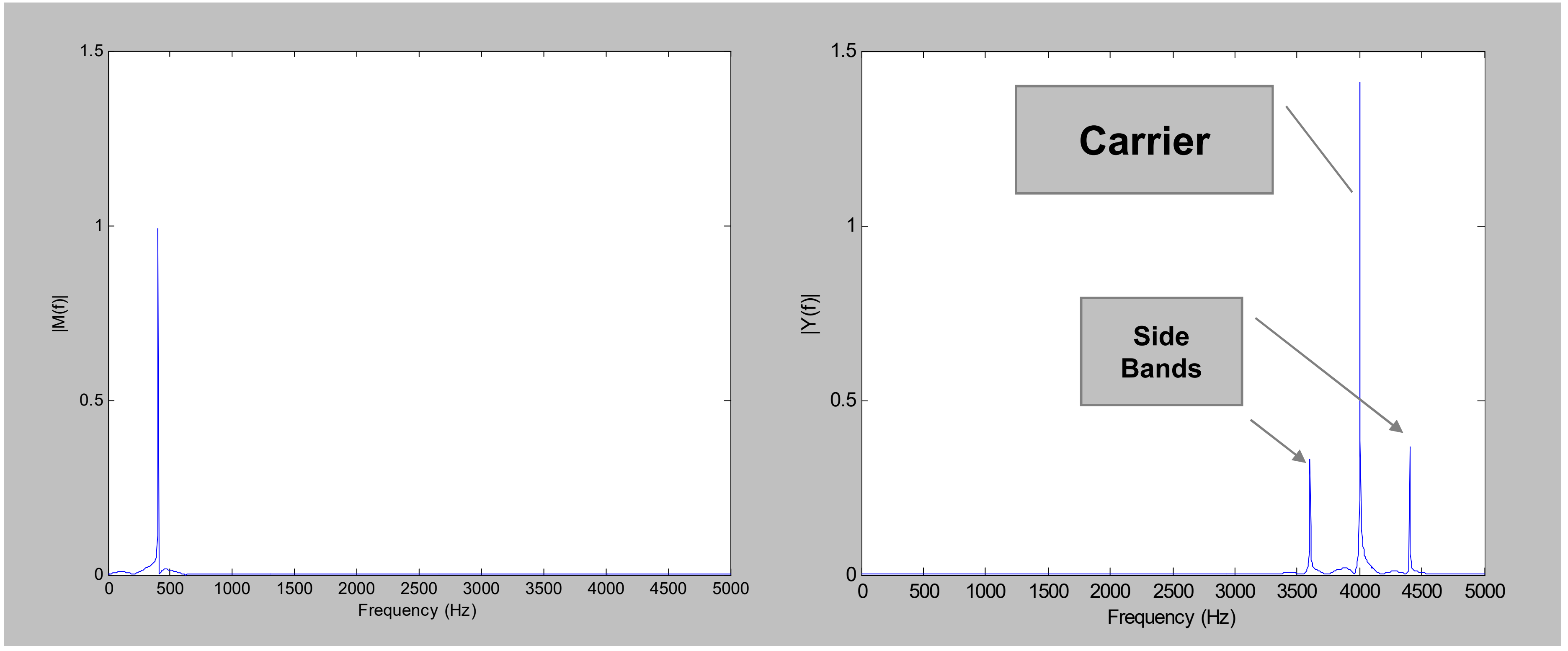
AMPLITUDE SPECTRUM

- Modulation produces two new components called sidebands, at frequencies above and below the carrier

- The spacing in frequency between carrier and sidebands is equal to fm (the modulating frequency)

- Bandwidth requirement : 2 fm

The AM Spectrum



Power Calculations of AM Wave

Consider the following equation of amplitude modulated wave.

$$s(t) = A_c \cos(2\pi f_c t) + \frac{A_c \mu}{2} \cos[2\pi (f_c + f_m) t] + \frac{A_c \mu}{2} \cos [2\pi (f_c - f_m) t]$$

Power of AM wave is equal to the sum of powers of carrier, upper sideband, and lower sideband frequency components.

$$P_t = P_c + P_{USB} + P_{LSB}$$

We know that the standard formula for power of cos signal is

$$P = \frac{{v_{rms}}^2}{R} = \frac{\left(v_m/\sqrt{2}\right)^2}{R}$$

Where,

v_{rms} is the rms value of cos signal.

v_m is the peak value of cos signal.

First, let us find the powers of the carrier, the upper and lower sideband one by one.

Carrier power

$$P_c = \frac{\left(A_c/\sqrt{2}\right)^2}{R} = \frac{{A_c}^2}{2R}$$

Upper sideband power

$$P_{USB} = \frac{\left(A_c \mu/2\sqrt{2}\right)^2}{R} = \frac{{A_c}^2 \mu^2}{8R}$$

Similarly, we will get the lower sideband power same as that of the upper side band power.

$$P_{LSB} = \frac{{A_c}^2 {\mu}^2}{8R}$$

Now, let us add these three powers in order to get the power of AM wave.

$$P_t = \frac{{A_c}^2}{2R} + \frac{{A_c}^2 {\mu}^2}{8R} + \frac{{A_c}^2 {\mu}^2}{8R}$$

$$\Rightarrow P_t = \left(\frac{{A_c}^2}{2R}\right)\left(1 + \frac{\mu^2}{4} + \frac{\mu^2}{4}\right)$$

$$\Rightarrow P_t = P_c \left(1 + \frac{\mu^2}{2}\right)$$

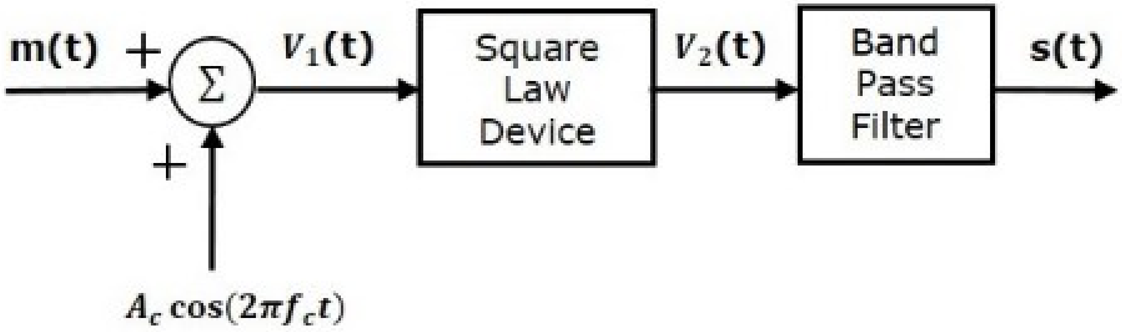
We can use the above formula to calculate the power of AM wave, when the carrier power and the modulation index are known.

If the modulation index $\mu = 1$ then the power of AM wave is equal to 1.5 times the carrier power. So, the power required for transmitting an AM wave is 1.5 times the carrier power for a perfect modulation.

Diode Modulator

Square Law Modulator

Following is the block diagram of the square law modulator



Let the modulating and carrier signals be denoted as $m\,(t)$ and $A\cos(2\pi f_c t)$ respectively. These two signals are applied as inputs to the summer (adder) block. This summer block produces an output, which is the addition of the modulating and the carrier signal. Mathematically, we can write it as

$$V_1 t = m\,(t) + A_c\cos(2\pi f_c t)$$

This signal $V_1 t$ is applied as an input to a nonlinear device like diode. The characteristics of the diode are closely related to square law.

$$V_2 t = k_1 V_1\,(t) + k_2 V_1^2\,(t) \qquad \text{(Equation 1)}$$

Where, k_1 and k_2 are constants.

Substitute $V_1(t)$ in Equation 1

$$V_2(t) = k_1 [m(t) + A_c \cos(2\pi f_c t)] + k_2 [m(t) + A_c \cos(2\pi f_c t)]^2$$

$$\Rightarrow V_2(t) = k_1 m(t) + k_1 A_c \cos(2\pi f_c t) + k_2 m^2(t) +$$

$$k_2 A_c^2 \cos^2(2\pi f_c t) + 2k_2 m(t) A_c \cos(2\pi f_c t)$$

$$\Rightarrow V_2(t) = k_1 m(t) + k_2 m^2(t) + k_2 A_c^2 \cos^2(2\pi f_c t) +$$

$$k_1 A_c \left[1 + \left(\frac{2k_2}{k_1}\right) m(t)\right] \cos(2\pi f_c t)$$

The last term of the above equation represents the desired AM wave and the first three terms of the above equation are unwanted. So, with the help of band pass filter, we can pass only AM wave and eliminate the first three terms.

Therefore, the output of square law modulator is

$$s(t) = k_1 A_c \left[1 + \left(\frac{2k_2}{k_1}\right) m(t)\right] \cos(2\pi f_c t)$$

The standard equation of AM wave is

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

Where, K_a is the amplitude sensitivity

By comparing the output of the square law modulator with the standard equation of AM wave, we will get the scaling factor as k_1 and the amplitude sensitivity k_a as $\frac{2k_2}{k1}$.

Envelop Detector

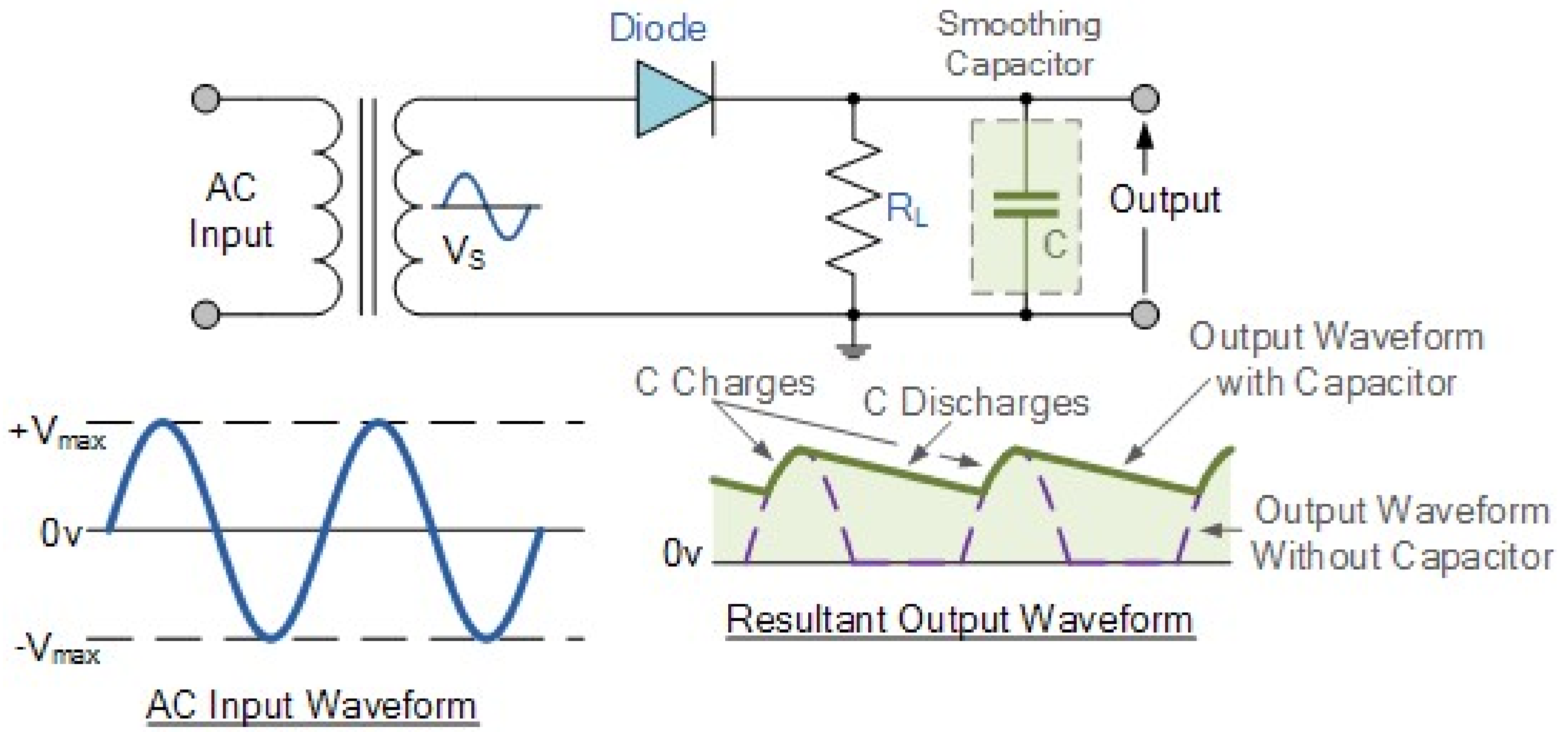
The signal diode detector consists of two main elements to the circuit:

Diode / rectifier: The diode in the detector serves to that enhances one half of the received signal over the other. In many instances Schottky diodes are used for this form of detector, because signal levels may be low, and Schottky diodes have a much lower turn on voltage (typically around 0.2 V) than standard silicon diodes (typically around 0.7 or 0.7 V).

Low pass filter: The low pass filter is required to remove the high frequency elements that remain within the signal after detection / demodulation. The filter usually consists of a very simple RC network but in some cases It can be provided simply by relying on the limited frequency response of the circuitry following the rectifier. As the capacitor in the circuit stores the voltage, the output voltage reflects the peak of the waveform. Sometimes these circuits are used as peak detectors.

When selecting the value of the capacitor used int he circuit, it should be large enough to hold the peak of the RF waveform, but not so large that it attenuates any modulation on the signal, i.e. it should act as a filter for the RF carrier and not the audio modulation.

Envelop Detector



Normally a resistor is placed across the capacitor - this may either be the load of the next stage, a volume control, or resistor in the circuit. This level of this should be determined by calculating the time constant of the capacitor and the load. This should be between the RF signal and audio modulation so that the RF is satisfactorily removed, but the audio modulation is left untouched.

The AM diode envelope detector has been successfully used for many years.

Envelope detector advantages:

Low cost: The diode detector only requires the use of a few low cost components. This made it ideal for use in transistor (and valve / vacuum tube) radios using discrete components.

Simplicity: Using very few components, the Diode AM detector was easy to implement. It was reliable and did not require any setup.

Envelope detector disadvantages:

Distortion: As the diode detector is non-linear it introduces distortion onto the detected audio signal.

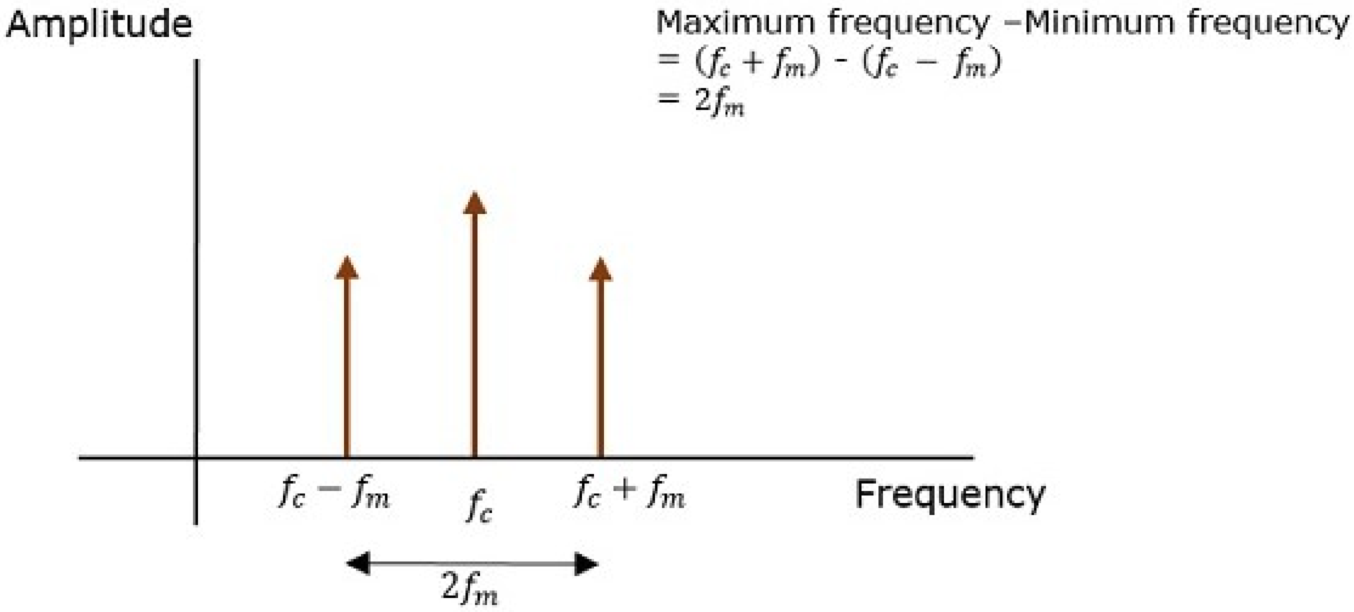
Selective fading: One of the issues often experienced on the short and medium wavebands where the AM transmissions are located is that of selective fading. The diode envelope detector is not able to combat the effects of this in the way that some other detectors are able, and as a result, distortion occurs when selective fading occurs.

Sensitivity: The diode detector is not as sensitive as some other types. If silicon diodes are used, these have a turn on voltage of around 0.6 volts as a result, germanium or Schottky diodes are used which have a lower turn on voltage of around 0.2 to 0.3 volts. Even with the use of the Schottky diode, the diode envelope detector still suffers from a poor level of sensitivity

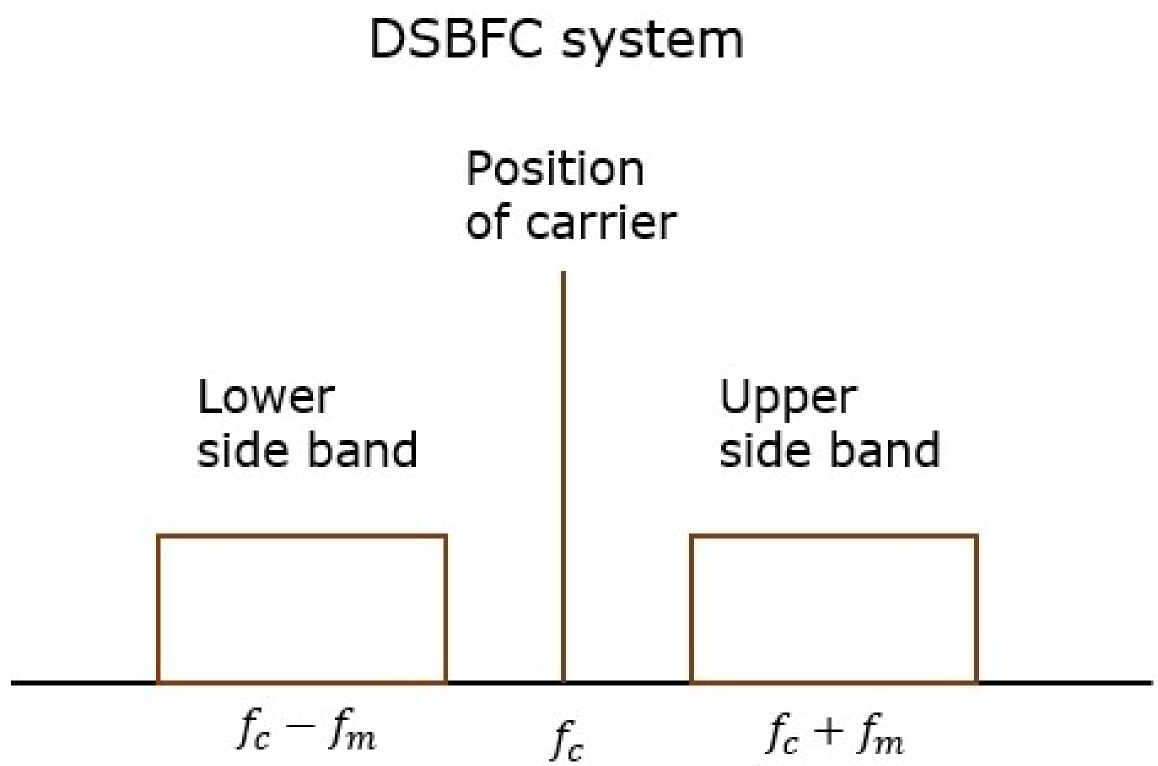
VARIATIONS OF AM

- **Double Sideband with carrier (AM)**: This is the most widely used type of AM modulation. In fact, all radio channels in the AM band use this type of modulation.
- **Double Sideband Suppressed Carrier (DSBSC):** This is the same as the AM modulation above but without the carrier.
- **Single Sideband (SSB):** In this modulation, only half of the signal of the DSBSC is used.
- **Vestigial Sideband (VSB):** This is a modification of the SSB to ease the generation and reception of the signal.

A **Sideband** is a band of frequencies, containing power, which are the lower and higher frequencies of the carrier frequency. Both the sidebands contain the same information. The representation of amplitude modulated wave in the frequency domain is as shown in the following figure.

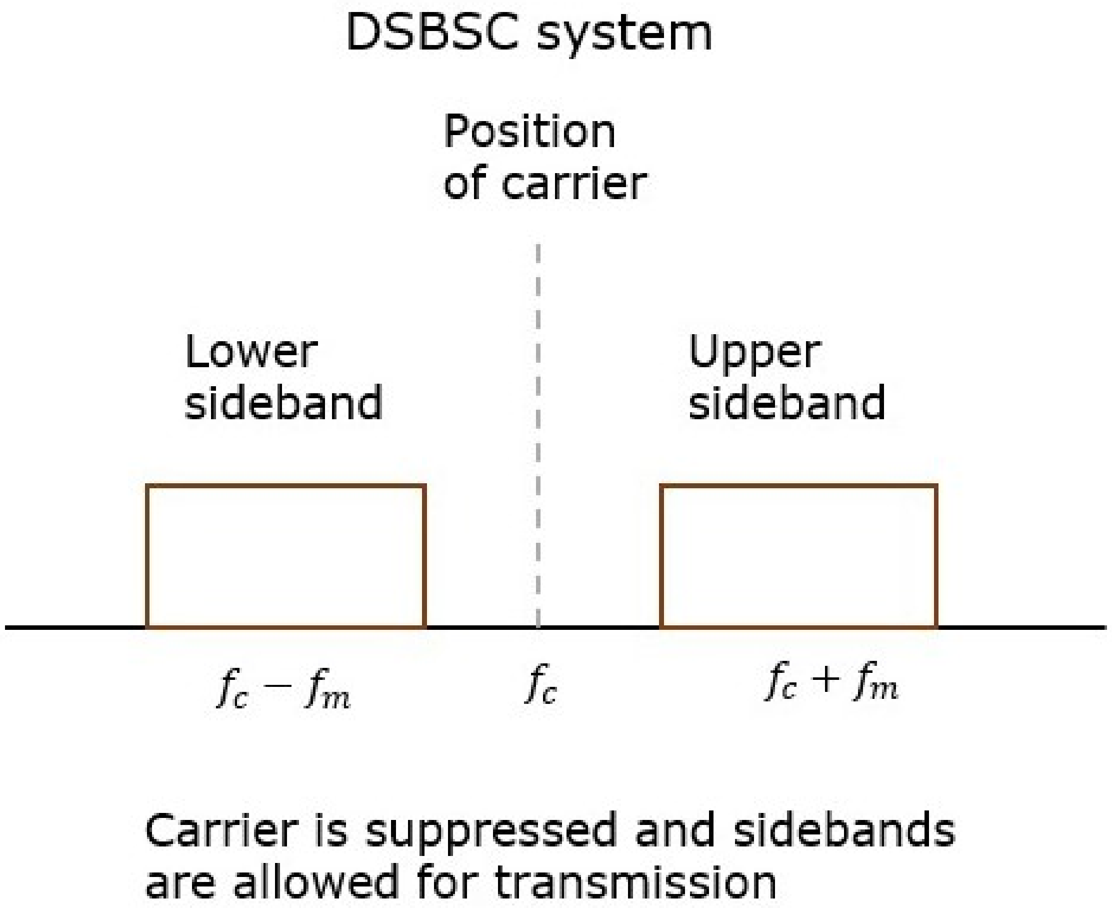


Both the sidebands in the image contain the same information. The transmission of such a signal which contains a carrier along with two sidebands, can be termed as **Double Sideband Full Carrier** system, or simply **DSB-FC**. It is plotted as shown in the following figure.



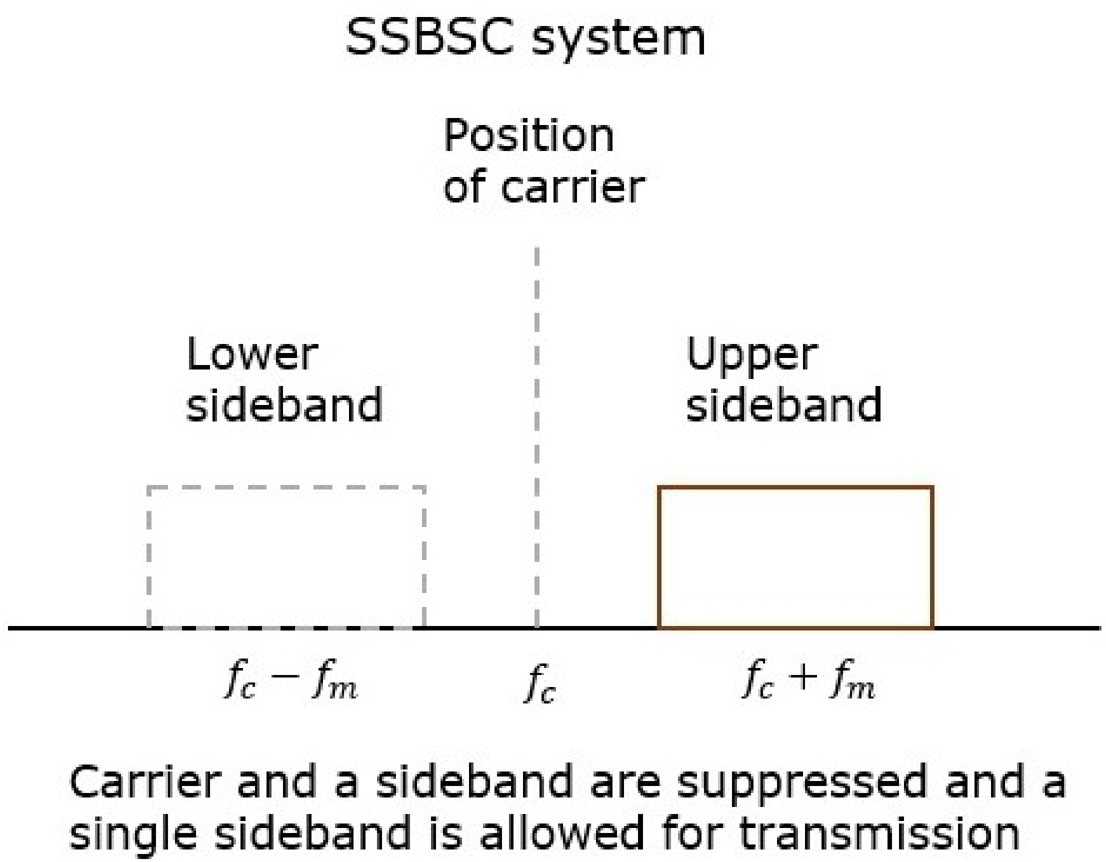
However, such a transmission is inefficient. Two-thirds of the power is being wasted in the carrier, which carries no information.

If this carrier is suppressed and the power saved is distributed to the two sidebands, such a process is called as **Double Sideband Suppressed Carrier** system, or simply **DSBSC**. It is plotted as shown in the following figure.



Now, we get an idea that, as the two sidebands carry the same information twice, why can't we suppress one sideband. Yes, this is possible.

The process of suppressing one of the sidebands, along with the carrier and transmitting a single sideband is called as **Single Sideband Suppressed Carrier** system, or simply **SSB-SC** or **SSB**. It is plotted as shown in the following figure.



This SSB-SC or SSB system, which transmits a single sideband has high power, as the power allotted for both the carrier and the other sideband is utilized in transmitting this **Single Sideband (SSB)**.

Hence, the modulation done using this SSB technique is called as **SSB Modulation**.

Sideband Modulation – Advantages

The advantages of SSB modulation are −

- Bandwidth or spectrum space occupied is lesser than AM and DSB signals.
- Transmission of more number of signals is allowed.
- Power is saved.
- High power signal can be transmitted.
- Less amount of noise is present.
- Signal fading is less likely to occur.

Sideband Modulation – Disadvantages

The disadvantages of SSB modulation are −

- The generation and detection of SSB signal is a complex process.
- Quality of the signal gets affected unless the SSB transmitter and receiver have an excellent frequency stability.

Sideband Modulation − Applications

The applications of SSB modulation are −

- For power saving requirements and low bandwidth requirements.
- In land, air, and maritime mobile communications.
- In point-to-point communications.
- In radio communications.
- In television, telemetry, and radar communications.
- In military communications, such as amateur radio, etc.

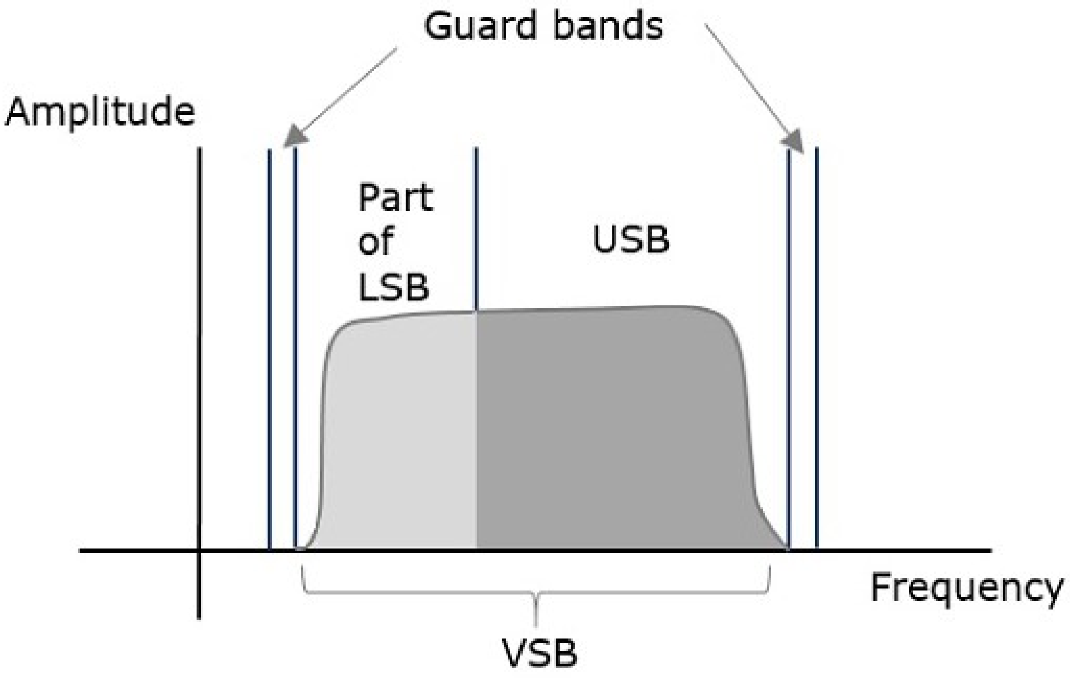
In case of SSB modulation, when a sideband is passed through the filters, the band pass filter may not work perfectly in practice. As a result of which, some of the information may get lost.

Hence to avoid this loss, a technique is chosen, which is a compromise between **DSB-SC** and **SSB**, called as **Vestigial Sideband (VSB)** technique. The word vestige which means “a part” from which the name is derived.

Vestigial Sideband

Both of the sidebands are not required for the transmission, as it is a waste. But a single band if transmitted, leads to loss of information. Hence, this technique has evolved.

Vestigial Sideband Modulation or **VSB Modulation** is the process where a part of the signal called as **vestige** is modulated, along with one sideband. A VSB signal can be plotted as shown in the following figure.



VSB Modulation

Along with the upper sideband, a part of the lower sideband is also being transmitted in this technique. A guard band of very small width is laid on either side of VSB in order to avoid the interferences. VSB modulation is mostly used in television transmissions.

VSB Modulation − Advantages

Following are the advantages of VSB −

- Highly efficient.
- Reduction in bandwidth.
- Filter design is easy as high accuracy is not needed.
- The transmission of low frequency components is possible, without difficulty.
- Possesses good phase characteristics.

VSB Modulation − Disadvantages

Following are the disadvantages of VSB −

- Bandwidth when compared to SSB is greater.
- Demodulation is complex.

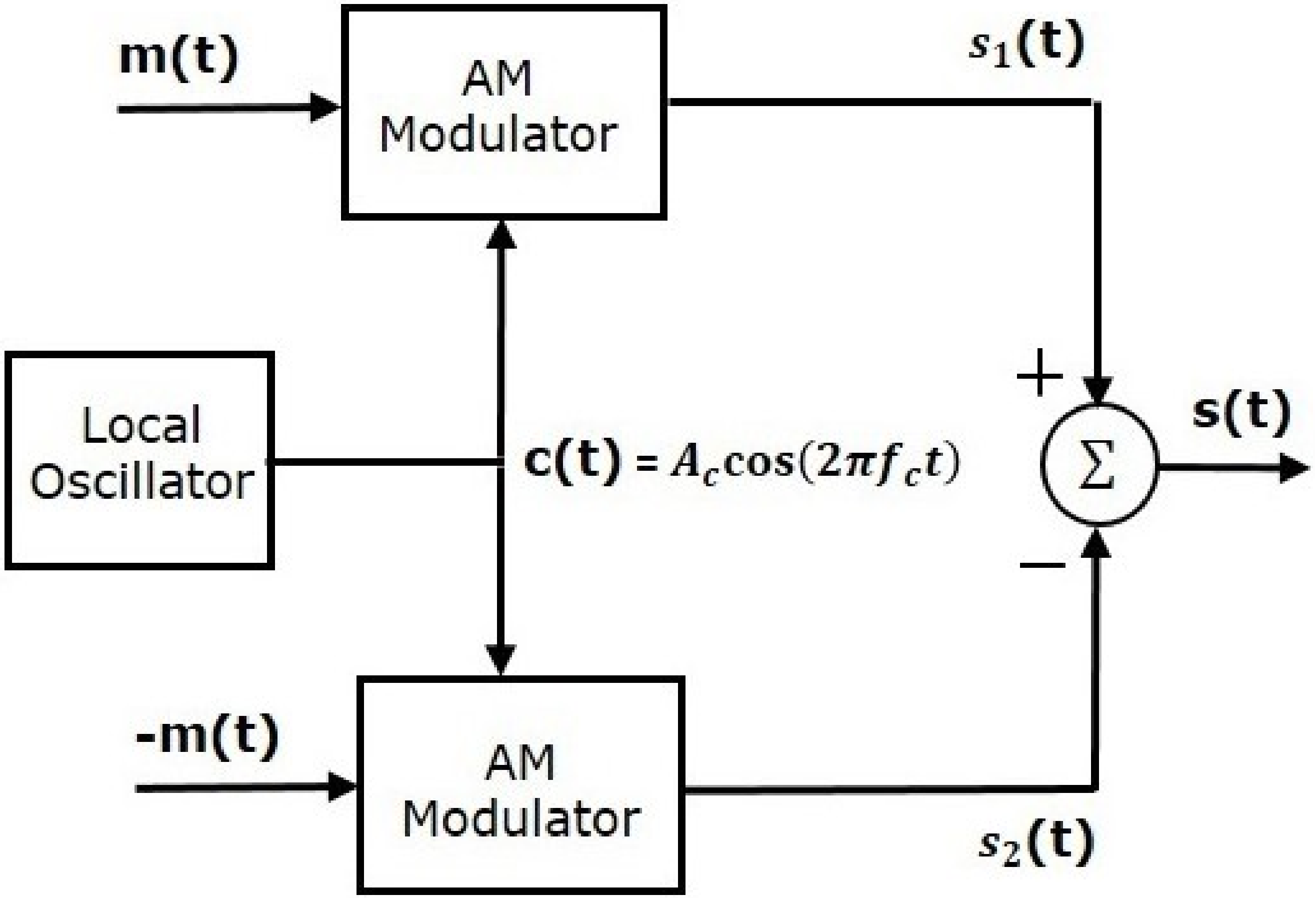
VSB Modulation − Application

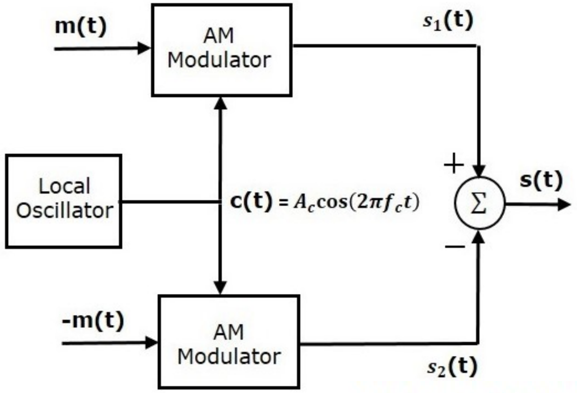
The most prominent and standard application of VSB is for the transmission of **television signals**. Also, this is the most convenient and efficient technique when bandwidth usage is considered.

DSBSC Modulator

Balanced Modulator

Following is the block diagram of the Balanced modulator.





Balanced modulator consists of two identical AM modulators. These two modulators are arranged in a balanced configuration in order to suppress the carrier signal. Hence, it is called as Balanced modulator.

The same carrier signal $c(t) = A_c \cos(2\pi f_c t)$ is applied as one of the inputs to these two AM modulators. The modulating signal $m(t)$ is applied as another input to the upper AM modulator. Whereas, the modulating signal $m(t)$ with opposite polarity, i.e., $-m(t)$ is applied as another input to the lower AM modulator.

Output of the upper AM modulator is

$$s_1(t) = A_c [1 + k_a m(t)] \cos(2\pi f_c t)$$

Output of the lower AM modulator is

$$s_2(t) = A_c [1 - k_a m(t)] \cos(2\pi f_c t)$$

We get the DSBSC wave $s(t)$ by subtracting $s_2(t)$ from $s_1(t)$. The summer block is used to perform this operation. $s_1(t)$ with positive sign and $s_2(t)$ with negative sign are applied as inputs to summer block. Thus, the summer block produces an output $s(t)$ which is the difference of $s_1(t)$ and $s_2(t)$.

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

$$\Rightarrow s(t) = A_c\cos(2\pi f_c t) + A_c k_a m(t)\cos(2\pi f_c t) - A_c\cos(2\pi f_c t) + A_c k_a m(t)\cos(2\pi f_c t)$$

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

We know the standard equation of DSBSC wave is

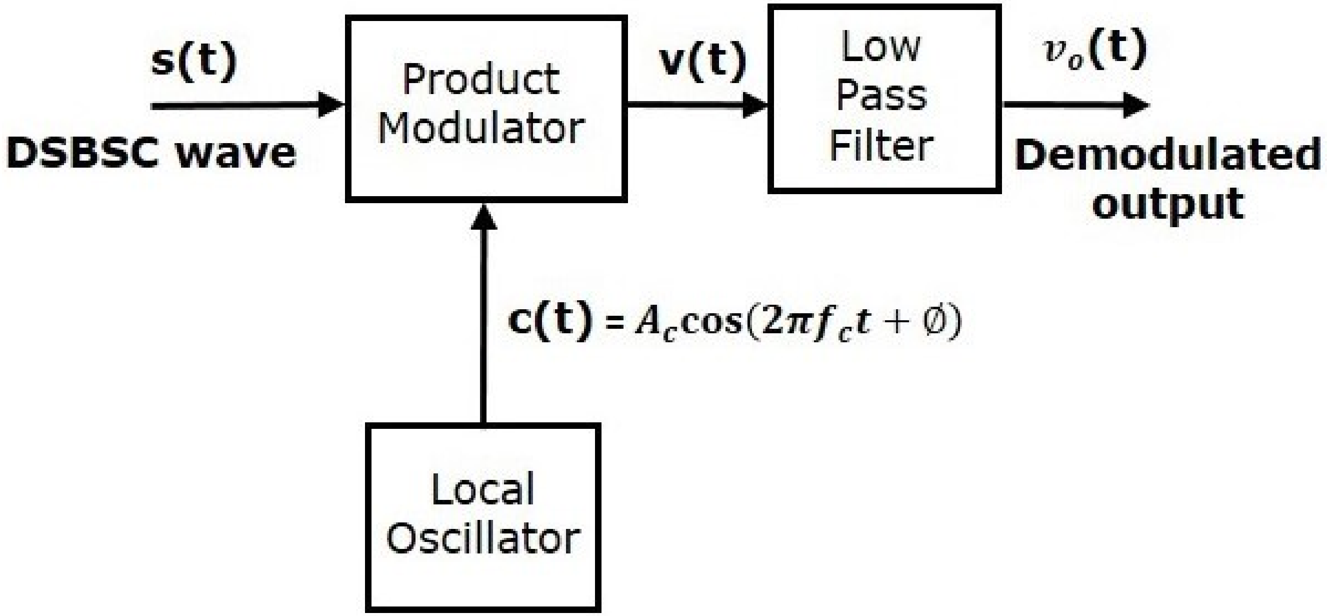
$$s(t) = A_c m(t)\cos(2\pi f_c t)$$

By comparing the output of summer block with the standard equation of DSBSC wave, we will get the scaling factor as $2k_a$

DSBSC Demodulator

Coherent Detector

Here, the same carrier signal (which is used for generating DSBSC signal) is used to detect the message signal. Hence, this process of detection is called as **coherent** or **synchronous detection**. Following is the block diagram of the coherent detector.



In this process, the message signal can be extracted from DSBSC wave by multiplying it with a carrier, having the same frequency and the phase of the carrier used in DSBSC modulation. The resulting signal is then passed through a Low Pass Filter. Output of this filter is the desired message signal.

Let the DSBSC wave be

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

The output of the local oscillator is

$$c(t) = A_c \cos(2\pi f_c t + \phi)$$

Where, ϕ is the phase difference between the local oscillator signal and the carrier signal,

which is used for DSBSC modulation.

From the figure, we can write the output of product modulator as

$$v(t) = s(t)\, c(t)$$

Substitute, $s(t)$ and $c(t)$ values in the above equation.

$$\Rightarrow v(t) = A_c \cos(2\pi f_c t) m(t)\, A_c \cos(2\pi f_c t + \phi)$$

$$= A_c^{\,2} \cos(2\pi f_c t) \cos(2\pi f_c t + \phi) m(t)$$

$$= \frac{{A_c}^2}{2}\left[\cos(4\pi f_c t + \phi) + \cos\phi\right] m(t)$$

$$v(t) = \frac{{A_c}^2}{2}\cos\phi m(t) + \frac{{A_c}^2}{2}\cos(4\pi f_c t + \phi) m(t)$$

In the above equation, the first term is the scaled version of the message signal. It can be extracted by passing the above signal through a low pass filter.

Therefore, the output of low pass filter is

$$v_0 t = \frac{{A_c}^2}{2}\cos\phi m(t)$$

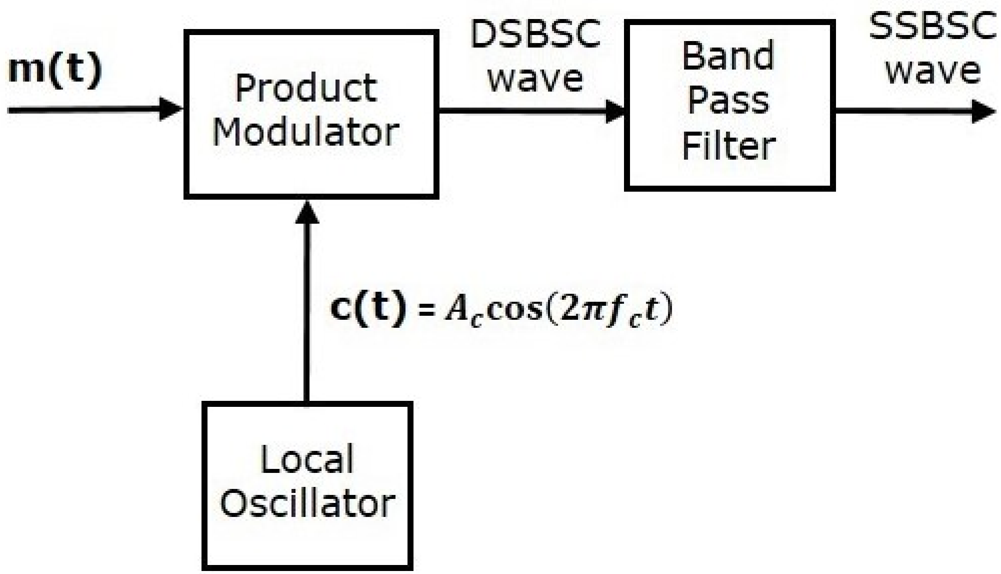
The demodulated signal amplitude will be maximum, when $\phi = 0^0$. That's why the local oscillator signal and the carrier signal should be in phase, i.e., there should not be any phase difference between these two signals.

The demodulated signal amplitude will be zero, when $\phi = \pm 90^0$.

SSBSC Modulator

Frequency Discrimination Method

The following figure shows the block diagram of SSBSC modulator using frequency discrimination method.



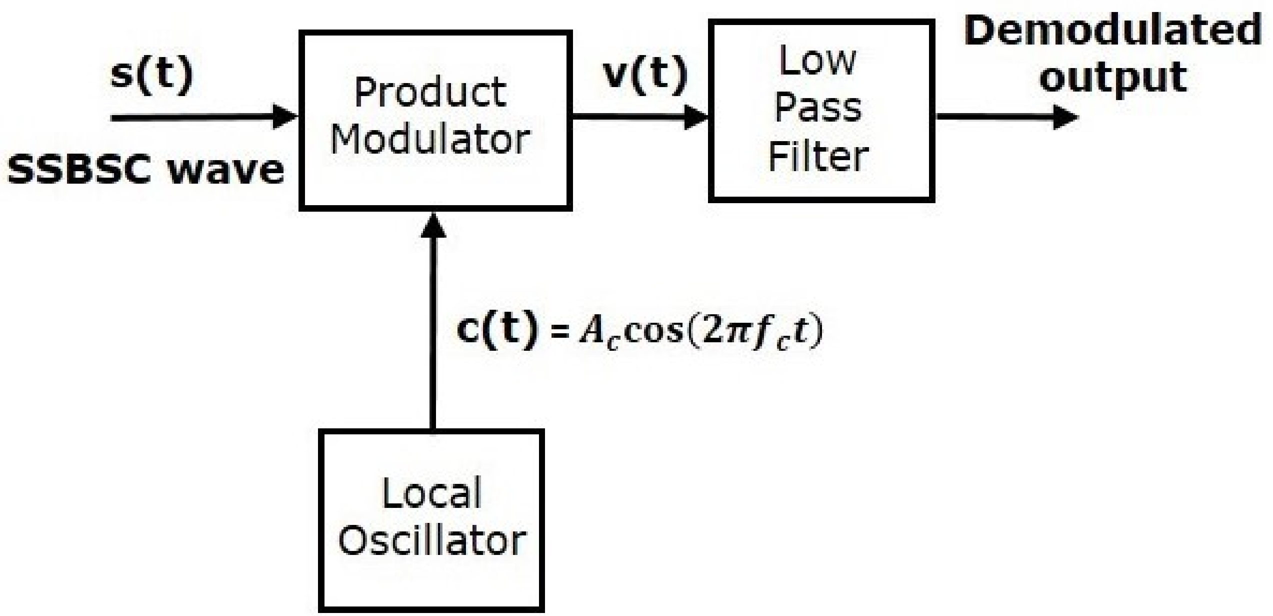
In this method, first we will generate DSBSC wave with the help of the product modulator. Then, apply this DSBSC wave as an input of band pass filter. This band pass filter produces an output, which is SSBSC wave.

Select the frequency range of band pass filter as the spectrum of the desired SSBSC wave. This means the band pass filter can be tuned to either upper sideband or lower sideband frequencies to get the respective SSBSC wave having upper sideband or lower sideband.

SSBSC Demodulator

Coherent Detector

Here, the same carrier signal (which is used for generating SSBSC wave) is used to detect the message signal. Hence, this process of detection is called as **coherent** or **synchronous detection**. Following is the block diagram of coherent detector.



In this process, the message signal can be extracted from SSBSC wave by multiplying it with a carrier, having the same frequency and the phase of the carrier used in SSBSC modulation. The resulting signal is then passed through a Low Pass Filter. The output of this filter is the desired message signal.

Consider the following **SSBSC** wave having a **lower sideband**.

$$s(t) = \frac{A_m A_c}{2} \cos[2\pi (f_c - f_m) t]$$

The output of the local oscillator is

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

From the figure, we can write the output of product modulator as

$$v(t) = s(t) c(t)$$

Substitute $s(t)$ and $c(t)$ values in the above equation.

$$v(t) = \frac{A_m A_c}{2} \cos[2\pi (f_c - f_m) t] A_c \cos(2\pi f_c t)$$

$$= \frac{A_m A_c^2}{2} \cos[2\pi (f_c - f_m) t] \cos(2\pi f_c t)$$

$$= \frac{A_m A_c^2}{4} \{\cos[2\pi (2f_c - fm)] + \cos(2\pi f_m) t\}$$

$$v(t) = \frac{A_m {A_c}^2}{4} \cos(2\pi f_m t) + \frac{A_m {A_c}^2}{4} \cos[2\pi (2f_c - f_m) t]$$

In the above equation, the first term is the scaled version of the message signal. It can be extracted by passing the above signal through a low pass filter.

Therefore, the output of low pass filter is

$$v_0 (t) = \frac{A_m {A_c}^2}{4} \cos(2\pi f_m t)$$

Here, the scaling factor is $\frac{{A_c}^2}{4}$.

We can use the same block diagram for demodulating SSBSC wave having an upper sideband. Consider the following **SSBSC** wave having an **upper sideband**.

$$s(t) = \frac{A_m A_c}{2} \cos[2\pi (f_c + f_m) t]$$

The output of the local oscillator is

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

We can write the output of the product modulator as

$$v(t) = s(t)\,c(t)$$

Substitute $s(t)$ and $c(t)$ values in the above equation.

$$\Rightarrow v(t) = \frac{A_m A_c}{2}\cos[2\pi(f_c + f_m)t]A_c\cos(2\pi f_c t)$$

$$= \frac{A_m A_c^{\,2}}{2}\cos[2\pi(f_c + f_m)t]\cos(2\pi f_c t)$$

$$= \frac{A_m A_c^{\,2}}{4}\{\cos[2\pi(2f_c + f_m)t] + \cos(2\pi f_m t)\}$$

$$v(t) = \frac{A_m A_c^{\,2}}{4}\cos(2\pi f_m t) + \frac{A_m A_c^{\,2}}{4}\cos[2\pi(2f_c + f_m)t]$$

In the above equation, the first term is the scaled version of the message signal. It can be extracted by passing the above signal through a low pass filter.

Therefore, the output of the low pass filter is

$$v_0(t) = \frac{A_m A_c^{\,2}}{4}\cos(2\pi f_m t)$$

Here too the scaling factor is $\frac{A_c^2}{4}$.

Therefore, we get the same demodulated output in both the cases by using coherent detector.