

Mixers, modulators and demodulators

- Semiconductor devices will always have some form of non-linearity and mixers, provide an example of the advantages of non-linear behaviour in semiconductor devices.
- An ideal mixer is a device for which the output is the product of two input signals.
- For purely sinusoidal inputs, this will imply outputs at the sum and difference frequencies.
- Mixers are essential for operations such as frequency translation, modulation and detection.
- As a consequence, they are an important building block for both transmitters and receivers.



Diode mixers

- The current i_D in a diode is related to the potential difference v_D across the diode through

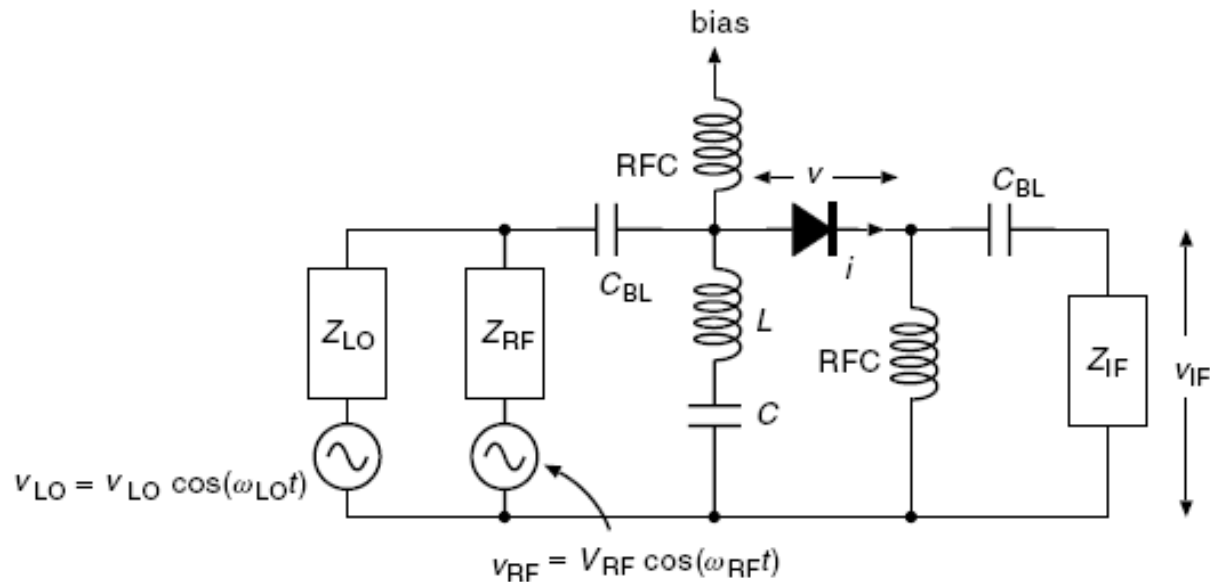
$$i_D = I_s \left[\exp \left(\frac{v_D}{n V_T} \right) - 1 \right]$$

- a single diode mixer that converts an RF input signal at frequency ω_{RF} into an intermediate frequency (IF) signal at frequency $\omega_{IF} = |\omega_{RF} - \omega_{LO}|$ by mixing it with a local oscillator (LO) signal at frequency ω_{LO} .
- It will be noted that there is a series LC combination on the source side of the mixer diode, the resonant frequency of which is set at ω_{IF} . This combination prevents any IF signal from reaching the signal sources by providing a direct path to ground at frequency ω_{IF} .



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- For small voltage fluctuations v about the quiescent state, the relation can be expanded in a Taylor series to yield

$$i = I_0 + a_1 v + a_2 v^2 + \dots$$

Diode mixers

- the component of current at the intermediate frequency $\omega_{IF} = |\omega_{RF} - \omega_{LO}|$ has amplitude

$$I_{IF} = -a_1 V_{IF} + a_2 V_{LO} V_{RF}$$

- Since $V_{IF} = I_{IF} Z_{IF}$, it follows that

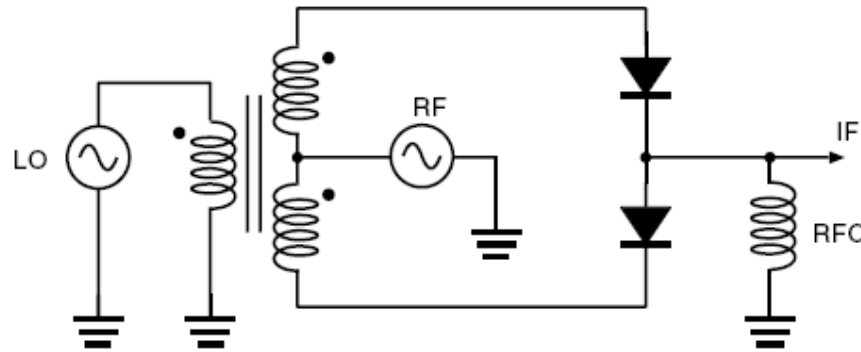
$$V_{IF} = \frac{Z_{IF} a_2 V_{LO} V_{RF}}{1 + Z_{IF} a_1}$$

- The voltage conversion gain* of the mixer is dependent upon the level of the local oscillator signal.
- A single diode mixer has the disadvantage that the output will contain strong contributions from both the RF input and LO signals. Consequently, there will need to be suitable filtering at the IF load Z_{IF} .



Diode mixers

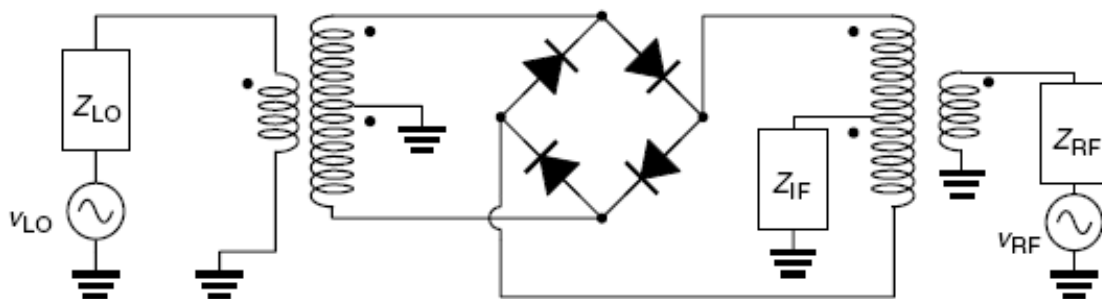
- A partial solution can be obtained by adopting the two diode mixer



- Together, the diode currents cause an IF voltage that has a component proportional to the product of the RF and LO signals, but with no component at the LO frequency.
- Besides the desired components at the sum and difference frequencies, however, the IF output will also contain a component at the RF frequency.
- As a consequence, the IF load will require filtering to remove any content at frequency ω_{RF} .

Diode mixers

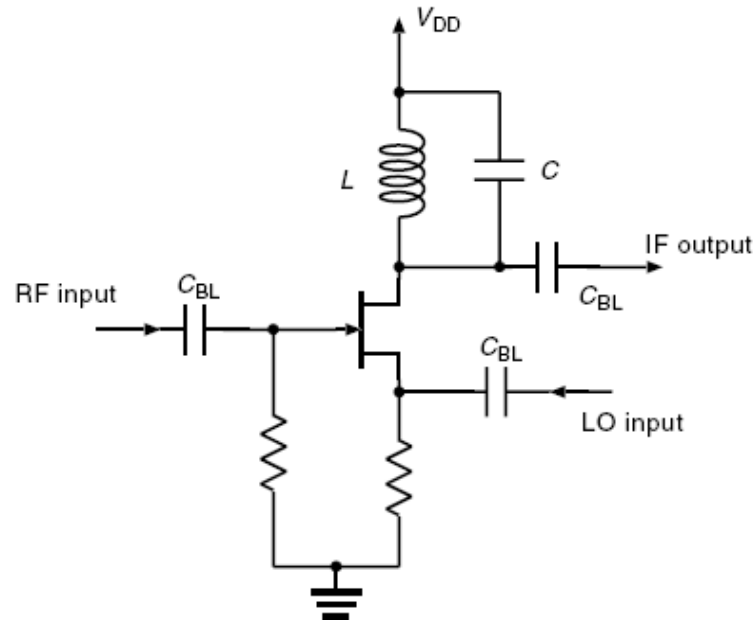
- An alternative is the *diode ring* mixer which exhibits a very high degree of isolation (the IF output has very little signal at other than the sum and difference frequencies $|\omega_{LO} \pm \omega_{RF}|$).
- The mixer works through the switching action of the diode bridge.
- As the LO signal switches between positive and negative, the conducting diodes switch between those on the right and those on the left of the bridge.
- The consequence is that the IF output will alternate between RF and inverted RF signals, the alternation taking place at a frequency equal to that of the LO signal.
- This turns out to be equivalent to the RF signal multiplied by a series of odd harmonics of the LO signal, the dominant term being that at the fundamental frequency.
- The result is an IF signal with dominant contributions at frequencies $|\omega_{LO} \pm \omega_{RF}|$ and very little signal at the frequencies ω_{LO} and ω_{RF} .



Transistor mixers

- a simple JFET mixer with the local oscillator fed in through the source of the transistor is in figure,
- the small signal drain current is given by (I_D is the quiescent current):

$$i_D = K(v_{RF} - v_{LO} - I_D R_S - V_t)^2$$



Transistor mixers - example

- Design an JFET mixer that can achieve a power conversion gain of 6 dB into a 2 k Ω external load from a 2 k Ω source.

- We design the mixer around the JFET for which typical parameters are:
 - $K = 1.3 \times 10^{-3} \text{ AV}^2$, $V_t = -3\text{V}$, $C_{GS} = 4 \text{ pF}$, $C_{GD} = 1.6 \text{ pF}$, $C_{DS} \approx 0$ and $r_d = 30 \text{ k}\Omega$.

- The device is biased such that the operation lies well within the square law region of the device characteristic.
 - If we choose a quiescent source voltage of about 1V, this will allow a local oscillator peak amplitude of up to approximately 1.5V without distortion (assuming the amplitude of the RF voltage V_{RF} to be restricted to a few hundred millivolts).
 - A quiescent source voltage of 1V will require a quiescent drain current of $I_{DQ} = K(V_{GS} - V_t)^2 = 5.2\text{mA}$ since the gate voltage will be zero. This implies a source resistor R_S of 192 Ω in order to achieve the 1 V source voltage.

- The mixer will present an impedance of approximately $1/j\omega C_{GS}$ to the RF source and an impedance of $g_m^{-1} || R_s \approx 100\Omega$ to the local oscillator.



Transistor mixers - example

- The power conversion gain G_c of the mixer will be given by:

$$G_c = \frac{\text{power available to load}}{\text{power available from source}} = \frac{|V_{IF}|^2/2R_{IF}}{|V_{RF}|^2/8R_{RF}}$$

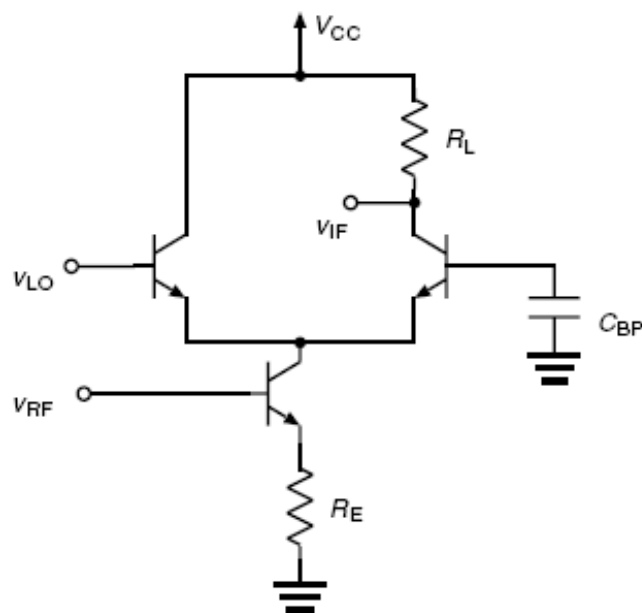
- where V_{IF} is the amplitude of the IF voltage, R_{IF} is the impedance of the external IF load and R_{RF} is the impedance of the RF source.
- Since $G_c = 4$, $R_{IF} = R_{RF} = 2 \text{ k}\Omega$ and $V_{IF} = R_{IF} \cdot K \cdot V_{RF} \cdot V_{LO}$, the above eq. implies that $V_{LO} = 385 \text{ mV}$.
- It is clear from this that the conversion gain can be increased by more than 10 dB (by increasing the local oscillator voltage) without significantly increasing intermodulation products.
- If the gain is increased, however, care must be taken to ensure that the output voltage excursions do not reach a level where significant distortion can occur.



Transconductance mixers

- The gain of a differential amplifier depends on the transconductance g_m of its transistors and this transconductance will, in turn, depend on the current flow. Consequently, a differential amplifier can be transformed into a mixer:

$$i_C \approx i_{RF} + I_E \approx I_E \exp\left(\frac{v_{RF} - R_E i_{RF}}{V_T}\right) \approx I_E \left(1 + \frac{v_{RF} - R_E i_{RF}}{V_T}\right)$$



Transconductance mixers

- Isolating the RF contribution we have:

$$i_{RF} \approx I_E v_{RF} / (V_T + R_E I_E)$$

- Noting that $V_T \ll I_E R_E$:

- Thus:

$$v_{RF} \approx R_E i_{RF}$$

- We can approximate the collector current with:

$$i_C \approx I_E + v_{RF} / R_E$$

- The output of a differential amplifier is:

$$v_{IF} = -g_m R_L v_{LO}$$

- Where

$$g_m = i_C / 2V_T$$

- And finally:

$$v_{IF} = - \left(\frac{R_L I_E}{2V_T} \right) v_{LO} \left(1 + \frac{v_{RF}}{R_E I_E} \right)$$

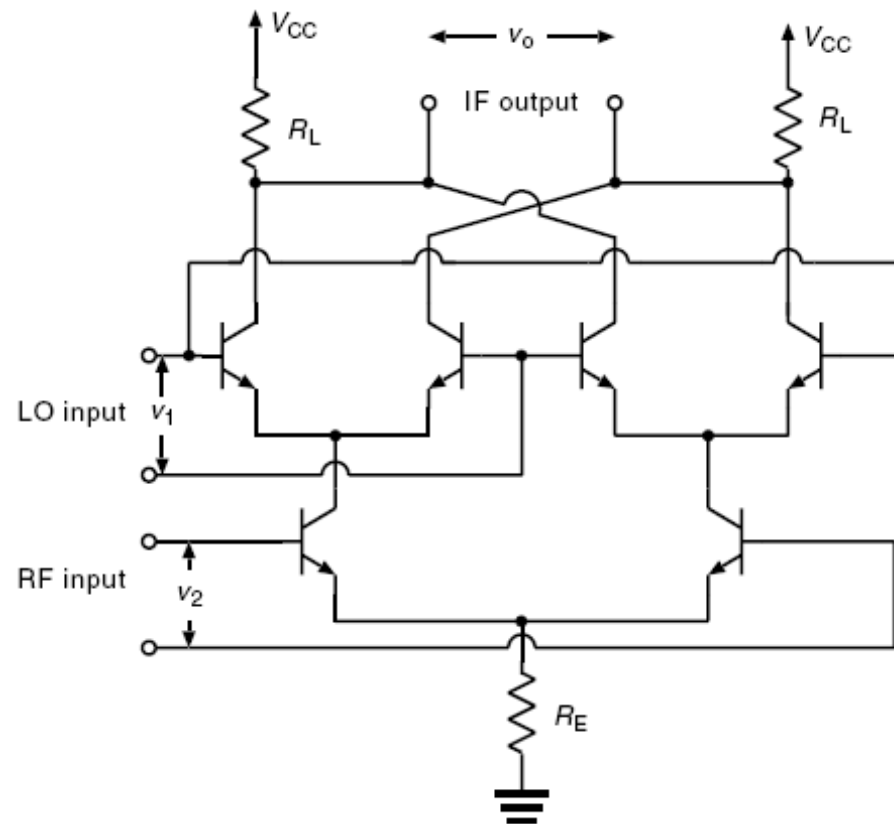
- The output at $\omega_{LO} - \omega_{RF}$ is:

$$R_L V_{LO} V_{RF} / 4 R_E V_T$$



Transconductance mixers

- Note, however, that the output will also contain a strong component at the local oscillator frequency. This component can be removed by putting together two transconductance mixers in a fashion that cancels the unwanted component. Such a mixer is known as a Gilbert cell



A simple receiver design

- This receiver is designed around a single dual-gate FET mixer and a Colpitts oscillator that uses a JFET source follower amplifier.
- The baseband output is taken from the mixer drain and there is a capacitor across the drain resistor in order to form a low-pass filter.
- The input circuit is resonated at the centre frequency ω_0 of the required reception band with Q chosen to produce the required bandwidth. Since $Q \approx R/\omega_0 L_2$ where R is the antenna resistance when transformed through the capacitive divider (C_3, C_4).
- The oscillator frequency can be varied, and hence the receiver tuned, by means of the back-to-back varactor diodes across the oscillator inductor.

