# UNIT V

# RF SYSTEM DESIGN CONCEPTS

Active RF components: Semiconductor basics in RF, bipolar junction transistors, RF field effect transistors, High electron mobility transistors Basic concepts of RF design, Mixers, Low noise amplifiers, voltage control oscillators, Power amplifiers, transducer power gain and stability considerations.

## Semiconductor Basics:

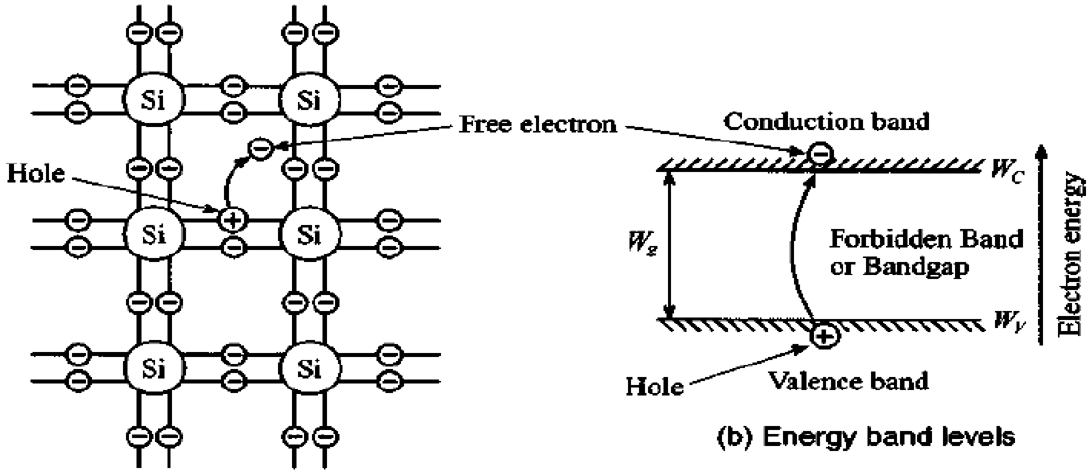
Germanium (Ge), silicon (Si), and gallium arsenide (gas)

Each silicon atom shares its four valence electrons with the four neighboring atoms, forming four covalent bonds.

When the temperature is equal to zero degree Kelvin all electrons are bonded to the corresponding atoms and the semiconductor is not conductive.

When the temperature increases some of the electrons obtain sufficient energy to break up the covalent bond and cross the energy gap $W_g = W_C - W_V$

At room temperature T = 300°K the **bandgap energy** is equal to 1.12 ev for Si, 0.62 ev for Ge, and 1.42 ev for gas.



(b) Energy band levels

(a) Planar representation of covalent bonds

The concentration of the conduction electrons in the semiconductor is denoted as n.

When an electron breaks the covalent bond it leaves behind a positively charged vacancy, which can be occupied by another free electron.

These types of vacancies are called **holes** and their concentration is denoted by p.

If an electron happens to meet a hole, they recombine and both charge carriers disappear.

In thermal equilibrium we have equal number of recombination and generations of holes and electrons.

$$n = N_C \exp\left[-\frac{W_C - W_F}{kT}\right]$$

$$p = N_V \exp\left[-\frac{W_F - W_V}{kT}\right]$$

$$N_{C,V} = 2(2m^*_{n,p}\pi kT/h^2)^{3/2}$$

**Effective carrier concentration** in the conduction ($N_c$) and valence ($N_v$) bands, respectively.

The terms $W_c$ and $W_V$ denote the energy levels associated with the conduction and valence bands and $W_F$ is the **Fermi energy level**

In an intrinsic semiconductor the number of free electrons produced by thermal excitation is equal to the number of holes (i.e. $N = p = n_i$).

Therefore, electron and hole concentrations are described by the concentration law.

$$np = n_i^2$$

$$n_i = \sqrt{N_C N_V}\exp\left[-\frac{W_C - W_V}{2kT}\right] = \sqrt{N_C N_V}\exp\left[-\frac{W_g}{2kT}\right]$$

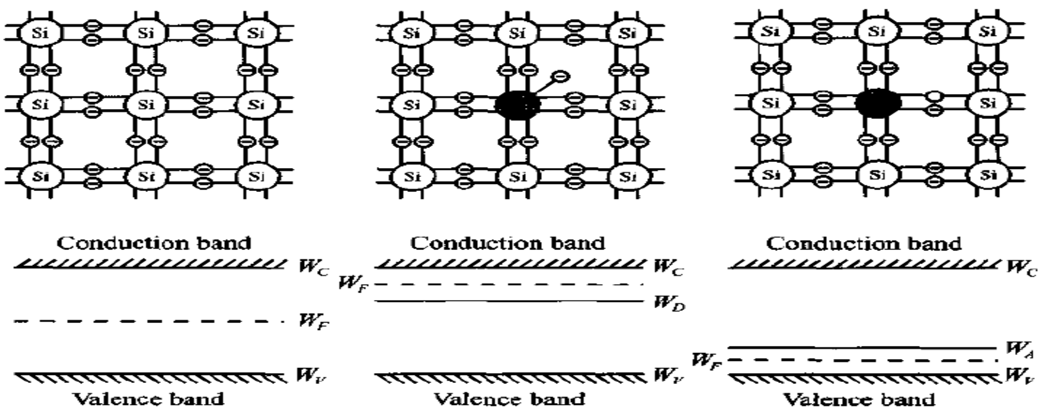
$$\sigma = J/E$$

where J is the current density and E is the applied electric field

$$\sigma = qn\mu_n + qp\mu_p$$

For intrinsic semiconductors n = p = $n_i$

$$\sigma = qn_i(\mu_n + \mu_p) = q\sqrt{N_C N_V}\exp\left[-\frac{W_g}{2kT}\right](\mu_n + \mu_p)$$

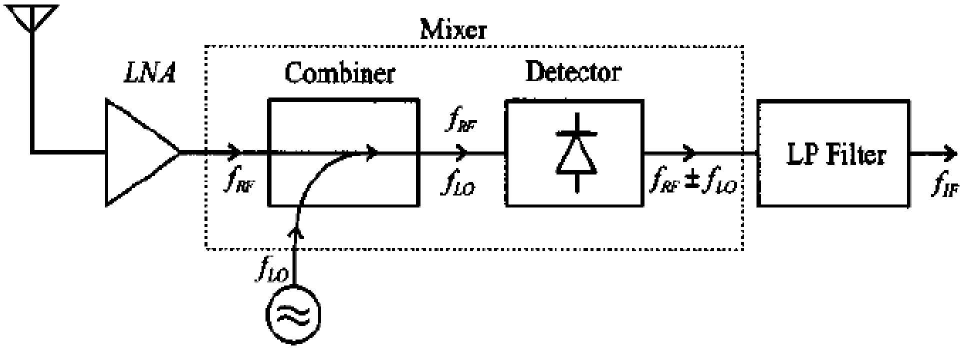


(a) Intrinsic (b) *n*-type (c) *p*-type

**Figure 6-3** Lattice structure and energy band model for (a) intrinsic, (b) *n*-type, and (c) *p*-type semiconductors at no thermal energy. $W_D$ and $W_A$ are donor and acceptor energy levels.

**Basic Characteristics of Mixers:**

It is used to multiply signals of different frequencies in an effort to achieve frequency translation.



Here the received signal is, after pre amplification in a low-noise amplifier(LNA), supplied to a mixer whose task is to multiply the input signal of centre frequency $f_{RF}$ with a local oscillator (LO) frequency $f_{Lo}$.

The signal obtained after the mixer contains the frequencies $f_{RF} \pm f_{LO}$,

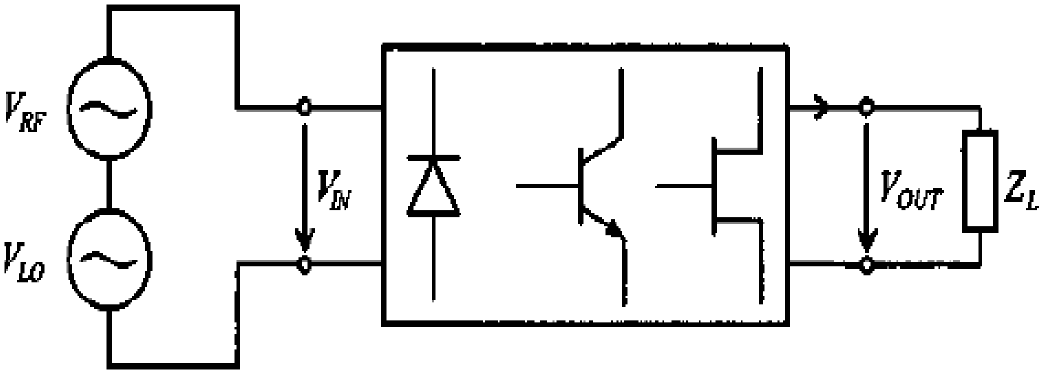
After low-pass (LP) filtering, the lower frequency component $f_{RF} - f_{LO}$, known as the intermediate frequency (IF), is selected for further processing.

The combiner can be implemented through the use of a $90^0$ (or $180^0$) directional coupler.

The directional coupler is normally used to split the input signal and distributed power.

The detector traditionally employs a single diode as a nonlinear device.

Two input frequencies are used to create new frequencies at the output of the system.



It is seen that the **RF** input voltage signal is combined with the LO signal and supplied

to a semiconductor device with a nonlinear transfer characteristic at its output side

driving a current into the load.

$$I = I_0(e^{V/V_T} - 1)$$

Alternatively, for a MESFET we have approximately a square behaviour:

$$I(V) = I_{DSS}(1 - V/V_{T0})^2$$

The input voltage is represented as the sum of the **RF** signal and LO signal and a bias $V_Q$. This voltage is applied to the nonlinear device whose current output characteristic can be found via a Taylor series expansion.

$$I(V) = I_Q + V\left(\frac{dI}{dV}\right)\bigg|_{V_Q} + \frac{1}{2}V^2\left(\frac{d^2I}{dV^2}\right)\bigg|_{V_Q} + \ldots = I_Q + VA + V^2B + \ldots$$

Neglecting the constant bias $V_Q$ and $I_Q$,

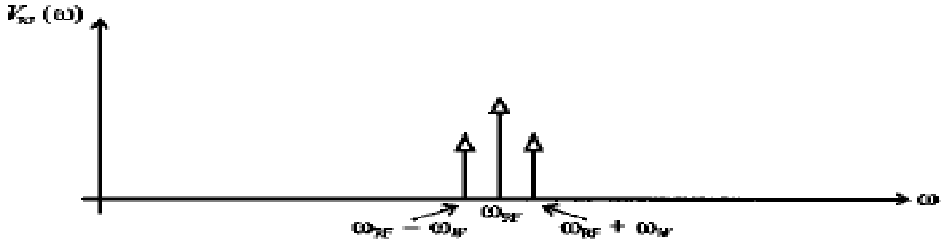
$$\begin{aligned} I(V) &= A\{V_{RF}\cos(\omega_{RF}t) + V_{LO}\cos(\omega_{LO}t)\} \\ &\quad + B\{V_{RF}^2\cos^2(\omega_{RF}t) + V_{LO}^2\cos^2(\omega_{LO}t)\} \\ &\quad + 2BV_{RF}V_{LO}\cos(\omega_{RF}t)\cos(\omega_{LO}t) + \ldots \end{aligned}$$

$$I(V) = \ldots + BV_{RF}V_{LO}\{\cos[(\omega_{RF} + \omega_{LO})t] + \cos[(\omega_{RF} - \omega_{LO})t]\}$$

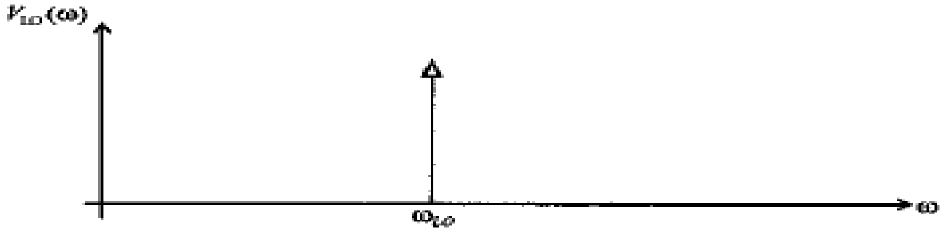
After performing mixing, according to the resulting spectral representation contains both **up converted** and **down converted** frequency Components.

- Lower sideband, or LSB ($\omega_{RF} - \omega_{LO}$)
- Upper sideband, or USB ($\omega_{RF} + \omega_{LO}$)
- Double sideband, or DSB ($\omega_{RF} + \omega_{LO}, \omega_{RF} - \omega_{LO}$)

$$\omega_{RF} - \omega_{LO} = \omega_{IF}$$



(a) RF signal



(b) LO signal

(c) Down- and upconverted spectral products

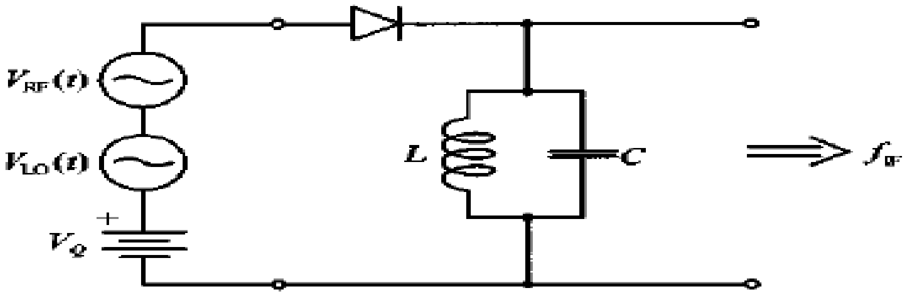
## Single-Ended Mixer Design:

The simplest and least efficient mixer is the single-ended design involving a Schottky diode.

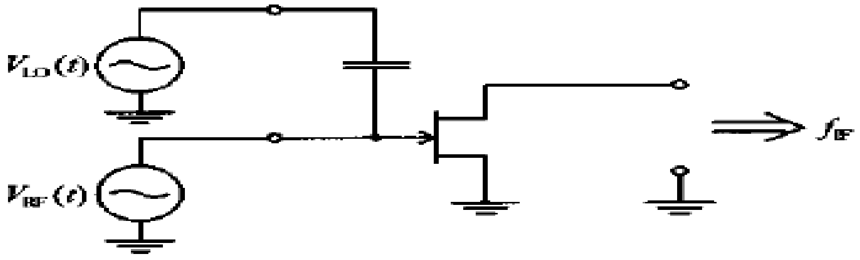
The RF and LO sources are supplied to an appropriately biased diode followed by a resonator circuit tuned to the desired IF.

In the improved design involving a FET is able to provide a gain to the incoming RF and LO signals.

In both cases the combined RF and LO signal is subjected to a nonlinear device with exponential (diode) or nearly quadratic (FET) transfer characteristic followed by a bandpass filter whose task is to isolate the IF signal.



(a) Diode mixer



(b) FET mixer

**Single-Balanced Mixer:**

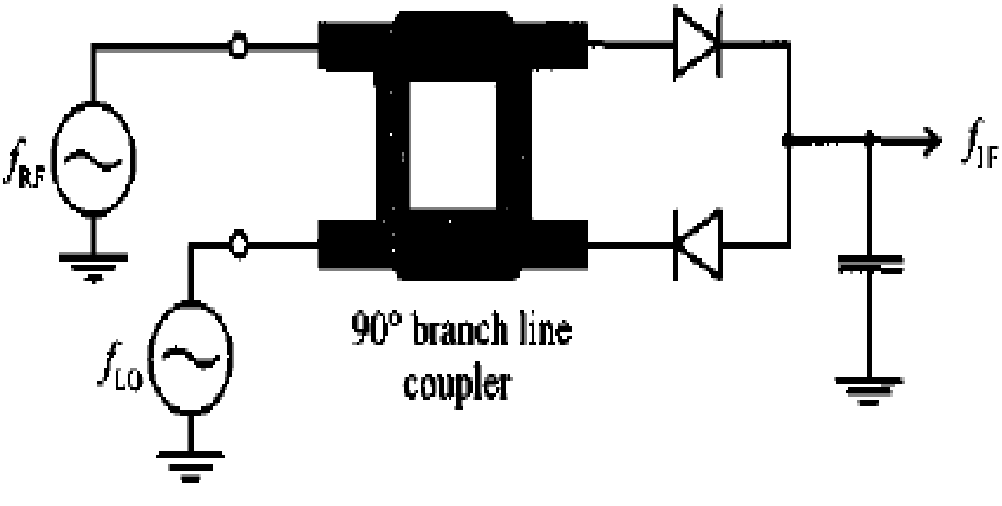


**Figure 10-41 Balanced mixer involving a hybrid coupler.**

This design is capable of suppressing a considerable amount of noise because the opposite diode arrangement in conjunction with the 90" phase shift provides a good degree of noise cancellation.

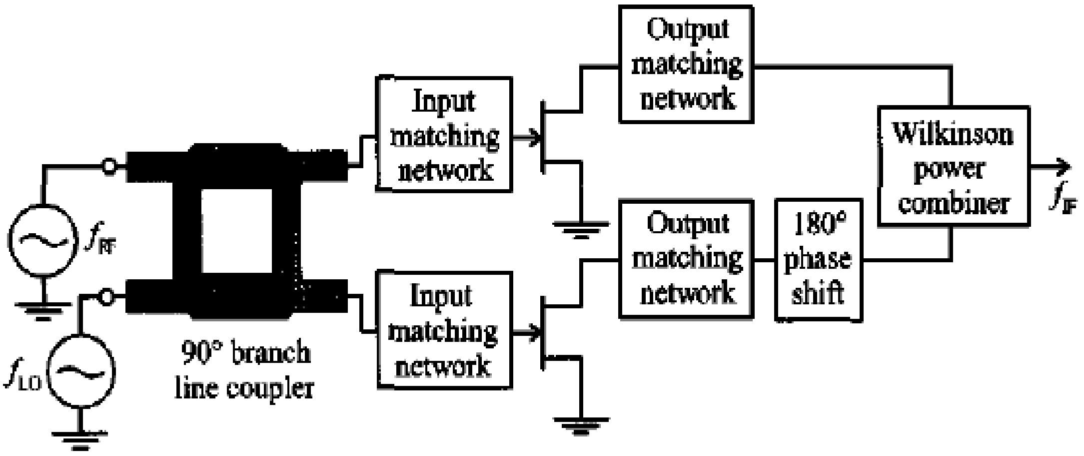


**Figure 10-42** Single-balanced MESFET mixer with coupler and power combiner.

The 180" phase shift is needed since the second

MESFET cannot easily be reversed as done in the anti-parallel diode configuration.

**Double-Balanced Mixer:**

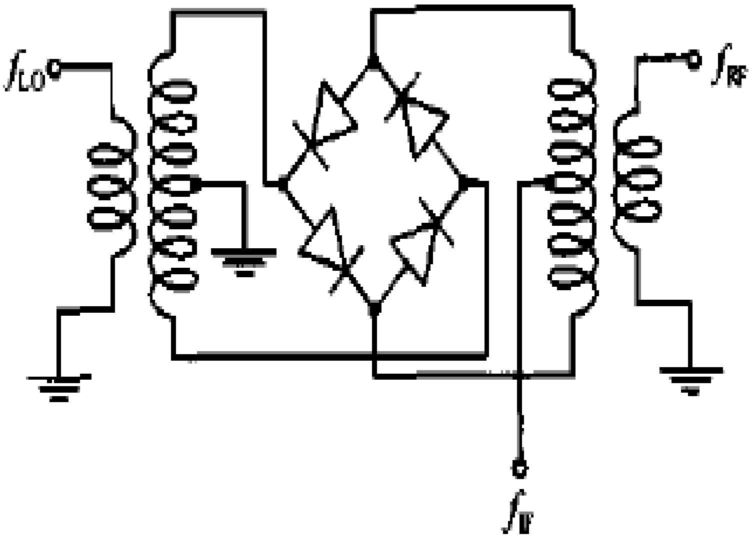


**Figure 10-43** Double-balanced mixer design.

The double-balanced mixer can be constructed by using four diodes arranged in a

rectifier configuration.

The additional diodes provided better isolation and an improved suppression of spurious modes.

Unlike the single-balanced approach, the double-balanced design eliminates all even harmonics of both the LO and **RF** signals.

**Voltage-Controlled Oscillator**

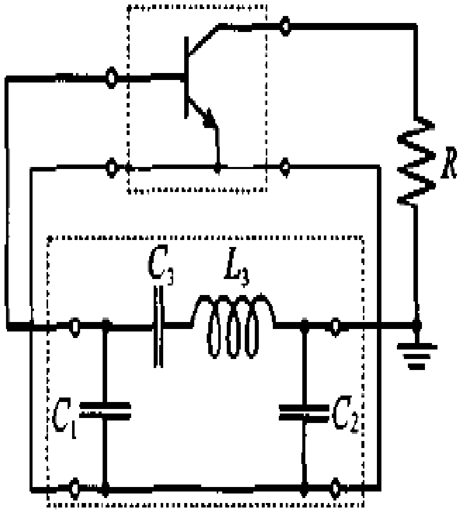
In which feedback loop for the Clapp oscillator

can be modified, by replacing $C_3$ with the varactor diode and an appropriate

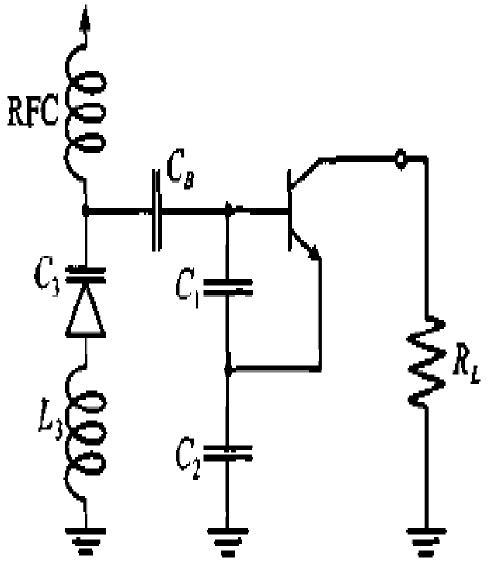
DC isolation.

In the varactor diode, with its variable capacitance that can be affected by the reverse bias $V_Q$

$$C_V = C_{V0}(1 - V_Q/V_{\text{diff}})^{-1/2}$$



(a) Pi-type feedback loop



(b) Redrawn circuit with DC isolation

The input impedance can be computed from two loop equations:

$$v_{IN} - i_{IN}X_{C1} - i_{IN}X_{C2} + i_BX_{C1} - \beta i_BX_{C2} = 0 \tag{10.43a}$$

$$h_{11}i_B + i_BX_{C1} - i_{IN}X_{C1} = 0 \tag{10.43b}$$

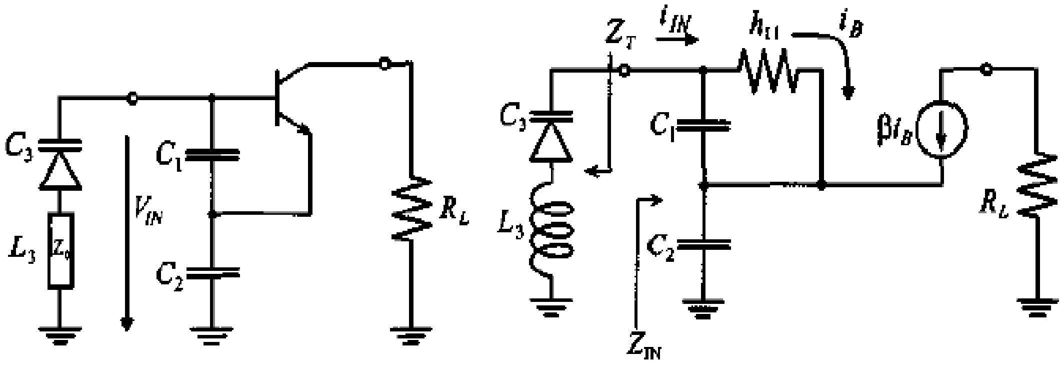


Figure 10-26 Circuit analysis of varactor diode oscillator.

Rearranging leads to

$$Z_{\mathrm{IN}} = \frac{1}{h_{11} + X_{C1}}[h_{11}(X_{C1} + X_{C2}) + X_{C1}X_{C2}(1+\beta)] \qquad (10.44)$$

The equation can be simplified by noting that $(1+\beta) \approx \beta$ and assuming that $h_{11} \gg X_{C1}$, which results in

$$Z_{\mathrm{IN}} = \frac{1}{j\omega}\left[\frac{1}{C_1} + \frac{1}{C_2}\right] - \frac{\beta}{h_{11}}\left(\frac{1}{\omega^2 C_1 C_2}\right) \qquad (10.45)$$

As expected from our previous discussion, the input resistance is negative. Therefore, with $g_m = \beta/h_{11}$,

$$R_{\mathrm{IN}} = -\frac{g_m}{\omega^2 C_1 C_2} \qquad (10.46a)$$

and

$$X_{\mathrm{IN}} = \frac{1}{j\omega C_{\mathrm{IN}}} \qquad (10.46b)$$

where $C_{\mathrm{IN}} = C_1C_2/(C_1 + C_2)$. The resonance frequency follows from the previously established condition $X_1 + X_2 + X_3 = 0$ (see Section 10.1.2), or

$$j\left(\omega_0 L_3 - \frac{1}{\omega_0 C_3}\right) - \frac{1}{j\omega_0}\left[\frac{1}{C_1} + \frac{1}{C_2}\right] = 0 \qquad (10.47)$$

with the result

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{L_3}\left(\frac{1}{C_3} + \frac{1}{C_2} + \frac{1}{C_1}\right)}$$

It can be concluded from (10.46a) that the combined resistance of the var
must be equal to or less than $|R_{\mathrm{IN}}|$ in order to create sustained oscillations.

## PART-A

1. **Write the function of matching networks? [Nov/dec-15, Nov/dec-11] BTL1**

   Matching networks can help stabilize the amplifier by keeping the source and load impedances in the appropriate range. Impedance matching (or tuning) is an important issue for - Maximum power is delivered when load is matched to line (assuming the generator is matched) - Power loss is minimized. S/N- ratio of receiver components is increased. - Amplitude and phase errors are reduced.

2. **What is function of input and output matching networks? BTL1**

   Input and output matching networks are needed to reduce undesired reflections and improve the power flow capabilities.

3. **What are the parameters used to evaluate the performance of an amplifier? [Nov/dec-15] BTL1**

   Key parameters of amplifier, to evaluate the performance are

   i. Gain and gain flatness(in dB)

   ii. Operating frequency and bandwidth (in Hz)

   iii. Output power (in dB)

   iv. Power supply requirements (in V and A)

   v. Input and output reflection coefficients (VSWR)

   vi. Noise figure (in dB)

4. **Define transducer power gain.[Nov/dec-13, April/May 2017] BTL1**

   Transducer power gain is nothing but the gain of the amplifier when placed between source and load.

   $G_T$= Power delivered to the load/Available power from the source.

   GT=PL/Pavg

5. **Write a short note on feedback of RF circuit. BTL1**

(1)If |T|>1, then the magnitude of the return voltage wave increases called positive feedback, which causes instability (oscillator).

**(2)If |T|<1, then the return voltage wave is totally avoided (amplifier). It is called as negative feedback.**

6. **Define power gain of amplifier in terms of S- parameter and reflection coefficient. [Nov/Dec-12, Nov/Dec13] BTL1**

**Transducer Power Gain**

Transducer Power Gain is nothing but the gain of the amplifier when placed between source and load

$$G_T = \frac{(1-|i|^2)|S21|^2(1-|S|^2)}{|1-_{sin}|^2|1-S22_L|^2}$$

The Operating power gain is defined as the ratio of power delivered to the load to the power supplied to the amplifier.

$$G_T = \frac{(1-|i|^2)|S21|^2}{|1-_{sin}|^2|1-S22_L|^2}$$

7. **What are the considerations in selecting a matching network? [Nov/Dec12] BTL1**

(i) Complexity of the system

(ii) Bandwidth requirement

(iii) Adjustability

(iv) Implementation

(v) Maximum power delivery

(vi) Optimal efficiency.

8. **Define Stability. [May/June-14] BTL1**

Stability refers to the situation where the amplifier remains stable for any passive source and load at the selected frequency and bias condition.