CDL Presents Wireless Communications

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Joe Wilkes, PhD
WA2SFF

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Joe's Background

- Electrical Engineer
  - Studied Wireless Communications in Grad School
  - Thesis Topic: Mitigating the effects of multipath fading on FM radio signals
- Co-author of three books on Wireless Communications
- Life Fellow of IEEE
- Amateur Radio Operator since 1961
  - Extra Class - WA2SFF

Weekly Classes

- Week 1, Jan 5, 2026, 7:30-9:30 PM
  - Radio Waves, Early Radio Equipment, and Techniques
- Week 2, Jan 12, 2026,7:30-9:30 PM
  - Radio Transmitter and Receivers
- Week 3, Jan 19, 2026,7:30-9:30 PM
  - Digital Modulation, Coding & Access
- Week 4, Jan 26, 2026,7:30-9:30 PM
  - Modern Wireless Systems

Class 1

Radio Waves, Early Radio Equipment, and Techniques

January 2026

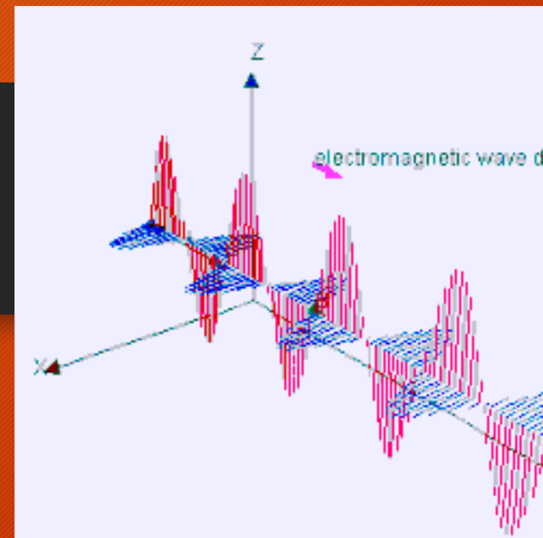
Electromagnetic Waves

- Scientists in the 1800s discovered the following phenomena
- Moving a magnet near a wire causes current to flow in the wire
- Passing a current through a wire causes a magnetic field to be created
- These two phenomena are related
- James Clerk Maxwell codified this in a set of equations now known as Maxwell's Equations
- Hertz demonstrated this by creating a spark and seeing a corresponding spark at another set of wires

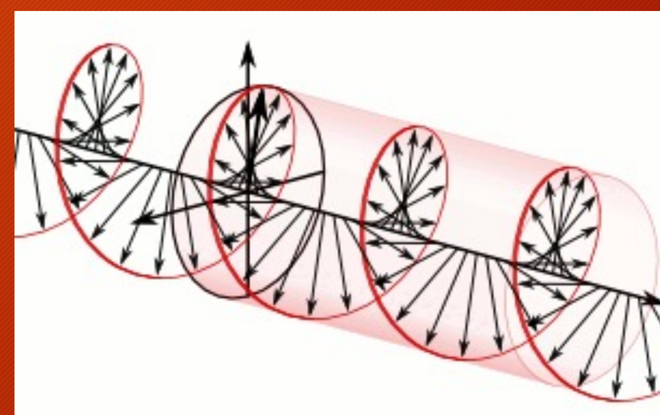
Maxwell’s Equations

- Maxwell defined an Electric Field (E) and a Magnetic Field (B)
- He also defined a set of equations that mathematically explained the interaction between the Electric Field and Magnetic Field
- The equations use Advanced Calculus and Partial Differential Equations
- The details can be found at https://en.wikipedia.org/wiki/Maxwell%27s_equations
- The equations show that light is also Electromagnetic Waves

Electromagnetic Waves



- The Electric Field and Magnetic Field are at right angles to each other
- Their Strength increases and decreases in the shape of the sine function
- The rate is measured in cycles per second (cps) now called Hertz to honor their discoverer
- Waves on the earth are polarized as horizontal or vertical
- A set of horizontal and vertical wave are called circular polarization

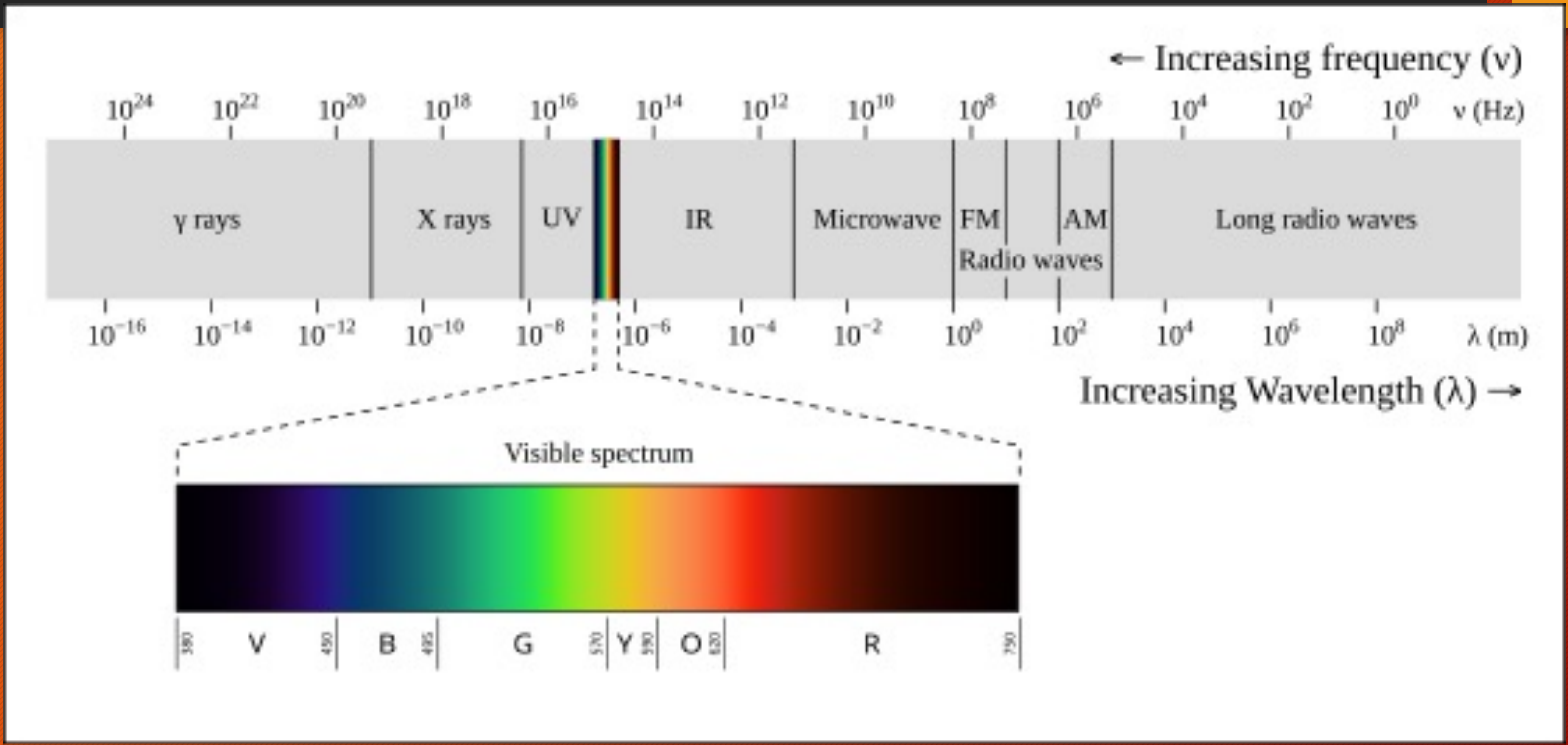


https://en.wikipedia.org/wiki/Electromagnetic_radiation

The Ether

- Because sound waves needed a medium to propagate
  - Air or water or something else
- Scientists of the 1800s could not understand how electromagnetic waves propagated.
- It appeared to be magic which is not scientific
- So they invented the ether
- It was only when Michelson and Morley preformed an experiment, in 1887, that showed the speed of light did not depend on the speed of the earth around the Sun that Scientists abandoned the ether as a concept
- So we now call these effects “forces” and describe them as action at a distance, but still do not know what they are

Electromagnetic Spectrum (Overview)



Definition of Radio Frequency Bands

- 30 Kilohertz (kHz) – 300 kHz
- 300 kHz – 3 Megahertz (MHz)
- 3 -30 MHz
- 30-300 MHz
- 300-3,000 MHz
- 3,000-30,000 MHz

- Very Low Frequencies (VLF)
- Low Frequencies (LF)
- High Frequencies (HF)
- Very High Frequencies (VHF)
- Ultra High Frequencies (UHF)
- Super High Frequencies (SHF)

Wireless Frequency Bands

- ISM Bands: 900 MHz, 2.4 GHz, 5 GHz
- Cellular: 600, 700, 800, 1800 MHz, 3.5, 6, 28, 38 GHz
- Higher frequency → more bandwidth but more path loss
- Ultra Wide Band Cellular has range of a few hundred meters

First Radio Communications

- Early transmitters use high voltages that created arcs of electricity
  - Called “Spark Gap” transmitters
- The frequency was not tuned and transmitters interfered with each other
- Later high power Alternating Current (AC) generators were used and different frequencies could be used
  - The signal sounded like a buzz saw
- Tuning was often done by the length of the antenna

First Receivers

- Before vacuum tubes were invented the receiver was very simple
- A tube was filled with iron filings
- The signal from the antenna was passed through the tube
- When a radio frequency signal is applied to the device, the metal particles would cling together or "cohere", reducing the initial high resistance of the device, thereby allowing a much greater direct current to flow through it.
- In a receiver, the current would activate a bell, or a Morse paper tape recorder to make a record of the received signal.
- The metal filings in the coherer remained conductive after the signal (pulse) ended so that the coherer had to be "decohered" by tapping it with a clapper actuated by an electromagnet, each time a signal was received, thereby restoring the coherer to its original state.

https://en.wikipedia.org/wiki/Coherer

Next generation of Radio using Vacuum Tubes

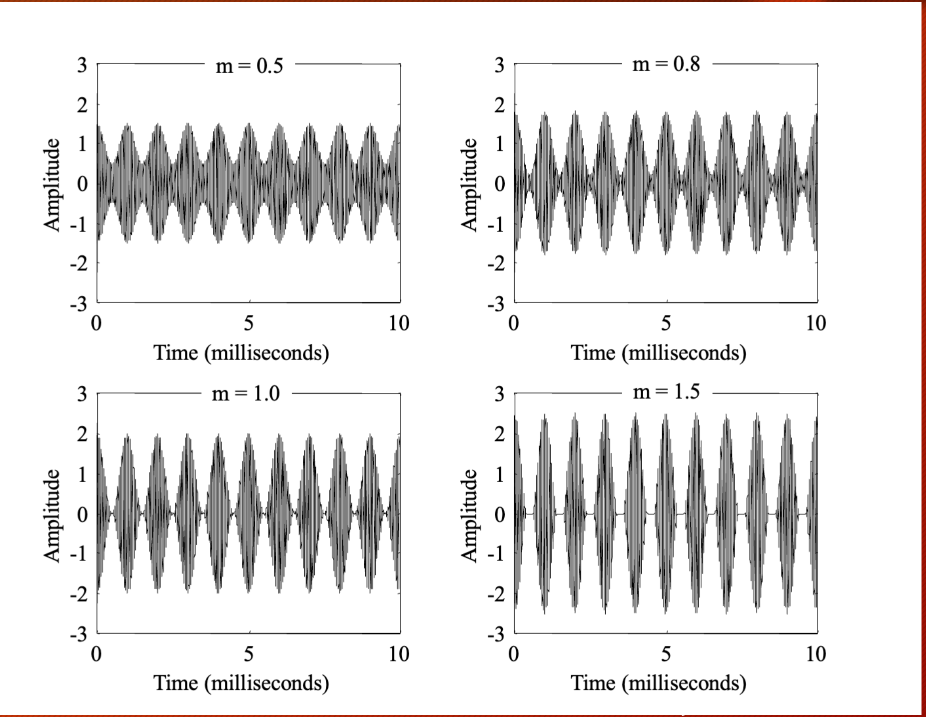
- When vacuum tubes were invented, radio signals improved
- Both Transmitters and receivers could be tuned a particular frequency
- The Morse code signals were called continuous waves (CW)
- Transmission of Speech was still not possible

Modulation Basics (AM/FM/PM)

- To send speech we need to change the characteristic of the CW signal in lock step with the amplitude and frequencies of the speech
- Sending of speech was called modulation of the signal
- Three systems were used to send speech
- Amplitude Modulation (AM)
  - The Amplitude of the signal changes with the speech
- Frequency Modulation (FM)
  - The Frequency of the signal changes with the speech
- Phase Modulation (PM)
  - The Phase of the signal changes with the speech

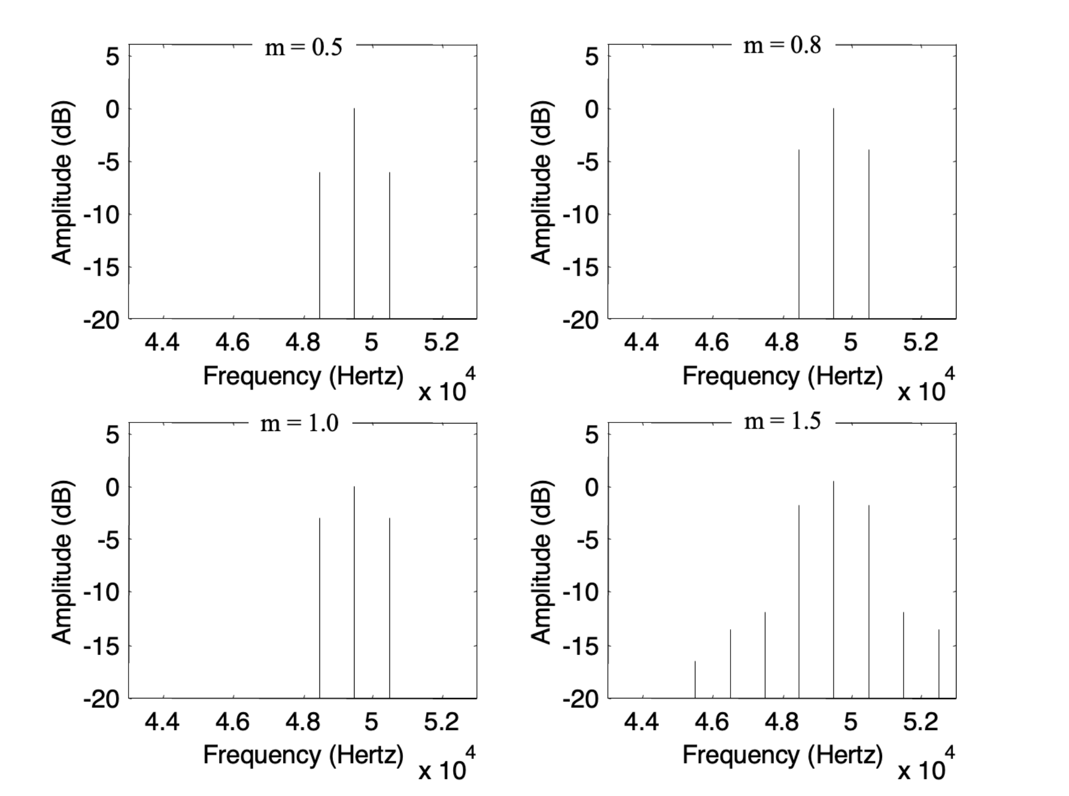
Amplitude Modulation (Time domain)

- How strong the speech is compared to the radio signal is called the index of modulation
- It varies from 0 to 1.0
- If it is higher than 1.0 distortion of the signal occurs
- $s(t) = (1 + m(t) \cos(\omega t))$
- $|m(t)| \leq 1.0$
- $2\pi\omega t$ is the carrier frequency



Amplitude Modulation (Frequency Domain)

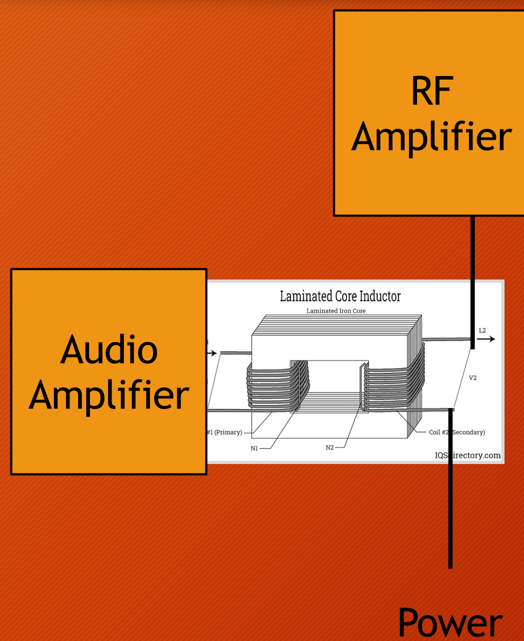
- In the frequency domain, the center frequency is called the "carrier"
- Two identical "side bands" contain the speech signal
- As the modulation index increases, the carrier signal remains the same but the side bands get stronger



How to Make an AM Signal

- We use a class C amplifier
- We add a transformer in series with the plate (or collector) power
- We build an audio Amplifier
- The output of the audio amplifier is connected to a second winding on the transformer
- As the audio amplifier changes level, it changes the power into to Class C amplifier resulting in the output power changing with the audio level

Block Diagram of AM Modulator

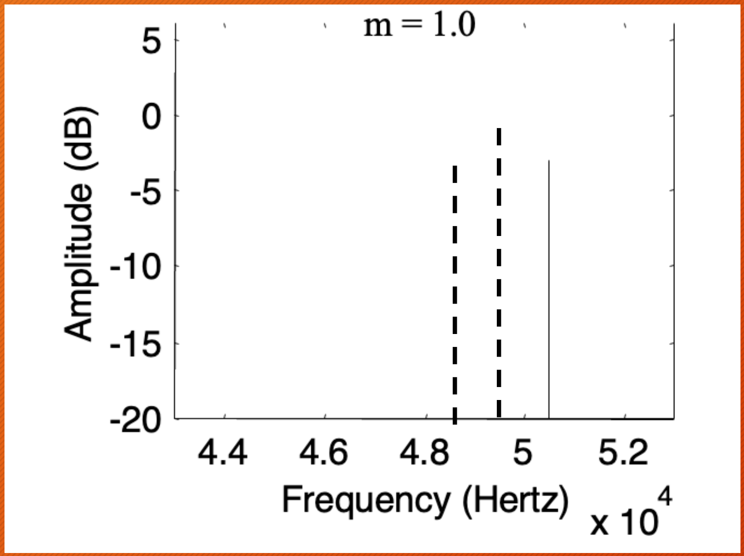


Single Side Band (SSB)

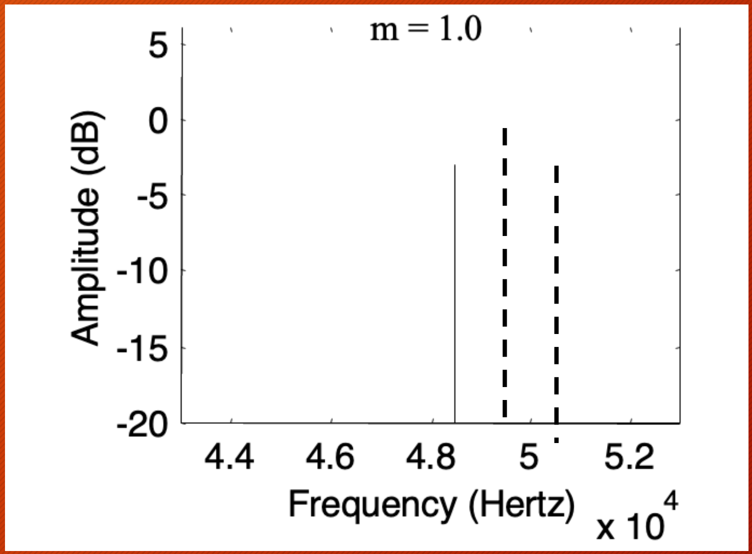
- Sometime during the 40s, engineers realized that AM was inefficient
- The carrier took up most of the power of the transmitter
- The two side bands were redundant
- If we just transmitted the one side band then all the power could be used for that side band and the system was more efficient
- It also took up less spectrum so more signals could be put in the same amount of spectrum
- It was first used for telephony systems then later used over radio
- There is another system rarely in use called Double Sideband (DSB) where both side bands are transmitted but not the carrier

SSB (Frequency Domain)

Upper Side Band



Lower Side Band

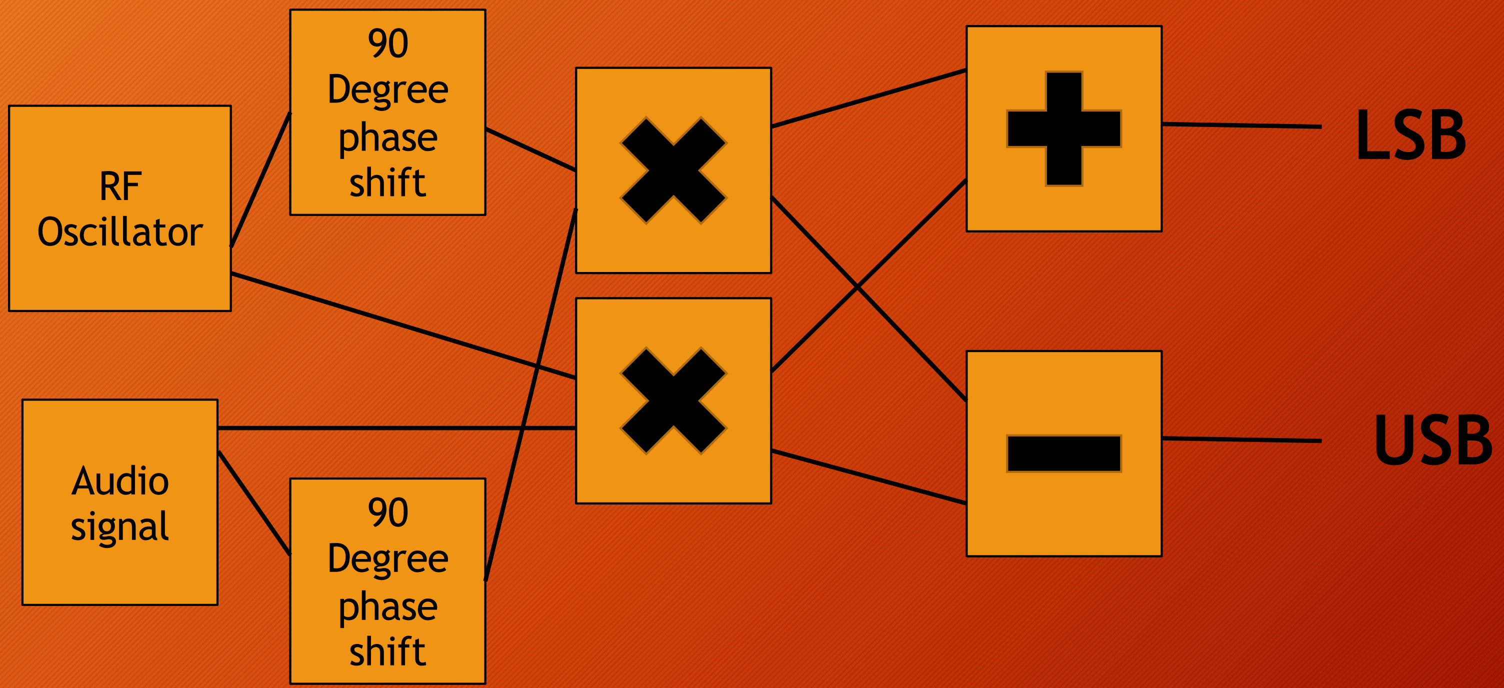


Dotted lines indicate carrier and other side band not transmitted

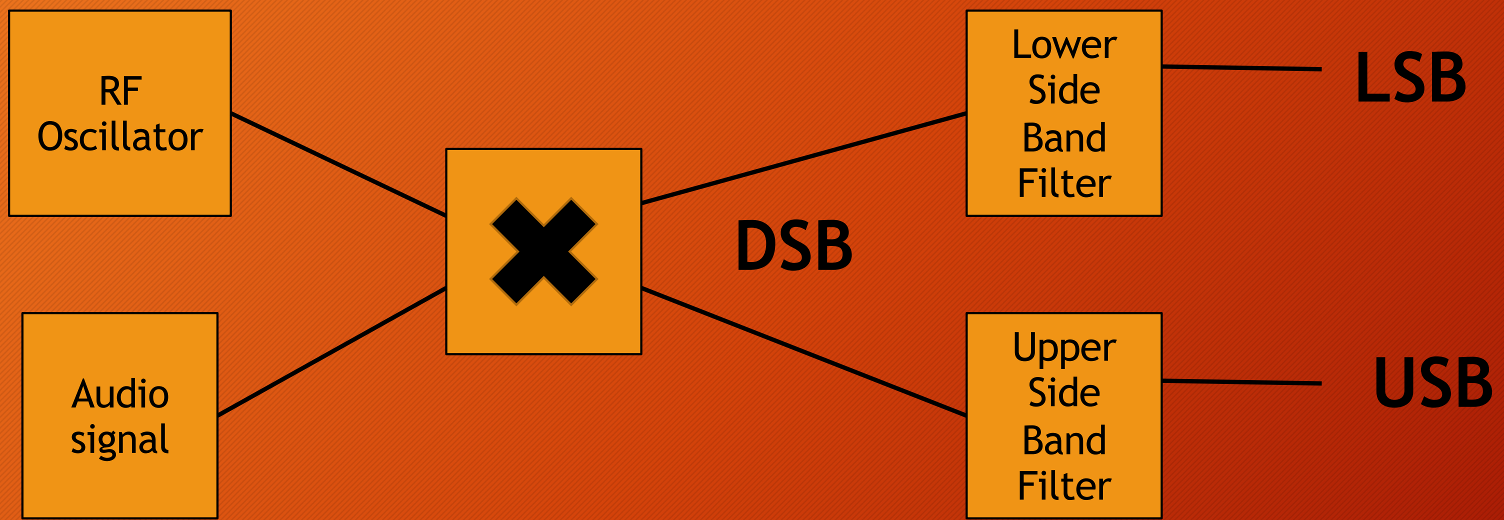
How to Modulation a SSB Signal

- There are two approaches to forming an SSB signal
- 1 - Create a Double Side Band (DSB) signal and filter out the unwanted Side Band
- 2 – Create
  - two RF signals 90 degrees out of phase, and
  - two Audio signals 90 degrees out of phase
  - Combine them using the trigonometric Identity
  - Cos A x Cos B - Sin A x Sin B = Cos (A+B) - Upper Side Band (USB)
  - Cos A x Cos B + Sin A x Sin B = Cos (A-B) – Lower Side Band (LSB)

Block Diagram of SSB Modulator (Phasing Type)

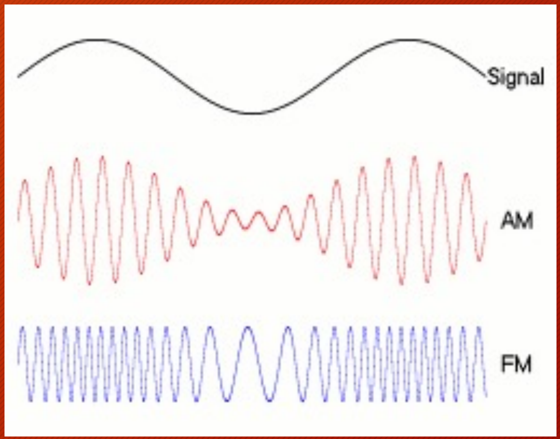


Block Diagram of SSB Modulator (Filter Type)



Frequency Modulation

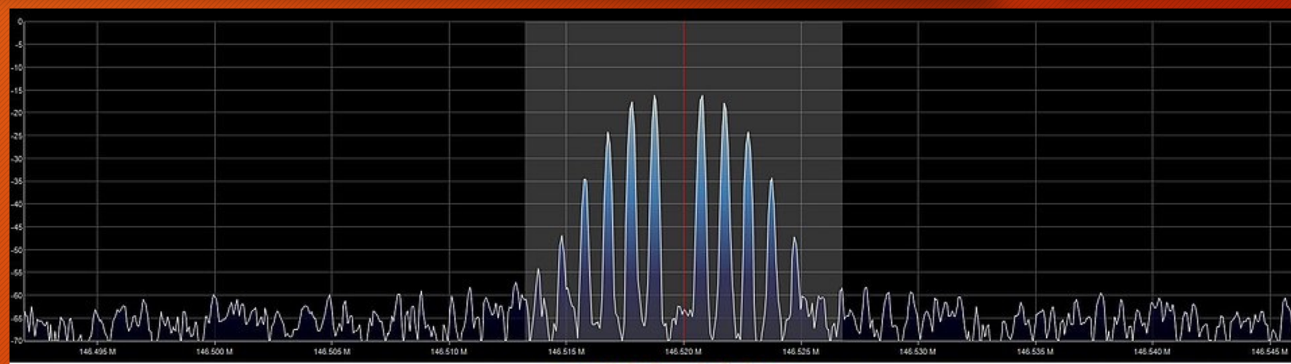
- In FM, the speech varies that frequency of the signal
- The modulation index is called Beta (β) = change in frequency/modulation frequency = $\Delta f / f_m$
- Fm has an infinite number of sidebands; but a some distance from the center it is close to zero
- The bandwidth of a FM signal is approximated by Carson's Rule - BW = $2(\Delta f + f_m)$
- The main advantage of FM is the improvement in signal to noise ratio in the receiver
- The wider the bandwidth lowers the noise in the receiver
- Early deep space systems used FM



https://en.wikipedia.org/wiki/Frequency_modulation

FM (Frequency Domain)

- FM has infinite side bands
- A some frequency away from the center, the strength of the sideband can be considered to be zero
- The strength of each side band is determined by the modulation index
- Engineers has determined an equation for the strength using a set of Bessel Functions
- $A_n = J_n(\beta)$
- For most applications, Carson's rule works



Frequency spectrum of a 146.52 MHz carrier, frequency modulated by a 1,000 Hz sinusoid.

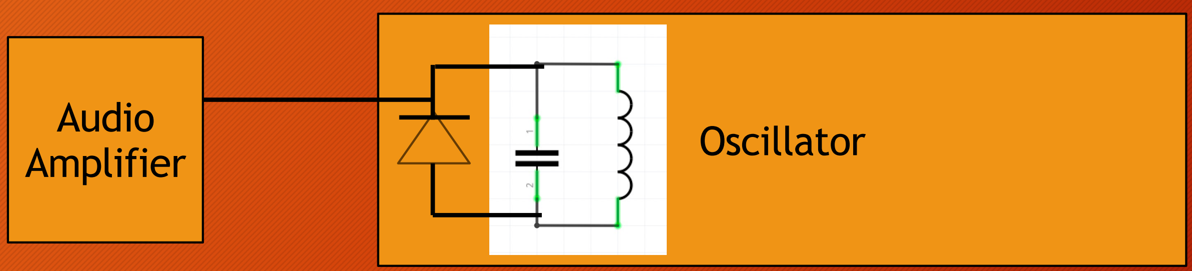
The modulation index, (β), has been adjusted to around 2.4

https://en.wikipedia.org/wiki/File:Waterfall_FM.jpg

https://en.wikipedia.org/wiki/Bessel_function

Frequency Modulation

- We create FM by varying the frequency of an oscillator proportional to the audio level
- Typically, we use a Varactor Diode across a tuned circuit
- The Diode changes its capacitance with changes in voltage across it



Phase Modulation

- Phase Modulation is a variation of frequency modulation
- The phase of the signal is varied with the speech
- We make a phase modulator by processing the audio signal and applying it to a frequency modulator
- FM and PM are very similar

Typical Bandwidth of Signals

- Spark Gap Transmitter
- Morse Code
- Broadcast Band AM
- Ham Radio AM
- Single Side Band (SSB)
- Ham Radio FM
- Analog TV (US)
- Original Cell Phone (FM)
- 2G Cell Phone
- 3G, 4G, 5G Cell Phone
- 5G Ultra Wide Band (UWB)

- Estimate 200 kHz
- 100-300 Hertz
- 10 kHz
- 4.8 kHz or Higher
- 2.4 kHz
- 15 kHz
- 6 MHz
- 30 kHz
- 30 kHz, 200 kHz, 1.25 MHz
- 5, 10, 15, 20, 30 MHz
- 850 MHz, 3 GHz

Questions?

References

- Recommended Textbooks
- ARRL: *The ARRL Handbook for Radio Communications*
- Make: *Radio*

- *Old but still good reference:*
- Rappaport, *Wireless Communications: Principles and Practice*
- Goldsmith, *Wireless Communications*
- Molisch, *Wireless Communications*
- Garg and Wilkes, *Wireless and Personal Communications Systems*

- Useful Online Resources
- FCC Spectrum Allocation Charts
- 3GPP Specifications (for LTE/5G)
- IEEE 802.11 Standards overview
- ITU Radio Regulations
- Simulation Tools
- MATLAB/Simulink Wireless Toolbox
- Python libraries: scipy, matplotlib, commpy
- Free online spectrum analyzers & demos