ECE 2C, notes set 11: Mixing, Modulation, Demodulation and Radio

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Goals of this note set

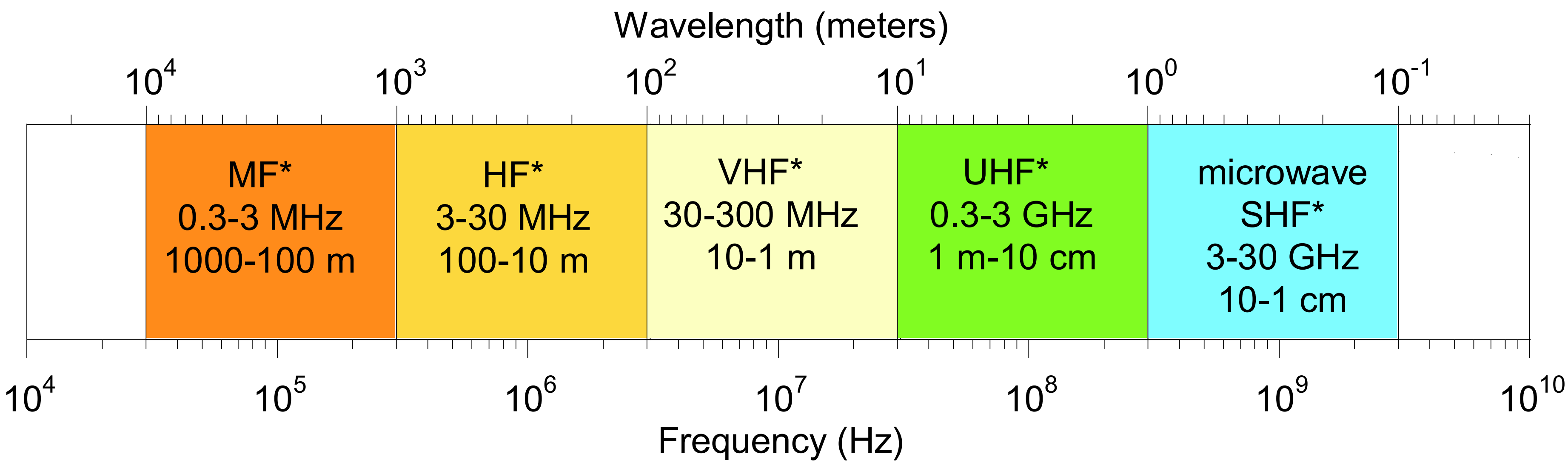
Mixing

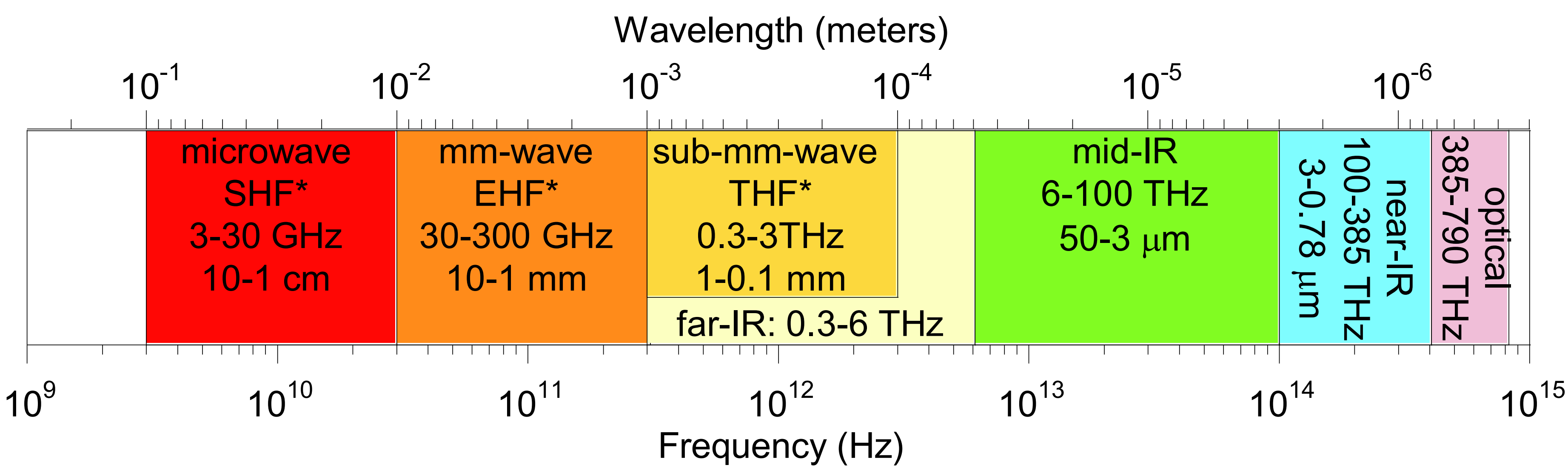
Modulation (AM)

Basic Structure of Radio Transmitter / Receiver

Rough concept of information bandwidth

The Radio Spectrum

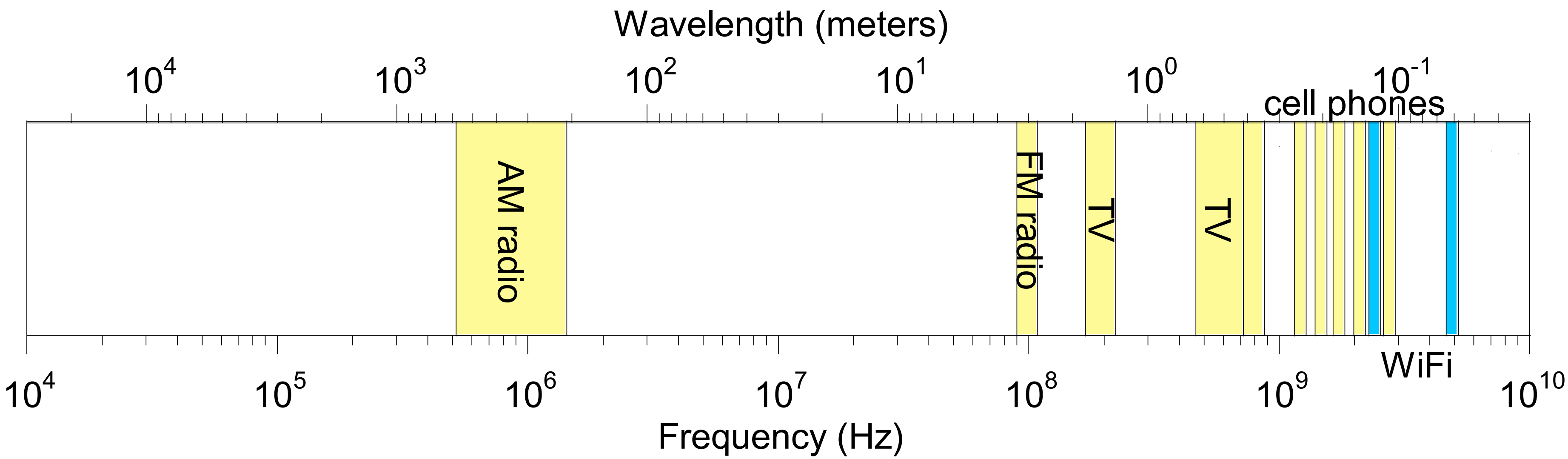


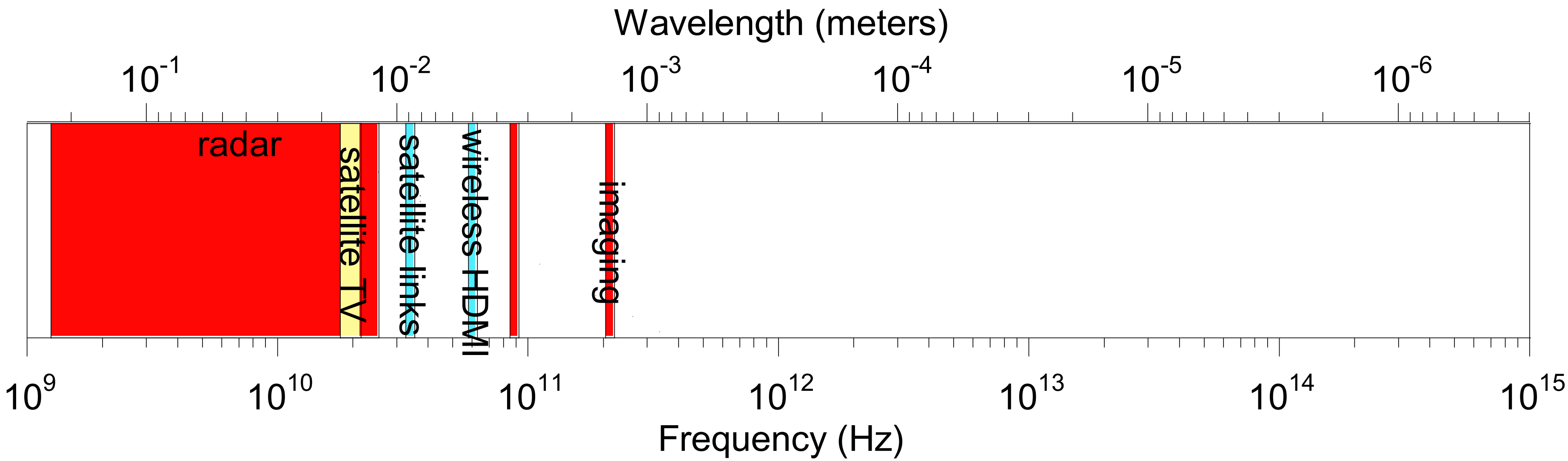


*ITU band designations

** IR bands as per ISO 20473

Frequencies of a Few Services (Rough #s)





Choice of Transmission Frequency

Government frequency allocation.

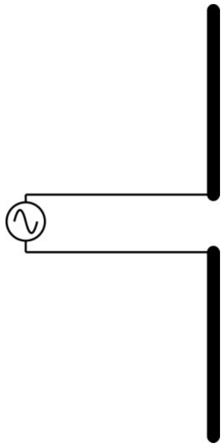
Atmospheric attenuation : good weather and bad.

Required antenna size.

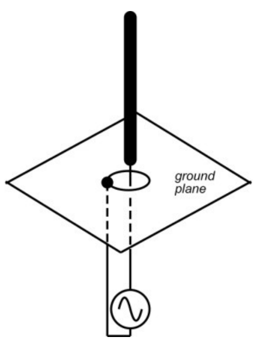
Ease of blocking beam.

Curvature of the earth

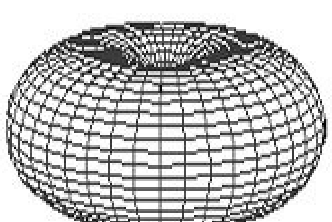
Nearly Isotropic Antennas



Dipole antenna : radiates effectively when lenght is $\sim \lambda/2$



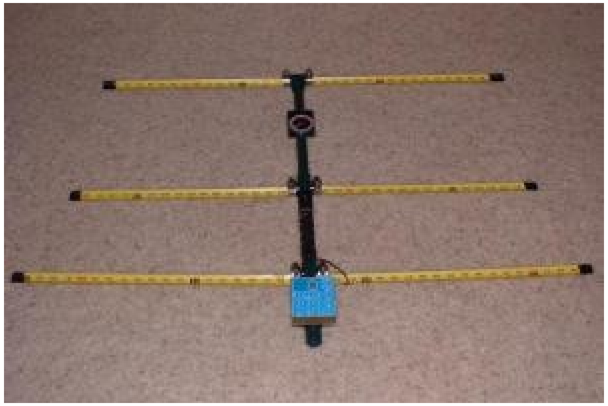
Antenna can be reduced 2:1 in length
by using wide ground plane.
"quarter - wave antenna"



radiation pattern is isotropic in vertical plane,
and varies as $\sim \cos(\theta)$ in vertical plane

http://en.wikipedia.org/wiki/File:Elem-doub-rad-pat-pers.jpg

Directional Antennas



Yagi - Uda

http://en.wikipedia.org/wiki/File:Two_meter_yagi.jpg

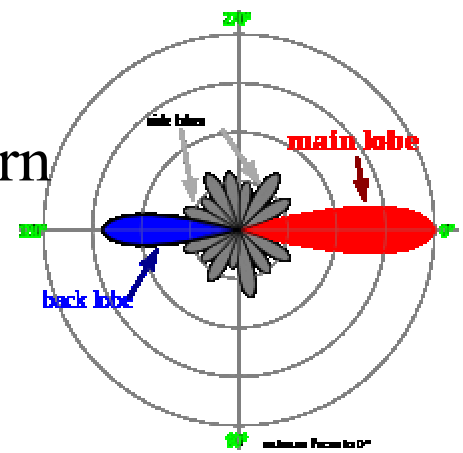
log - periodic

http://en.wikipedia.org/wiki/Log-periodic_antenna

parabolic reflector

http://en.wikipedia.org/wiki/File:SuperDISH121.jpg

Typical plot of radiation pattern

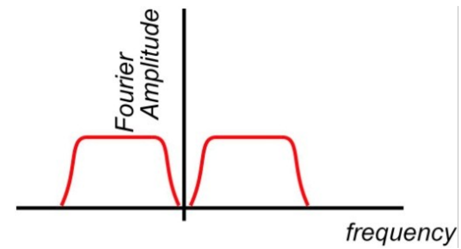


http://en.wikipedia.org/wiki/Radiation_pattern

Signals we might want to transmit by radio

Voice - quality sound transmission : 0.4 - 4 kHz

Range of human hearing (optimistic) : 20Hz - 20kHz



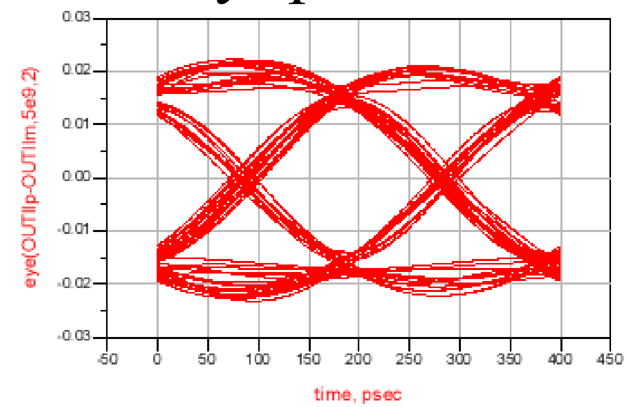
Uncompressed HDTV : about 1.5 Gb/sec

Compressed HDTV : about 15 Mb/s

WiFi : ~ 100 Mb/s

MP3 compressed audio : 32 - 320 kb/s

eye pattern

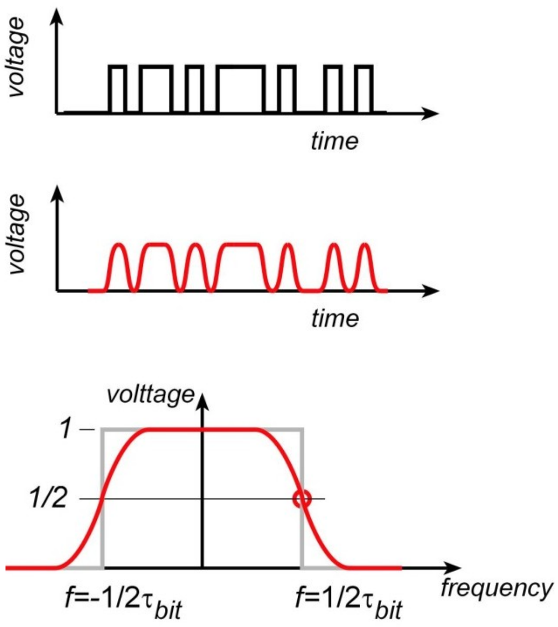


These signals must be translated in frequency if we are to transmit them by radio waves.

Spectra of Digital Signals

After filtering so that risetimes
are somewhat less than a bit period,
the spectrum of a pulse train extends
from $\approx -B/2$ to $B/2$
where B is the bit rate.

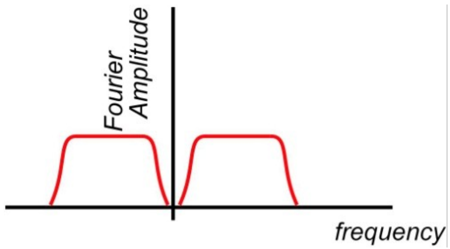
Explaining this
is beyond the scope of ece2c

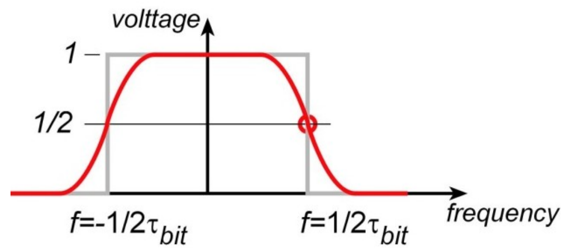


Frequency Conversion / Modulation

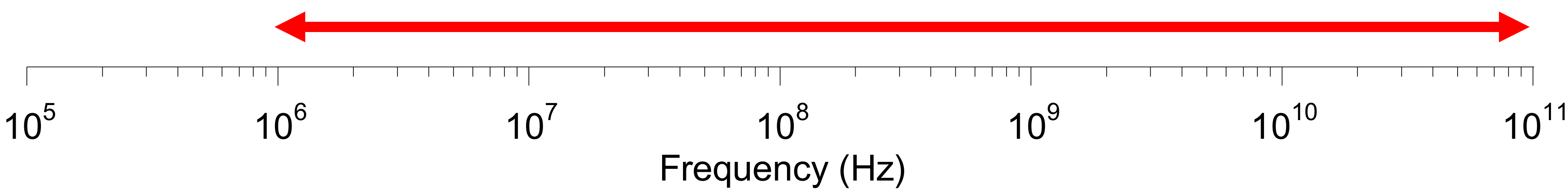
Our signal has a spectrum occupying some bandwidth.

The spectrum is centered at DC





We transmit the signal using radio frequencies between perhaps few MHz to 100 GHz.

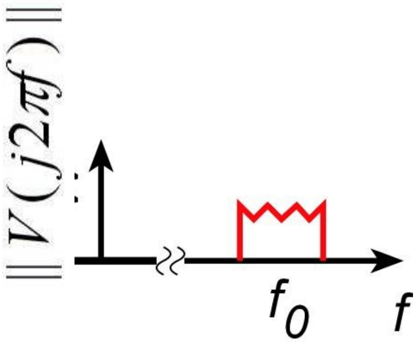


To do this, we must impose our signal on the high - frequency carrier.

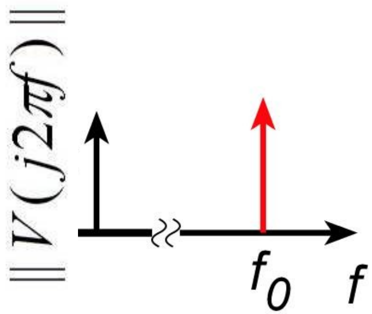
This is called modulation; it is done by mixing (multiplication).

Signal representation in this note set

Real signals carry random information, and usually have continuous spectra



But the presentation will be easier if we represent these signals as discrete spectral lines (sine waves).



Multiplying sinewaves easily (1)

We will need to calculate

$$V_{RF}(t)=V_{LO}(t)\cdot V_M(t)/V_0$$

where

$$V_{LO}(t)=V_{LO}\cos(\omega_{LO}t) \text{ and } V_M(t)=V_M\cos(\omega_M t)$$

We should learn to do this easily. How?

Multiplying sinewaves easily (2)

The trick : suppose we have some signal at frequency ω_M.

$\rightarrow$ write $z_M = e^{j\omega_M t}$

So : $z_M + 1/z_M = e^{j\omega_M t} + e^{-j\omega_M t} = 2 \cdot \cos(\omega_M t)$

And : $z_M - 1/z_M = e^{j\omega_M t} - e^{-j\omega_M t} = 2j \cdot \sin(\omega_M t)$

We have turned* sinewaves and cosinewaves into z's and $(1/z)$'s !

* Next year you will use this to convert the Fourier transform into the z - transform.

Multiplying sinewaves easily (3)

$$2\cdot\cos(\omega_M t) = e^{j\omega_M t} + e^{-j\omega_M t} = z_M^{1} + z_M^{-1}$$

$$2\cdot\cos(\omega_{LO} t) = e^{j\omega_{LO} t} + e^{-j\omega_{LO} t} = z_{LO}^{1} + z_{LO}^{-1}$$

so

$$4\cdot\cos(\omega_M t)\cdot\cos(\omega_{LO} t)$$

$$= (z_M^{1} + z_M^{-1})(z_{LO}^{1} + z_{LO}^{-1})$$

$$= z_M^{1} z_{LO}^{1} + z_{LO}^{1} z_M^{-1} + z_M^{1} z_{LO}^{-1} + z_M^{-1} z_{LO}^{-1}$$

$$= e^{j\omega_M t} e^{j\omega_{LO} t} + e^{j\omega_{LO} t} e^{-j\omega_M t} + e^{j\omega_M t} e^{-j\omega_{LO} t} + e^{-j\omega_M t} e^{-j\omega_{LO} t}$$

$$= (e^{j\omega_M t} e^{j\omega_{LO} t} + e^{-j\omega_M t} e^{-j\omega_{LO} t}) + (e^{j\omega_{LO} t} e^{-j\omega_M t} - e^{j\omega_M t} e^{-j\omega_{LO} t})$$

$$= 2\cdot\cos\big((\omega_{LO} + \omega_M)t\big) + 2\cdot\cos\big((\omega_{LO} - \omega_M)t\big)$$

Multiplying sinewaves easily (4)

Summarize :

$$\cos(\omega_M t)\cdot\cos(\omega_{LO} t) = \frac{1}{2}\cdot\cos\big((\omega_{LO}+\omega_M)t\big)+\frac{1}{2}\cdot\cos\big((\omega_{LO}-\omega_M)t\big)$$

Multiplication of two signals in a mixer (1)

Message

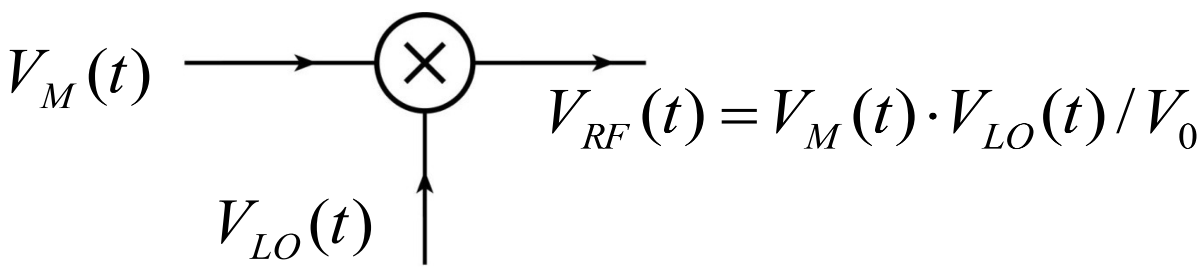
$$V_M(t) = V_M \cos(\omega_M t)$$

Sinewave from Local Oscillator

$$V_{LO}(t) = V_{LO} \cos(\omega_{LO} t)$$

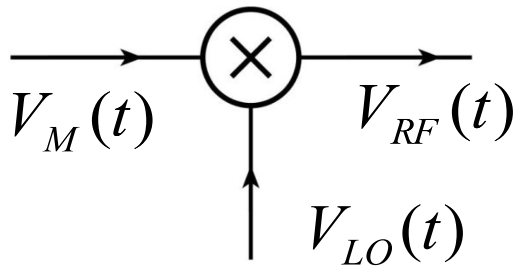
Radio - Frequency signal to be transmitted

$$V_{RF}(t) = V_M(t) \cdot V_{LO}(t) / V_0$$



$$\boxed{V_{RF}(t) = V_M \cos(\omega_M t) \cdot V_{LO} \cos(\omega_{LO} t) / V_0}$$

Multiplication of two signals in a mixer (2)



$$V_{RF}(t) = V_M \cos(\omega_M t) \cdot V_{LO} \cos(\omega_{LO} t) / V_0$$

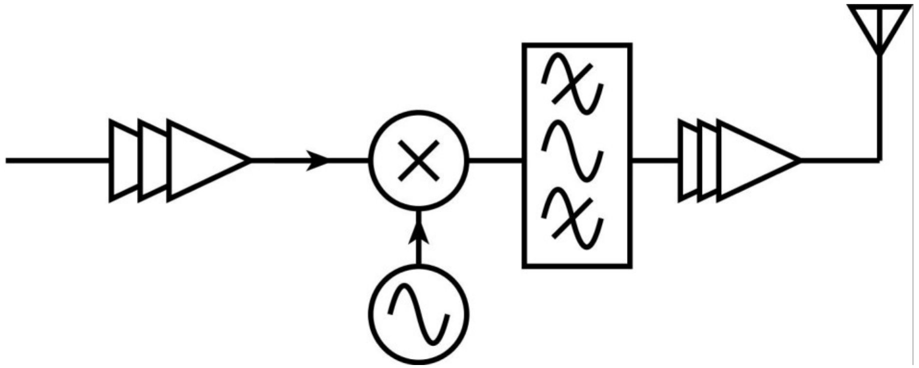
but

$$\cos(\omega_M t) \cdot \cos(\omega_{LO} t) = \frac{1}{2} \cdot \cos\big((\omega_{LO} + \omega_M)t\big) + \frac{1}{2} \cdot \cos\big((\omega_{LO} - \omega_M)t\big)$$

so

$$V_{RF}(t) = \frac{V_M V_{LO}}{2V_o} \cos\big((\omega_{LO} + \omega_M)t\big) + \frac{V_M V_{LO}}{2V_o} \cos\big((\omega_{LO} - \omega_M)t\big)$$

(Suppressed Carrier) Amplitude Modulation Transmitter



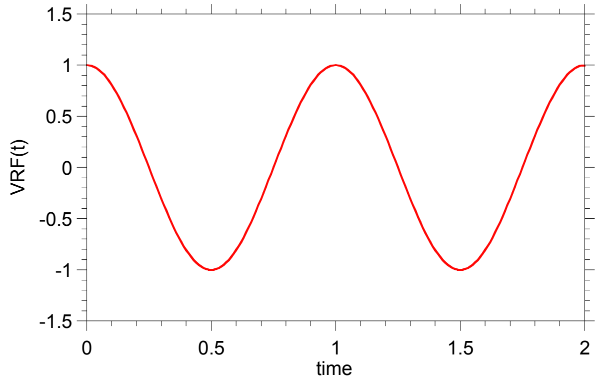
Message signal is multiplied against local oscillator, then filtered, amplified, and radiated

$$V_{RF}(t) = V_M(t) \cdot V_{LO}\cos(\omega_{LO}t)/V_0$$

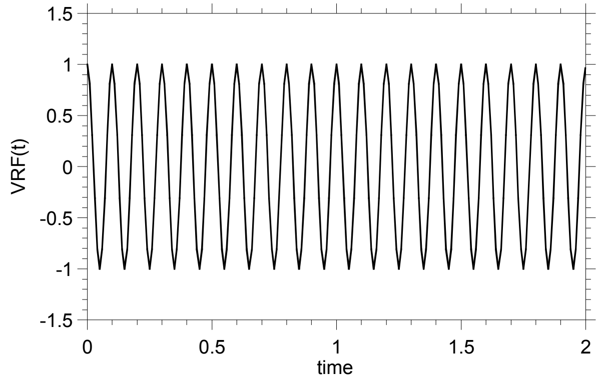
So if $V_M(t) = V_M\cos(\omega_M t)$, then

$$V_{RF}(t) = \frac{V_M V_{LO}}{2V_o}\cos\left((\omega_{LO}+\omega_M)t\right) + \frac{V_M V_{LO}}{2V_o}\cos\left((\omega_{LO}-\omega_M)t\right)$$

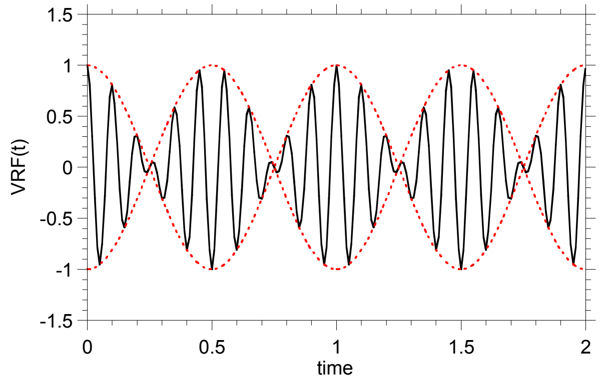
(Suppressed Carrier) AM Waveforms



Message



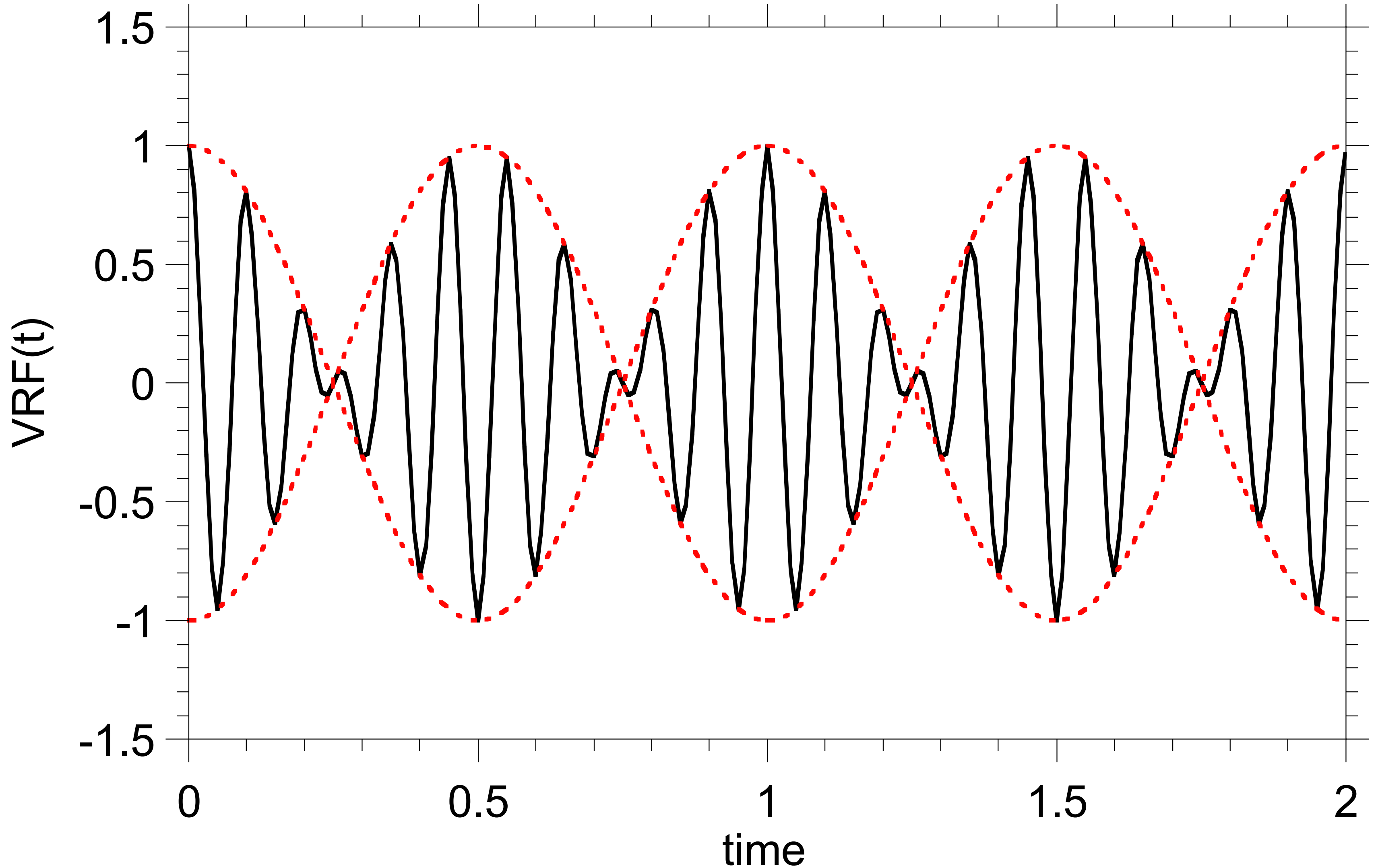
Local Oscillator



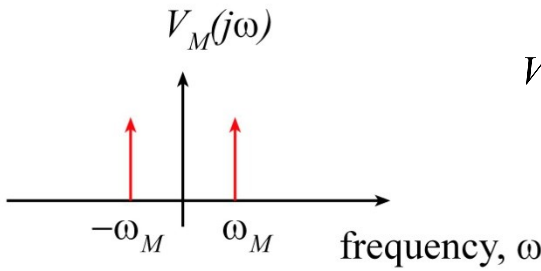
Transmitted Signal

(Suppressed Carrier) AM Waveforms

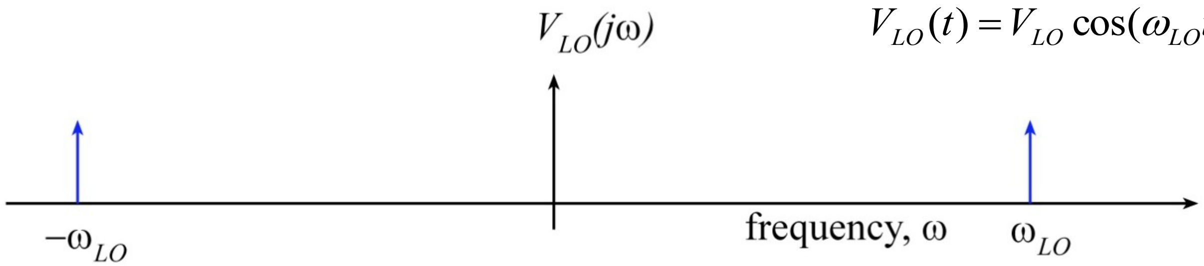
Transmitted Signal : drawn bigger



(Suppressed Carrier) AM Fourier Spectra



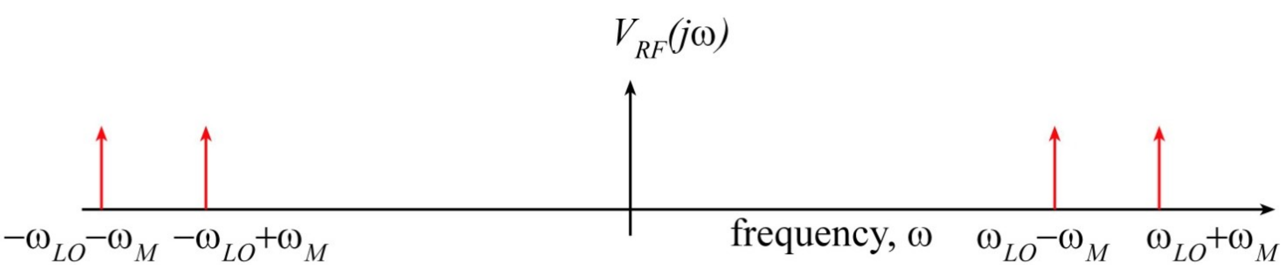
$$V_M(t) = V_M\cos(\omega_M t) = \frac{V_M}{2}e^{j\omega_M t} + \frac{V_M}{2}e^{-j\omega_M t}$$



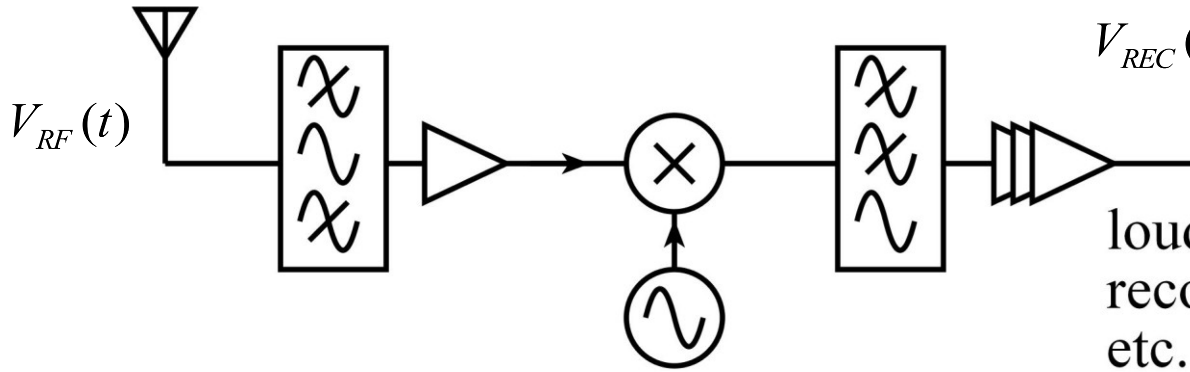
$$V_{LO}(t) = V_{LO}\cos(\omega_{LO} t) = \frac{V_{LO}}{2}e^{j\omega_{LO} t} + \frac{V_{LO}}{2}e^{-j\omega_{LO} t}$$

$$V_{RF}(t) = \frac{V_M V_{LO}}{2V_o}\cos\big((\omega_{LO}+\omega_M)t\big) + \frac{V_M V_{LO}}{2V_o}\cos\big((\omega_{LO}-\omega_M)t\big)$$

$$= \frac{V_M V_{LO}}{4V_o}\left[e^{j(\omega_{LO}+\omega_M)t} + e^{j(-\omega_{LO}-\omega_M)t} + e^{j(\omega_{LO}-\omega_M)t} + e^{-j(\omega_{LO}-\omega_M)t}\right]$$



(Suppressed Carrier) AM Receiver



$$V_{REC}(t) = V_{RF}(t) \cdot V_{LO}\cos(\omega_{LO}t)/V_0$$

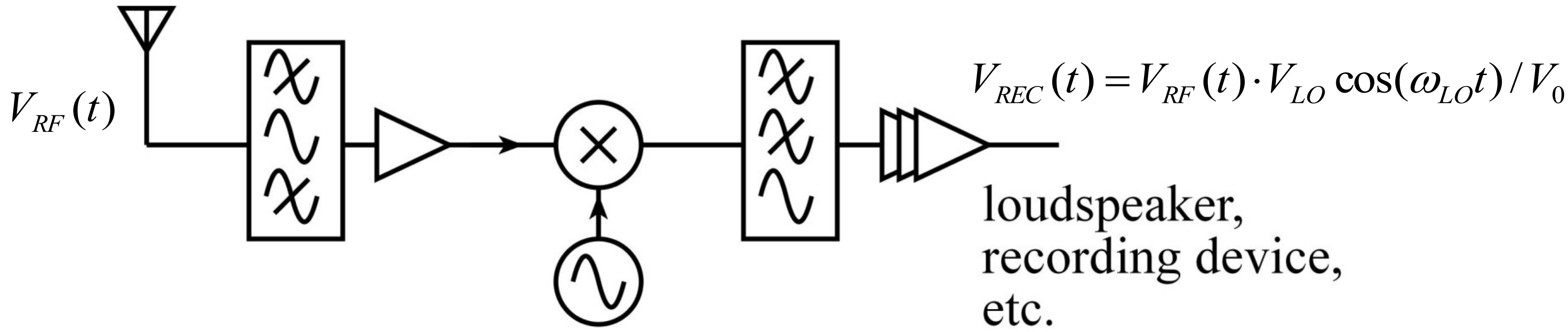
The received signal is multiplied against a sine wave at ω_{LO}

$$V_{RF}(t) = V_M\cos(\omega_M t) \cdot V_{LO}\cos(\omega_{LO}t)/V_0$$

$$\begin{aligned}
V_{REC}(t) &= V_{RF}(t) \cdot V_{LO}\cos(\omega_{LO}t)/V_0 \\
&= V_M(t) \cdot (V_{LO}/V_0)^2 \cos^2(\omega_{LO}t) \\
&= V_M(t) \cdot (V_{LO}/V_0)^2 (1/2)[1+\cos(2\omega_{LO}t)] \\
&= V_M(t) \cdot \left(\frac{V_{LO}^2}{2V_0^2}\right) + V_M(t) \cdot \left(\frac{V_{LO}^2}{2V_0^2}\right)\cos(2\omega_{LO}t)
\end{aligned}$$

Typical receivers use a *superheterodyne* configuration. This is beyond our scope

(Suppressed Carrier) AM Receiver



$$V_{REC}(t) = V_M(t) \cdot \left(\frac{V_{LO}^2}{2V_0^2} \right)$$

← The transmitted message

$$+V_M(t) \cdot \left(\frac{V_{LO}^2}{2V_0^2} \right) \cos(2\omega_{LO}t)$$

← Plus the message modulating a sine wave at $2\omega_{LO}$.

$\rightarrow$ removed by filter

The absolute signal amplitudes are changed by amplifier gains, propagation losses, etc.

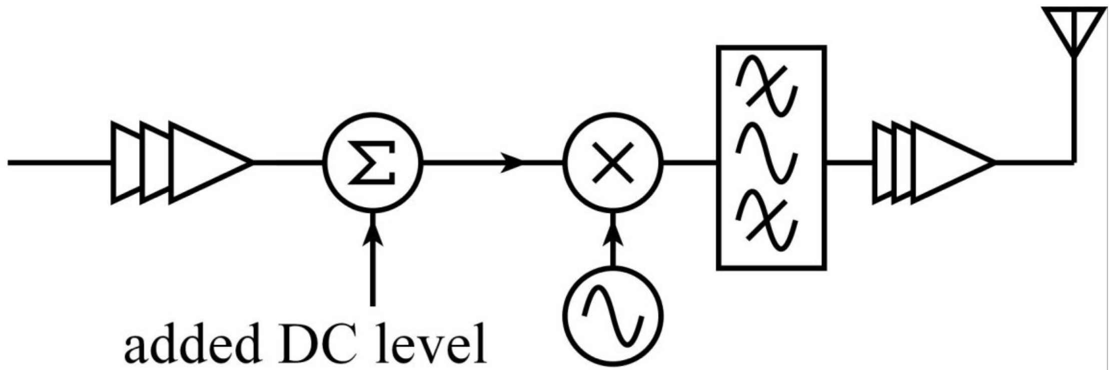
Suppressed Carrier AM: Comments

If the message is a series of digital pulses,
suppressed carrier AM is known as BPSK.
"Binary phase shift keying"
Widely used digital modulation format

Signal Recovery requires synchronized LO in the receiver.
Easy today, using phase-locked-loop.
Difficult in the early days of radio, difficult until ~1970

$\rightarrow$ Early radio systems used a modified technique: "AM"

Amplitude Modulation Transmitter



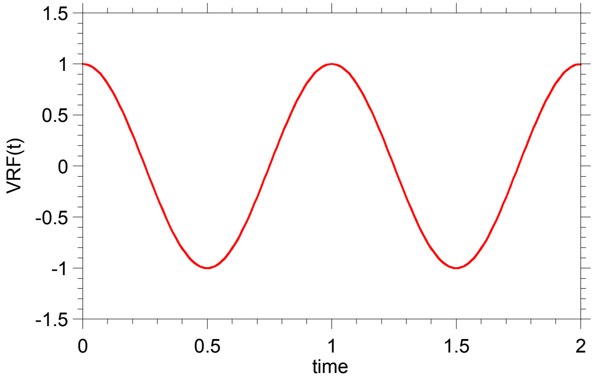
DC level is added to the message before modulation

$$V_{RF}(t) = \left(V_M(t) + V_{DC}\right) \cdot V_{LO}\cos(\omega_{LO} t) / V_0$$

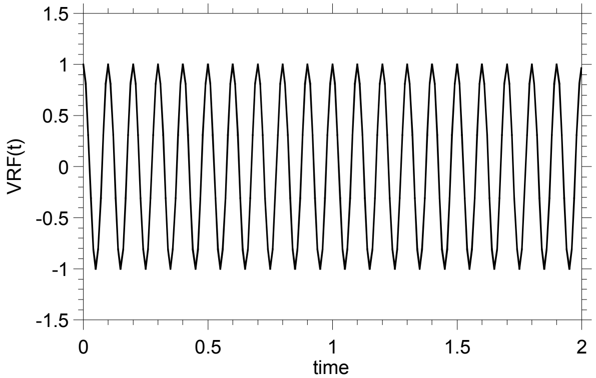
So if $V_M(t) = V_M \cos(\omega_M t)$, then

$$V_{RF}(t) = \frac{V_M V_{LO}}{2V_o}\cos\left((\omega_{LO} + \omega_M)t\right) + \frac{V_M V_{LO}}{2V_o}\cos\left((\omega_{LO} - \omega_M)t\right) + \frac{V_{DC} V_{LO}}{V_o}\cos\left(\omega_{LO} t\right)$$

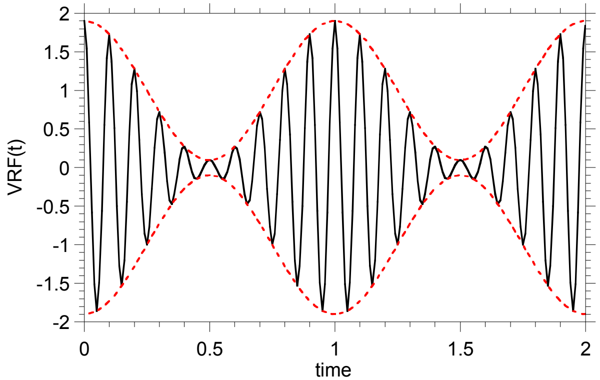
AM Waveforms



Message



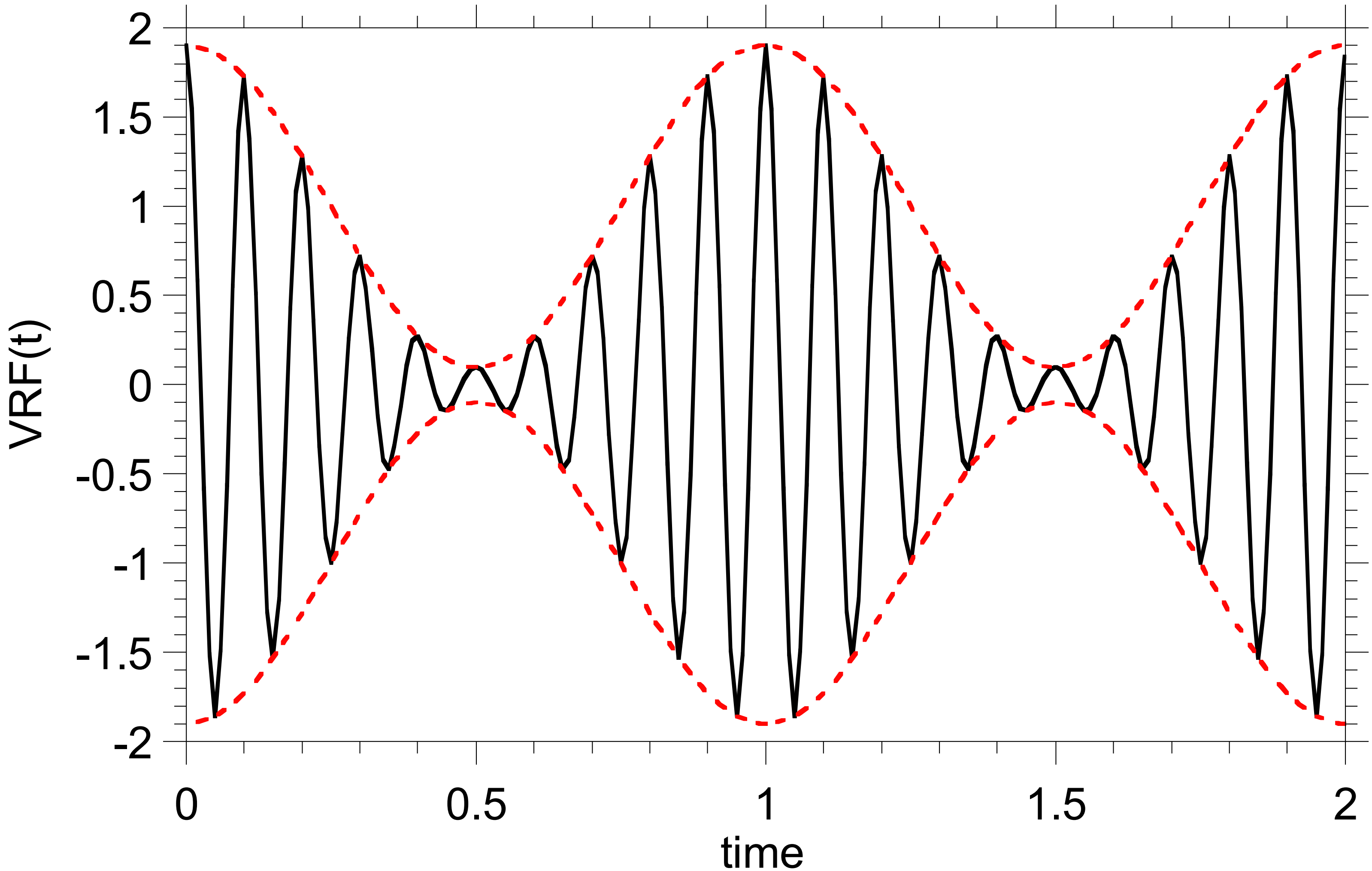
Local Oscillator



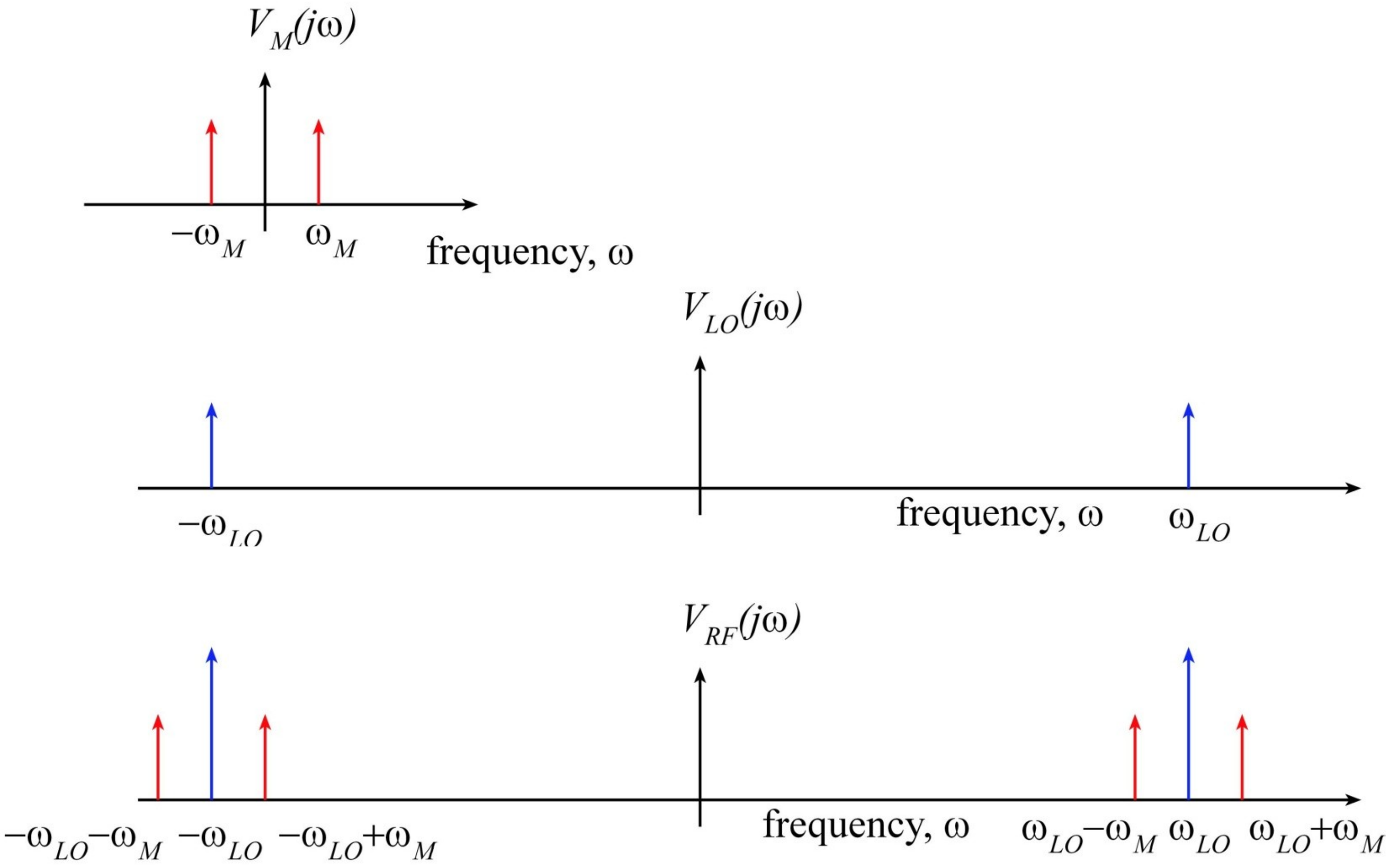
Transmitted Signal

AM Waveforms

Transmitted Signal : drawn bigger



AM Fourier Spectra

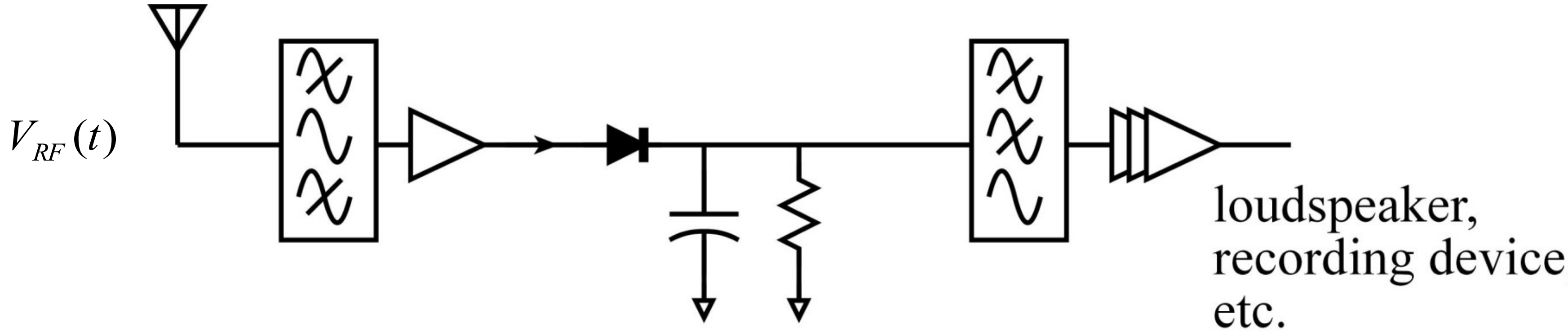


AM differs in that the transmitted signal carries power at $\pm\omega_{LO}$

Wasteful of transmitted RF power.

Makes demodulation easy.

AM Receiver



The amplitude of the received signal is detected with a diode peak-detector

Capacitor charges to peak of RF waveform amplitude

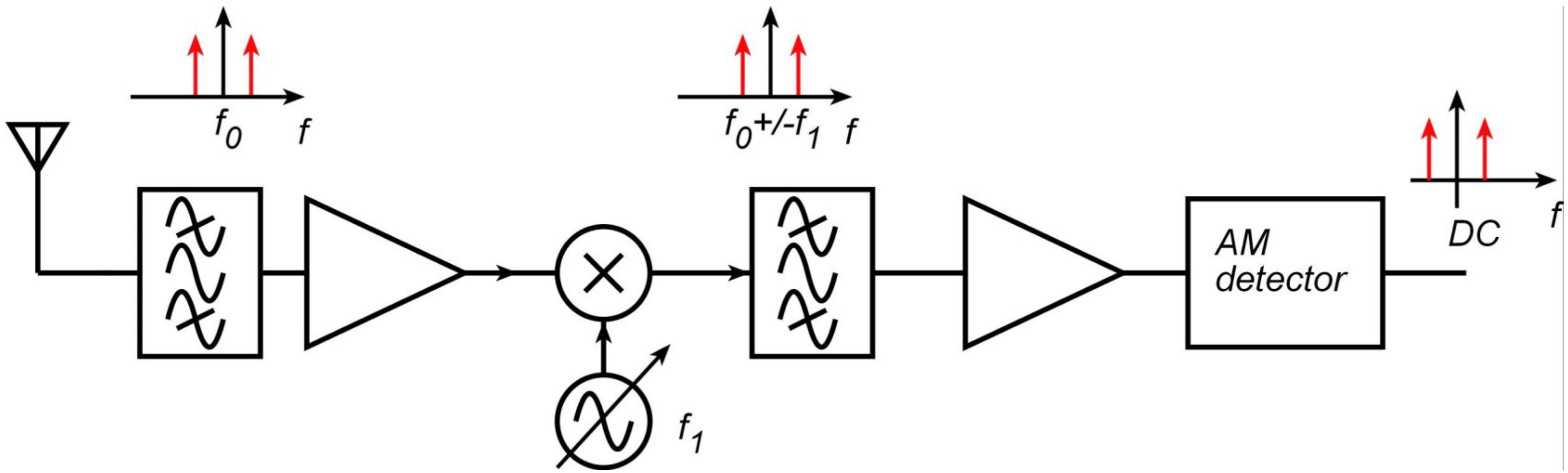
RC time constant : much longer than carrier waveform period.

RC time constant : much shorter than signal waveform period.

Simple receiver circuit : feasible since early days of radio

Typical receivers use a *superheterodyne* configuration. This is beyond our scope

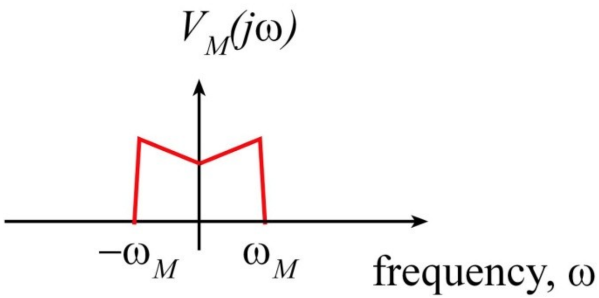
Superheterodyne Receiver (Amstrong, 1918)

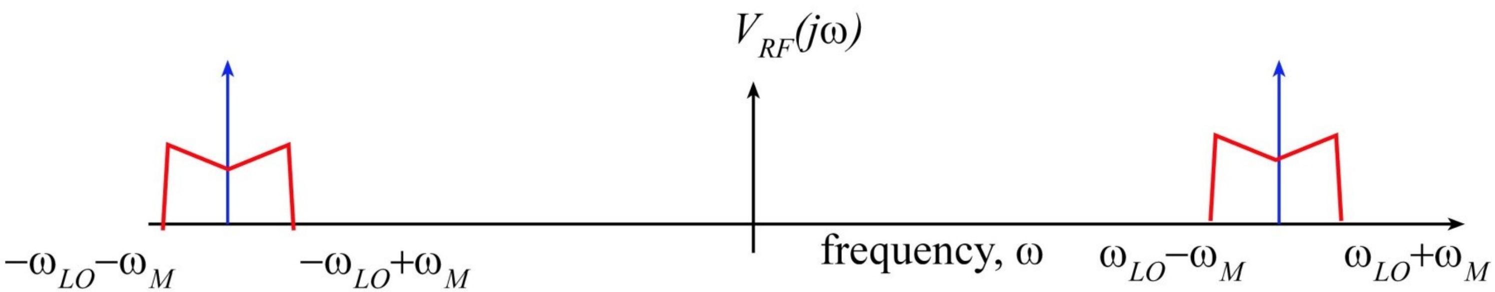


Receive radio signal is converted to an intermediate frequency before detection.

Received signal frequency is tuned by varying the LO frequency.
Sharp fixed - tuned IF filters are used for channel selection.

Spectral Requirements: AM

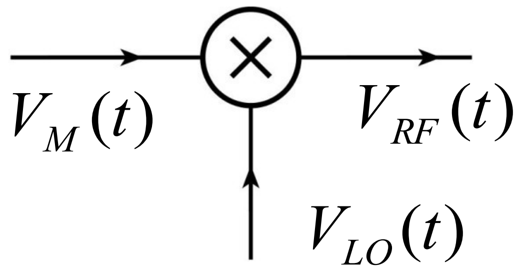




If the voice/music signal is resistricted to (say) DC - 5kHz,
then the transmitted signal occupies 10kHz bandwidth

So : If we want DC - 5kHz music, then AM signals
must be spaced by > 10kHz.

Mixers and Modulators are Usually Switches



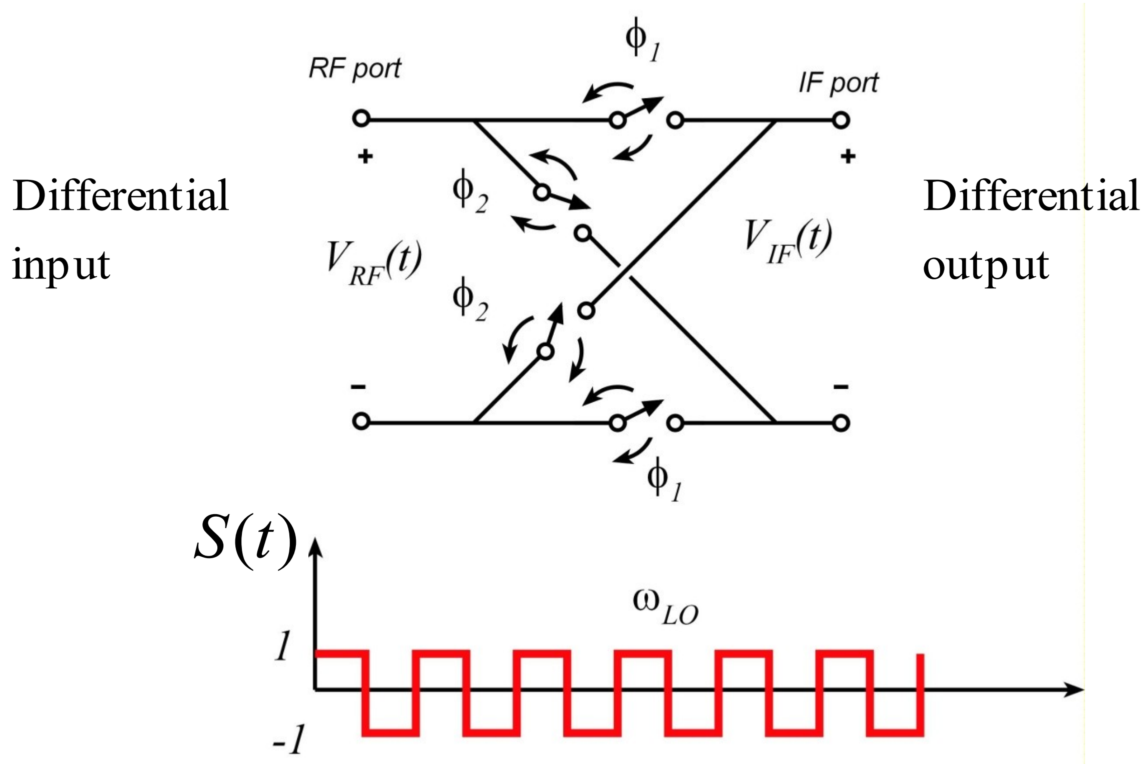
How do we construct a circuit which multiplies two signals ?

True multipliers are possible---but take effort.

True multipliers are not necessary : a switch is usually enough.

Most mixers : simple switches turned on/off at frequency ω_{LO}

Mixing with a Switch



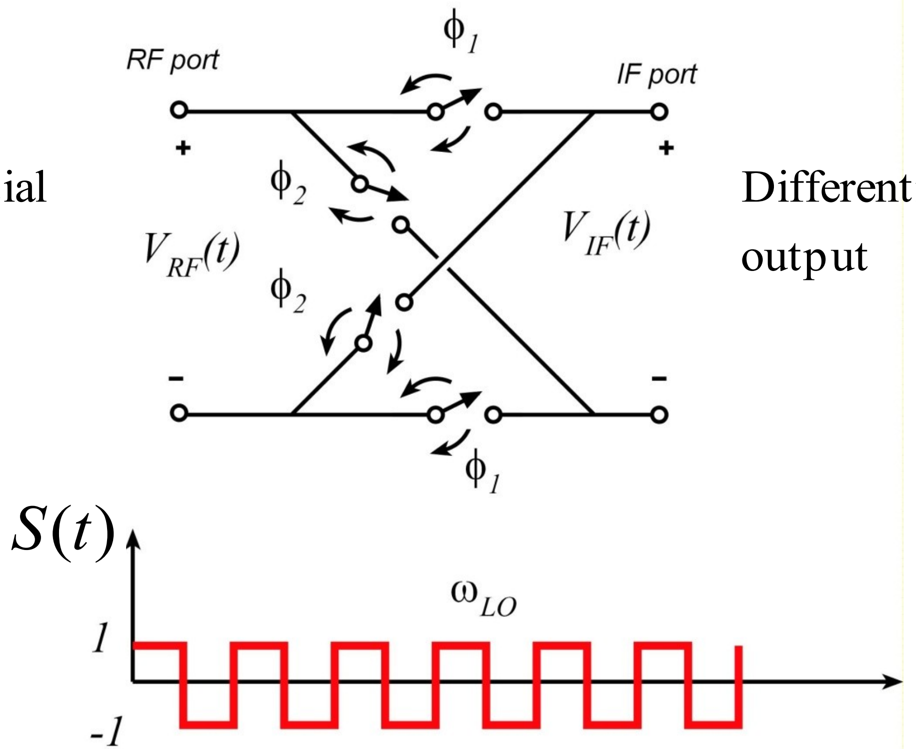
We multiply signal $V_{RF}(t)$ with a squarewave $S(t)$

This is done with four switches:

ϕ_1 is open when ϕ_2 is closed.

Mixing with a Switch

Differential input



Differential output

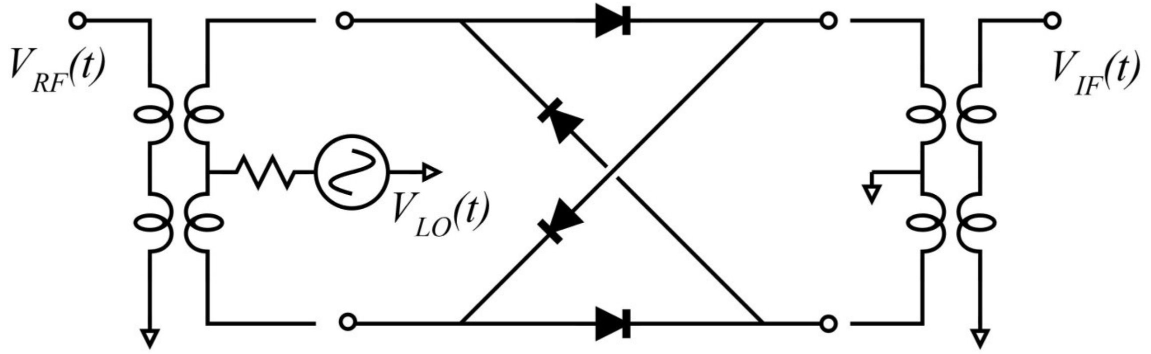
$$V_{IF}(t) = S(t)V_{RF}(t)$$

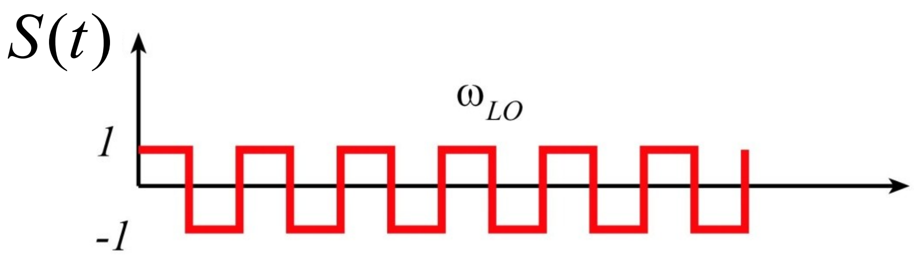
$$S(t) = \frac{4}{\pi}\left[\cos(\omega_{LO}t) + \frac{\cos(3\omega_{LO}t)}{3} + \frac{\cos(5\omega_{LO}t)}{5} + ...\right]$$

$$\frac{4}{\pi}[\cos(\omega_{LO}t)] \rightarrow \text{desired mixing terms} ...(\omega_{RF} \pm \omega_{LO})$$

$$\cos(3\omega_{LO}t), \cos(5\omega_{LO}t) \text{ etc.} \rightarrow \text{undesired mixing mixing terms}$$

Diode Double Balanced Mixer



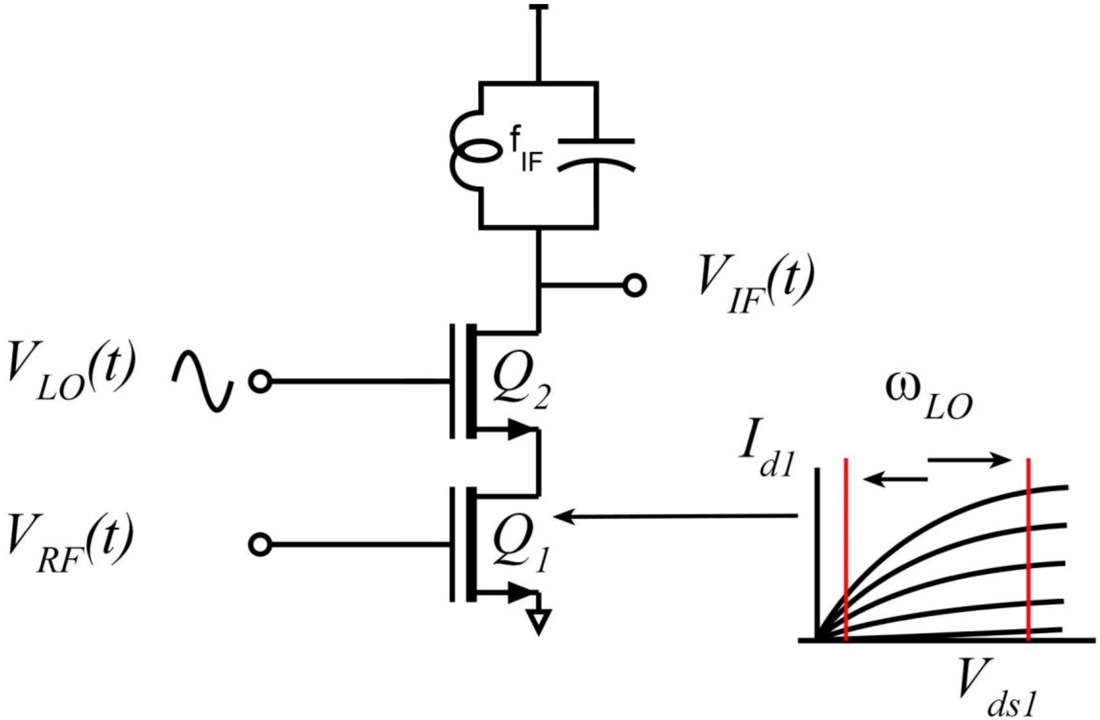


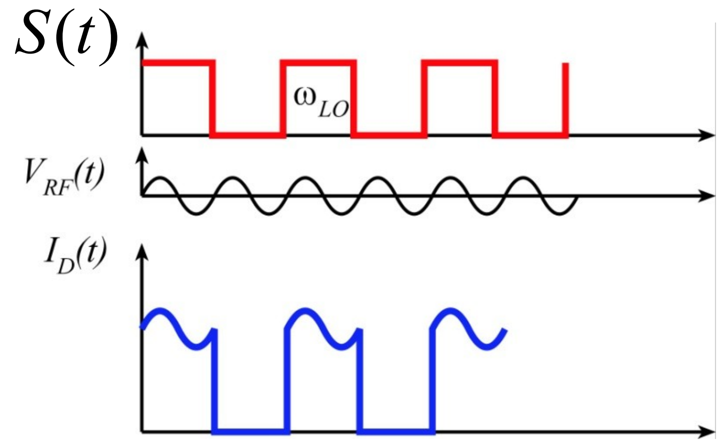
The 4 switches are implemented with (Schottky) diodes.

Positive LO $\rightarrow$ Positive RF - IF connection

Negative LO $\rightarrow$ crossed diodes on, negative RF - IF connection

FET Unbalanced Mixer





When LO is high, Q2 operates as common - gate stage for RF signal...

....signal path is on.

When LO is low, V_{ds} of Q1 is reduced to zero, reducing g_{m1} to zero.

....signal path is off.

IF current is RF wave form mulitiplied by square wave.

IF port also has strong LO and RF currents.