1. What is meant by tuned amplifiers?
   Tuned amplifiers are amplifiers that are designed to reject a certain range of frequencies below a lower cut off frequency $\omega_L$ and above a upper cut off frequency $\omega_H$ and allows only a narrow band of frequencies.

2. Classify tuned amplifiers.
   1. Single tuned amplifier.
   2. Double tuned amplifier.
   4. Stagger tuned amplifier.

3. What are the advantages of double tuned amplifier?
   - In double tuned amplifiers, the tuning is done both at the primary and secondary.
   - The double tuned amplifiers provide a wider bandwidth, flatter pass band and a greater selectivity.

4. Define resonance.
   The reactance of the capacitor equals that of the inductor reactance. i.e $\omega_C = 1/\omega_L$.

5. What is Quality factor?
   The ratio of inductive reactance of the coil at resonance to its resistance is known as quality factor.
   $$Q = \frac{X_L}{R}.$$ 

6. Define gain bandwidth product of a tuned amplifier.
   The gain bandwidth (GBW) product is a figure of merit defined in terms of mid band gain and upper 3-db frequency $f_h$ as $\text{GBW} = |A_{\text{im}}|f_h = g_m/2\pi c$.

7. What is the other name for tuned amplifier?
   Tuned amplifiers used for amplifying narrow band of frequencies hence it is also known as “narrow band amplifier” or “Band pass amplifier”.

8. What is a synchronously tuned amplifier?
   When tuned amplifiers are cascaded if all the amplifier stages are identical and tuned to same frequency $f_o$ then it is called as synchronously tuned amplifier. This results in a increased in gain and reduction in bandwidth.

9. What is meant by neutralization?
   It is the process by which feedback can be cancelled by introducing a current that is equal in magnitude but 180° out of phase with the feedback signal at the input of the active device. The two signals will cancel and the effect of feedback will be eliminated. This technique is termed as neutralization.

10. What is unilateralisation?
    It is the phenomenon by which a signal can be transmitted from the input to the output alone and not vice versa. In a unilateralised amplifier both resistive and reactive effects are cancelled.
11. What is stagger tuned amplifier?

In this configuration one or more tuned amplifiers are cascaded each amplifier stage is tuned to different frequencies. This results in decreased gain and increased bandwidth.

12. What is the effect of ‘Q’ on stability?

Higher the value of Q provides better selectivity, but smaller bandwidth and larger gain. Hence it provides less stability.

13. What is the application of tuned amplifiers?

The application of tuned amplifiers to obtain a desired frequency and rejecting all other frequency in
   (i). Radio and T.V broadcasting as tuning circuit.
   (ii). Wireless communication system.

14. What is meant by unloaded and loaded Q of tank circuit? [APR – 2003]

- Unloaded Q is the ratio of stored energy to dissipated energy in a reactor or resonator.
- The loaded Q (or) Q_L of a resonator is determined by how tightly the resonator is coupled to its terminations.

15. Mention the applications of class ‘c’ tuned amplifier.[APR – 2003]

- One of the most common applications for mixer is in radio receivers. The mixer is used to convert incoming signal to a lower frequency where it is easier to obtain the high gain and selectivity required.
- Mixer circuits are used to translate signal frequency to some lower frequency or to some higher frequency. When it is used to translate signal to lower frequency it is called down converter. When it is used to translate signal to higher frequency, it is called up converter.

16. Mention the need for stagger-tuned amplifier.

The double tuned amplifier gives greater 3 db bandwidth having steeper sides and flat top. But alignment of double tuned amplifier is difficult. To overcome this problem two single tuned amplifiers are cascaded.

17. What are the advantages of tuned circuit?

- High selectivity
- Smaller collector supply voltage
- Small power gain.

18. Mention the bandwidth of a double tuned amplifier.

Bandwidth \((\omega_2 - \omega_1) = \omega_o / Q \sqrt{(b^2 - 1) + 2b}\)

Where, \(\omega_o\) is the resonance frequency in cycle per sec.
- Q is the Quality factor of the coil alone.
- B is a constant.

19. What is principle of Hazel tine neutralization?

Hazel tine introduced a circuit in which the troublesome effect of the collector to base capacitance of the transistor was neutralized by introducing a signal which cancels the signal coupled through the collector to base capacitance.

20. List the performance measure of a tuned amplifier.

- Selection of a desired radio frequency signal.
- Effective quality factor.
- Gain
- Bandwidth.
21. What are the characteristics of an ideal tuned amplifier?
   - Selects a single radio frequency and amplifies the same by rejecting all other frequencies.
   - Bandwidth is zero.
   - Harmonic distortion is zero.

22. Write down the relationship between bandwidth and effective Q of a tuned amplifier?
   \[ \text{Bandwidth} = \frac{\omega_0}{Q_{\text{effective}}} \]

23. What are the different methods of coupling? (or) Point out different methods of coupling the load to a tuned amplifier.
   - The different methods of coupling the load to a tuned amplifier are:
     - Capacitive coupling,
     - Inductive coupling.

24. Why tuned amplifier cannot be used at low frequency?
   - For low frequencies the size L and C are large. So the circuit will be bulky and expensive, hence the tuned amplifiers cannot be used at low frequency.

25. What are band pass amplifiers?
   - Band pass amplifiers are amplifiers circuits which allow a certain range of frequencies in between two cut off frequencies \( f_1, f_2 \) and attenuates all the other frequencies or rejects all other frequencies.

26. What are the drawbacks of a single tuned amplifier?
   - Narrow bandwidth on smaller pass band, which will result in poor production of the audio signal.
   - The sides (and the top) of a gain versus frequency curve are not steeper.

27. The bandwidth of single tuned amplifier is 10 KHz. If four such stages are connected in series, what is its effective bandwidth.
   - The bandwidth of \( n \) number of tuned amplifiers connected in series is, \( BW_T = BW_1 \)
   - Where, \( BW_T \) = Total (effective) Bandwidth.
   - \( BW_1 \) = Single tuned amplifier bandwidth.
   - \( n \) = number of stages.
   - \( BW_T = 10 \times 10^3 \)
   - \( BW_T = 43.5 \text{ KHz} \)

28. The bandwidth of a double-tuned amplifier is 10 KHz. Calculate the number of such stages to be connected to obtain the bandwidth of 5.098 KHz.
   - \( BW_T = BW_1 \left(2^{1/n} - 1\right)^{1/4} \)
   - \( 2^{1/n} = 1.0676 \)
   - Taking log on both sides,
   - \( 1/n \log (2) = \log (1.0676) \)
   - \( n = 10 \)

29. Calculate the resonant frequency of a class c tuned amplifier whose capacitor \( c=10 \text{pf} \) and inductor \( L=1 \text{mH} \).
   - The resonant frequency of class-c tuned amplifier is \( f_r = \frac{1}{2 \pi} = 1/2 \times 3.14 \)
   - \( f_r = 1.59 \text{ MHz} \)

30. What do you mean by tuned amplifiers?
   - The amplifiers which amplify only selected range of frequencies (narrow band of frequencies) with the help of tuned circuits (parallel LC circuit) are called tuned amplifiers.
31. What are the various types of tuned amplifiers?
   (1) Small signal tuned amplifiers
       a. Single tuned amplifiers
       (i) Capacitive coupled
       (ii) Inductively coupled (or) Transformer coupled
       b. Double tuned amplifiers
c. Stagger tuned amplifiers
   (2) Large signal tuned amplifiers.

32. Give the expressions for the resonance frequency and impedance of the tuned circuit.
   \[ f = \frac{1}{2\pi\sqrt{LC}} \]
   \[ L \frac{Z}{R} = \frac{1}{2\pi LC CR} \]

33. What is the response of tuned amplifiers?
   The response of tuned amplifier is maximum at resonant frequency and it falls sharply for frequencies below and above the resonant frequency.

34. When tuned circuit is like resistive, capacitive and inductive?
   (1) At resonance, circuit is like resistive.
   (2) For frequencies above resonance, circuit is like capacitive. (3) For frequencies below resonance, circuit is like inductive.

35. What are the various components of coil losses?
   (1) Copper loss
   (2) Eddy current loss
   (3) Hysteresis loss

36. Define Q factor of resonant circuit.
   (1) It is the ratio of reactance to resistance.
   (2) It also can be defined as the measure of efficiency with which inductor can store the energy.
   \[ Q = \frac{2\pi * (\text{Maximum Energy Stored per cycle})}{\text{Energy dissipated per cycle}} \]

37. What is dissipation factor?
   (1) It is defined as \(1/Q\).
   (2) It can be referred to as the total loss within a component.

38. Define unloaded and loaded Q of tuned circuit.
   (1) The unloaded Q or QU is the ratio of stored energy to dissipated energy in a reactor or resonator.
   (2) The loaded Q or QL of a resonator is determined by how tightly the resonator is coupled to its terminations.

39. Why quality factor is kept as high as possible in tuned circuits?
   1. When Q is high, bandwidth is low and we get better selectivity. Hence Q is kept as high as possible in tuned circuits.
   2. When Q is high inductor losses are less.

40. List various types of cascaded Small signal tuned amplifiers.
   1. Single tuned amplifiers.
   2. Double tuned amplifiers.
   3. Stagger tuned amplifiers.
41. How single tuned amplifiers are classified?
   1. Capacitance coupled single tuned amplifier.
   2. Transformer coupled or inductively coupled single tuned amplifier.

42. What are single tuned amplifiers?
   Single tuned amplifiers use one parallel resonant circuit as the load impedance in each stage and all the tuned circuits are tuned to the same frequency.

43. What are double tuned amplifiers?
   Double tuned amplifiers use two inductively coupled tuned circuits per stage, both the tuned circuits being tuned to the same frequency.

44. What are stagger tuned amplifiers?
   Stagger tuned amplifiers use a number of single tuned stages in cascade, the successive tuned circuits being tuned to slightly different frequencies. (OR)
   It is a circuit in which two single tuned cascaded amplifiers having certain bandwidth are taken and their resonant frequencies are adjusted that they are separated by an amount equal to the bandwidth of each stage. Since resonant frequencies are displaced it is called stagger tuned amplifier.

45. What is the effect of cascading single tuned amplifiers on bandwidth?
   Bandwidth reduces due to cascading single tuned amplifiers.

46. List the advantages and disadvantages of tuned amplifiers.
   **Advantages:**
   1. They amplify defined frequencies.
   2. Signal to Noise ratio at output is good.
   3. They are well suited for radio transmitters and receivers.
   4. The band of frequencies over which amplification is required can be varied.
   **Disadvantages:**
   1. Since they use inductors and capacitors as tuning elements, the circuit is bulky and costly.
   2. If the band of frequency is increased, design becomes complex.
   3. They are not suitable to amplify audio frequencies.

47. What are the advantages of double tuned amplifier over single tuned amplifier?
   1. It provides larger 3 dB bandwidth than the single tuned amplifier and hence provides the larger gain-bandwidth product.
   2. It provides gain versus frequency curve having steeper sides and flatter top.

48. What the advantages are of stagger tuned amplifier?
   The advantage of stagger tuned amplifier is to have better flat, wideband characteristics.

49. Mention the applications of class C tuned amplifier.
   1. Class C amplifiers are used primarily in high-power, high-frequency applications such as Radio-frequency transmitters.
   2. In these applications, the high frequency pulses handled by the amplifier are not themselves the signal, but constitute what is called the Carrier for the signal.
   3. Amplitude modulation is one such example.
   4. The principal advantage of class-C amplifier is that it has a higher efficiency than the other amplifiers.
50. What is Neutralization?

The technique used for the elimination of potential oscillations is called neutralization. (OR) The effect of collector to base capacitance of the transistor is neutralized by introducing a signal that cancels the signal coupled through collector base capacitance. This process is called neutralization.

51. What is the use of Neutralization?

1. BJT and FET are potentially unstable over some frequency range due to the feedback parameter present in them.
2. If the feedback can be cancelled by an additional feedback signal that is equal in amplitude and opposite in sign, the transistor becomes unilateral from input to output the oscillations completely stop.
3. This is achieved by Neutralization.

52. What are the different types of neutralization?

1. Hazeltine neutralization
2. Rice neutralization

53. What is rice neutralization?

It uses center tapped coil in the base circuit. The signal voltages at the end of tuned base coil are equal and out of phase.

Part – B (16 marks)

1. Classification of tuned amplifiers. (Apr / May 10)

Multistage amplifiers are used to obtain large overall gain. The cascaded stages of multistage tuned amplifiers can be categorized as given below:

- Single tuned amplifiers
- Double tuned amplifiers
- Stagger tuned amplifiers.

These amplifiers are further classified according to coupling used to cascade the stages of multistage amplifier.

- Capacitive coupled
- Inductive coupled
- Transformer coupled.

Small signal tuned amplifier:

A common emitter amplifier can be converted into a single tuned amplifier by including a parallel tuned circuit.
Assumptions:
1. $R_L << R_C$
2. $r_{bb'} = 0$

With these assumptions, the simplified equivalent circuit for a single tuned amplifier is as shown in Fig. 3.8.

Fig. 3.8 Equivalent circuit of single tuned amplifier

where
$$C_{eq} = \frac{C'}{1 + g_m R_L} C_{h'}$$

$C'$: External capacitance used to tune the circuit

$(1 + g_m R_L) C_{h'}$: The Miller capacitance

$r_s$: Represents the losses in coil
The series RL circuit in Fig. 3.7 is replaced by the equivalent RL circuit in Fig. 3.8 assuming coil losses are low over the frequency band of interest, i.e., the coil Q high.

\[
Q_c = \frac{\omega L}{r_c} \gg 1
\]

\[\therefore\quad Y_1 = \frac{1}{\omega^2 L^2 + j\omega L}
\]

\[Y_2 = \frac{1}{R_p + j\omega L}\]

\[\therefore\quad \frac{r_c}{\omega^2 L^2 + j\omega L} = \frac{1}{R_p + j\omega L}
\]

The conditions for equivalence are most easily established by equating the admittances of the two circuits shown in Fig. 3.9.

\[Y_1 = \frac{1}{r_c + j\omega L} = \frac{r_c - j\omega L}{r_c^2 + \omega^2 L^2}
\]

\[= \frac{r_c}{r_c^2 + \omega^2 L^2} - \frac{j\omega L}{r_c^2 + \omega^2 L^2}
\]

\[\therefore\quad \omega L \gg r_c \text{ from equation (1)}
\]
Therefore, equating \( Y_1 \) and \( Y_2 \) we get,
\[
\frac{r_c}{\omega^2 L^2} + \frac{1}{j\omega L} = \frac{1}{R_p} + \frac{1}{j\omega L}
\]
\[
\Rightarrow \quad \frac{1}{R_p} = \frac{r_c}{\omega^2 L^2}
\]
\[
= \frac{r_c^2}{r_c \omega^2 L^2} = \frac{1}{r_c Q_r^2}
\]
\[
\therefore \quad R_p = r_c Q_r^2 = \omega L Q_r
\]
\[
\therefore \quad \omega L = Q_r r_c \text{ from equation (1)} \quad \ldots \quad (2)
\]

Looking at Fig. 3.8 we have,
\[
R = r_i \parallel R_p \parallel r_{i'e'}
\]
\[
\therefore \quad \ldots \quad (3)
\]

The current gain of the amplifier is then
\[
A_i = \frac{-g_m R}{1 + j(\omega RC - R/\omega L)} = \frac{-g_m R}{1 + j\omega RC(\omega / \omega_o - \omega_c / \omega)} \quad \ldots \quad (4)
\]

where
\[
\omega_o^2 = \frac{1}{LC}
\]

We define the \( Q \) of the tuned circuit at the resonant frequency \( \omega_o \) to be
\[
Q_i = \frac{R}{\omega_o L} = \omega_o RC \quad \ldots (5)
\]
\[
\therefore \quad \ldots \quad (5)
\]

\[
A_i = \frac{-g_m R}{1 + jQ_i(\omega / \omega_o - \omega_c / \omega)}
\]
At \( \omega = \omega_o \), gain is maximum and it is given as,
\[
\therefore \quad A_i (\text{max}) = -g_m R \quad \ldots (6)
\]

The Fig. 3.10 shows the gain versus frequency plot for single tuned amplifier. It shows the variation of the magnitude of the gain as a function of frequency.
At 3 dB frequency,

\[ |A_1| = \frac{g_m R}{\sqrt{2}} \] ... (7)

.: At 3 dB frequency

\[ 1 + jQ \left( \frac{\omega}{\omega_o} - \frac{\omega_o}{\omega} \right) = \sqrt{2} \]

\[ 1 + Q^2 \left( \frac{\omega}{\omega_o} - \frac{\omega_o}{\omega} \right)^2 = 2 \] ... (8)

This equation is quadratic in \( \omega^2 \) and has two positive solutions, \( \omega_H \) and \( \omega_L \). After solving equation (8) we get 3 dB bandwidth as given below.

\[ BW = f_H - f_L = \frac{\omega_o}{2\pi Q_i} = \frac{1}{2\pi RC} \] ... (9)

\[ BW = \frac{1}{2\pi RC} \]

**Single tuned FET amplifier:**
The equivalent circuit for the given amplifier is as shown in the Fig. 3.12.

![Equivalent circuit of single tuned FET amplifier](image)

**Fig. 3.12 Equivalent circuit of single tuned FET amplifier**

The voltage gain is given by,

\[ A_v = -a g_m \left( r_{ds} || R_f \right) \left[ (r_f || R_p) / r_f \right] \]  \hspace{1cm} (1)

where

\[ C_i = a^2 \left[ C_{gs} + C_{gd} \left[ 1 + g_m \left( r_{ds} || R_f \right) \right] \right] \]  \hspace{1cm} (2)

\[ Q_i = \omega_0 \left( r_f || R_p \right) (C' + C_i) \]  \hspace{1cm} (3)

\[ \omega_0^2 = \frac{1}{L (C' + C_i)} \]  \hspace{1cm} (4)

At centre frequency, i.e., at \( \omega = \omega_0 \) gain is

\[ A_{v_{\text{max}}} = -a g_m \left( r_{ds} || R_f \right) \frac{R_p}{r_f + R_p} \]  \hspace{1cm} (5)

The 3 dB bandwidth is given by,

\[ BW = \frac{1}{2 \pi (r_f || R_p) (C' + C_i)} \]  \hspace{1cm} (6)

**Single tuned capacitive coupled amplifier:**

Single tuned multistage amplifier circuit uses one parallel tuned circuit as a load in each stage with tuned circuits in all stages tuned to the same frequency. Fig. 3.13 shows a typical single tuned amplifier in CE configuration.

As shown in Fig. 3.13 tuned circuit formed by \( L \) and \( C \) acts as collector load and resonates at frequency of operation. Resistors \( R_1, R_2 \) and \( R_F \) along with capacitor \( C_E \) provides self bias for the circuit.

![Single tuned capacitive coupled transistor amplifier](image)

**Fig. 3.13 Single tuned capacitive coupled transistor amplifier**
Fig. 3.14 Equivalent circuit of single tuned amplifier

The Fig. 3.14 shows the equivalent circuit for single tuned amplifier using hybrid π parameters.

As shown in the Fig. 3.14, $R_i$ is the input resistance of the next stage and $R_o$ is the output resistance of the current generator $g_m V_{bc}$. The reactances of the bypass capacitor $C_B$ and the coupling capacitors $C_C$ are negligibly small at the operating frequency and hence these elements are neglected in the equivalent circuit shown in the Fig. 3.14.

The equivalent circuit shown in Fig. 3.14 can be simplified by applying Miller’s theorem. Fig. 3.15 shows the simplified equivalent circuit for single tuned amplifier.

Fig. 3.15 Simplified equivalent circuit for single tuned amplifier

Here $C_i$ and $C_{eq}$ represent input and output circuit capacitances, respectively. They can be given as,

$$C_i = C_{bc} + C_{bc} (1 - A) \quad \text{where } A \text{ is the voltage gain of the amplifier.} \quad \ldots (1)$$

$$C_{eq} = C_{bc} \left( \frac{A - 1}{A} \right) + C \quad \text{where } C \text{ is the tuned circuit capacitance.} \quad \ldots (2)$$

The $g_{oe}$ is represented as the output resistance of current generator $g_m V_{bc}$.

$$g_{oe} = \frac{1}{r_{ce}} = h_{oe} - g_m h_{re} = h_{oe} = \frac{1}{h_{oe}} \quad \ldots (3)$$
The series RL circuit is represented by its equivalent parallel circuit. The conditions for equivalence are most easily established by equating the admittances of the two circuits shown in Fig. 3.16.

Admittance of the series combination of RL is given as,

\[ Y = \frac{1}{R + j\omega L} \]

Multiplying numerator and denominator by \( R - j\omega L \) we get,

\[ Y = \frac{R - j\omega L}{R^2 + \omega^2 L^2} = \frac{R}{R^2 + \omega^2 L^2} - \frac{j\omega L}{R^2 + \omega^2 L^2} \]

\[ = \frac{R}{R^2 + \omega^2 L^2} - \frac{j\omega L}{\omega(R^2 + \omega^2 L^2)} \]

\[ = \frac{1}{R_p} + \frac{1}{j\omega L_p} \]

where

\[ R_p = \frac{R^2 + \omega^2 L^2}{R} \]

... (4)

and

\[ L_p = \frac{R^2 + \omega^2 L^2}{\omega^2 L} \]

... (5)

Centre frequency

The centre frequency or resonant frequency is given as,

\[ f_c = \frac{1}{2\pi\sqrt{L_p C_{eq}}} \]

... (6)

where

\[ L_p = \frac{R^2 + \omega^2 L^2}{\omega^2 L} \]

and

\[ C_{eq} = C_{eq} \left( \frac{A-1}{A} \right) + C \]

... (7)

\[ = C_o + C \]

Therefore, \( C_{eq} \) is the summation of transistor output capacitance and the tuned circuit capacitance.

Quality factor \( Q \)

The quality factor \( Q \) of the coil at resonance is given by,

\[ Q_c = \frac{\omega_c L}{R} \]

... (8)

where \( \omega_c \) is the centre frequency or resonant frequency.
This quality factor is also called unloaded $Q$, but in practice, transistor output resistance and input resistance of next stage act as a load for the tuned circuit. The quality factor including load is called as loaded $Q$ and it can be given as follows:

The $Q$ of the coil is usually large so that $\omega L \gg R$ in the frequency range of operation.

From equation (4) we have,

$$R_p = \frac{R^2 + \omega^2 L^2}{R} = R + \frac{\omega^2 L^2}{R}$$

As $\frac{\omega^2 L^2}{R} \gg 1$, $R_p = \frac{\omega^2 L^2}{R}$ \hspace{1cm} \ldots (9)

From equation (5) we have,

$$L_p = \frac{R^2 + \omega^2 L^2}{\omega^2 L} = \frac{R^2}{\omega^2 L} + L = L \therefore \omega L \gg R \hspace{1cm} \ldots (10)$$

From equation (9), we can express $R_p$ at resonance as,

$$R_p = \frac{\omega^2 L^2}{R}$$

$$= \omega \cdot Q_L \cdot L \therefore Q_L = \frac{\omega L}{R} \hspace{1cm} \ldots (11)$$

Therefore, $Q_L$ can be expressed in terms of $R_p$ as,

$$Q_L = \frac{R_p}{\omega L} \hspace{1cm} \ldots (12)$$

The effective quality factor including load can be calculated looking at the simplified equivalent output circuit for single tuned amplifier.

![Fig. 3.17 Simplified output circuit for single tuned amplifier](image)

**Fig. 3.17** Simplified output circuit for single tuned amplifier

Effective quality factor $Q_{eff} = \frac{\text{Susceptance of inductance } L \text{ or capacitance } C}{\text{Conductance of shunt resistance } R_t}$

$$= \frac{R_t}{\omega \cdot \frac{1}{C}} \text{ or } \omega \cdot L \cdot \frac{1}{C} \cdot R_t \hspace{1cm} \ldots (13)$$
**Voltage gain (A_v)**

The voltage gain for single tuned amplifier is given by,

\[ A_v = -g_m \frac{r_{b'e}}{r_{b'b} + r_{b'e}} \times \frac{R_t}{1 + 2|Q_{eff}|} \]

where

\[ R_t = R_c || R_p || R_i \]

\[ \delta = \text{Fraction variation in the resonant frequency} \]

\[ A_v \text{ (at resonance)} = -g_m \frac{r_{b'e}}{r_{b'b} + r_{b'e}} \times R_t \]

\[ \therefore \frac{A_v}{A_v \text{ (at resonance)}} = \frac{1}{\sqrt{1 + (2\delta Q_{eff})^2}} \quad \ldots (14) \]

**3 dB bandwidth**

The 3 dB bandwidth of a single tuned amplifier is given by,

\[ \Delta f = \frac{1}{2 \pi R_t C_{eq}} \]

\[ = \frac{\omega_t}{2 \pi Q_{eff}} \quad \therefore Q_{eff} = \frac{\omega_t R_t C_{eq}}{Q_{eff}} \quad \ldots (15) \]

\[ = \frac{f_t}{Q_{eff}} \quad \therefore \omega_t = 2\pi f_t \quad \ldots (16) \]

**Double tuned amplifier:**

The below figure shows double tuned RF amplifier in CE configuration. Here, voltage developed across tuned circuit is coupled inductively to another tuned circuit. Both tuned circuits are tuned to the same frequency.
The double tuned circuit can provide a bandwidth of several percent of the resonant frequency and gives steep sides to the response curve. **Analysis of double tuned circuits:**

The Fig. 3.19 (a) shows the coupling section of a transformer coupled double tuned amplifier. The Fig. 3.19 (b) shows the equivalent circuit for it. In which transistor is replaced by the current source with its output resistance ($R_o$). The $C_1$ and $L_1$ are the tank circuit components of the primary side. The resistance $R_1$ is the series resistance of the inductance $L_1$. Similarly, on the secondary side $L_2$ and $C_2$ represents tank circuit components of the secondary side and $R_2$ represents resistance of the inductance $L_2$. The resistance $R_i$ represents the input resistance of the next stage.

The Fig. 3.19 (c) shows the simplified equivalent circuit for the Fig. 3.19 (b). In simplified equivalent circuit the series and parallel resistances are combined into series elements. Referring equation (9) we have,

$$R_p = \frac{\omega^2 L^2}{R} \text{ i.e. } R = \frac{\omega^2 L^2}{R_p}$$

where $R$ represents series resistance and $R_p$ represents parallel resistance.
Therefore we can write,

\[ R_{11} = \frac{\omega_0^2 L_1^2}{R_0} + R_1 \]

\[ R_{12} = \frac{\omega_0^2 L_2^2}{R_1} + R_2 \]

In the simplified circuit the current source is replaced by voltage source, which is now in series with \( C_1 \). It also shows the effect of mutual inductance on primary and secondary sides.

We know that, \( Q = \frac{\omega \cdot L}{R} \)

Therefore, the Q factors of the individual tank circuits are

\[ Q_1 = \frac{\omega \cdot L_1}{R_{11}} \text{ and } Q_2 = \frac{\omega \cdot L_2}{R_{22}} \]...

(1)

Usually, the Q factors for both circuits are kept same. Therefore, \( Q_1 = Q_2 = Q \) and the resonant frequency \( \omega_0^2 = 1/L_1 \cdot C_1 = 1/L_2 \cdot C_2 \).

Looking at Fig. 3.19 (c), the output voltage can be given as,

\[ V_o = -\frac{j}{\omega_0 C_2} I_2 \]...

(2)

To calculate \( V_o/V_1 \) it is necessary to represent \( I_2 \) in terms of \( V_1 \). For this we have to find the transfer admittance \( Y_T \). Let us consider the circuit shown in Fig. 3.20. For this circuit, the transfer admittance can be given as,
\[ Y_T = \frac{I_2}{V_1} = \frac{I_2}{I_1 Z_{11}} = \frac{A_i}{Z_{11}} \]

\[ = \frac{Z_f}{Z_f^2 - Z_i (Z_n + Z_f)} \]

where \[ Z_{11} = \frac{V_1}{I_1} = Z_i - \frac{Z_f^2}{Z_n + Z_L} \] and

\[ A_i = \frac{I_2}{I_1} = -\frac{Z_i}{Z_n + Z_L} \]

The simplified equivalent circuit for double tuned amplifier is similar to the circuit shown in Fig. 3.20 with

\[ Z_f = j \omega M \]

\[ Z_i = R_{11} + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \]

\[ Z_n + Z_L = R_{22} + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \]

The equations for \( Z_f, Z_i \) and \( Z_n + Z_L \) can be further simplified as shown below.

\[ Z_f = j \omega M = j \omega k \sqrt{L_1 L_2} \]

where \( k \) is the coefficient of coupling.
Multiplying numerator and denominator by \( \omega_c L_1 \) for \( Z_i \) we get,

\[
Z_i = \frac{R_{11} \omega_c L_1}{\omega_c L_1} + j \omega_c L_1 \left( \frac{\omega L_1}{\omega_c L_1} - \frac{1}{\omega C_1 \omega_i L_1} \right)
\]

\[
= \frac{\omega_c L_1}{Q} + j \omega_c L_1 \left( \frac{\omega}{\omega_c} - \frac{\omega_c}{\omega} \right) \quad \therefore \frac{\omega}{\omega_c} - \frac{\omega_c}{\omega} = 1 + \delta - (1 - \delta) = 2 \delta
\]

\[
= \frac{\omega_c L_1}{Q} + (1 + j2Q\delta)
\]

\[
Z_o + Z_L = R_{22} + j \left( \frac{\omega L_2}{\omega C_2} - \frac{1}{\omega C_2} \right)
\]

By doing similar analysis as for \( Z_i \) we can write,

\[
Z_o + Z_L = \frac{\omega_c L_2}{Q} + (1 + j 2Q\delta)
\]

Then

\[
Y_T = \frac{Z_i}{Z_i^*} - (Z_o + Z_L) = \frac{1}{Z_i - Z_i \left( \frac{Z_o + Z_L}{Z_i} \right)}
\]

\[
Y_T = \frac{1}{j \omega_c k \sqrt{L_1 L_2} - \frac{\omega_c L_1}{Q} \left( 1 + j2Q\delta \right) \left( \frac{\omega_c L_2}{Q} \left( 1 + j2Q\delta \right) \right)}
\]

\[
Y_T = \frac{kQ^2}{\omega_c \sqrt{L_1 L_2} \left[ 4Q\delta - j(1 + k^2Q^2 - 4Q^2 \delta^2) \right]} \quad \ldots (3)
\]

Substituting value of \( L_2 \), i.e. \( V_i \times Y_T \) we get,

\[
V_o = \frac{-j}{\omega_c C_2} \frac{j g_m V_i}{\omega_c \sqrt{L_1 L_2}} \frac{kQ^2}{\omega_c \sqrt{L_1 L_2} \left[ 4Q\delta - j(1 + k^2Q^2 - 4Q^2 \delta^2) \right]} \]

\[
\therefore V_o = \frac{j g_m V_i}{\omega_c C_1}
\]

\[
A_v = \frac{V_o}{V_i} = g_m \omega_i^2 L_1 L_2 \left[ \frac{kQ^2}{\omega_c \sqrt{L_1 L_2} \left[ 4Q\delta - j(1 + k^2Q^2 - 4Q^2 \delta^2) \right]} \right]
\]

\[
\therefore \frac{1}{\omega_c C} = \omega_i L
\]
\[ \left[ \frac{g_m \omega_r \sqrt{L_1L_2}}{4Q \delta - j(1 + k^2Q^2 - 4Q^2 \delta^2)} \right] \]

... (4)

Taking the magnitude of equation (4) we have,

\[ |A_v| = g_m \omega_r \sqrt{L_1L_2} Q \frac{kQ}{\sqrt{1 + k^2Q^2 - 4Q^2 \delta^2 + 16Q^2 \delta^2}} \]

... (5)

The Fig. 3.21 shows the universal response curve for double tuned amplifier plotted with kQ as a parameter.

The frequency deviation \( \delta \) at which the gain peaks occur can be found by maximizing equation (4), i.e.

\[ 4Q \delta - j(1 + k^2Q^2 - 4Q^2 \delta^2) = 0 \]

... (6)
At $k^2Q^2 = 1$, i.e. $k = \frac{1}{Q}$, $f_1 = f_2 = f_r$. This condition is known as critical coupling. For values of $k < 1/Q$, the peak gain is less than maximum gain and the coupling is poor.

At $k > 1/Q$, the circuit is overcoupled and the response shows the double peak. Such double peak response is useful when more bandwidth is required.

The gain magnitude at peak is given as,

$$|A_p| = \frac{g_m \omega_0 \sqrt{L_1 L_2}}{2} kQ$$

And gain at the dip at $\delta = 0$ is given as,

$$|A_d| = \frac{|A_p|}{1 + k^2Q^2} \frac{2kQ}{1 + k^2Q^2}$$

The ratio of peak gain and dip gain is denoted as $\gamma$ and it represents the magnitude of the ripple in the gain curve.

$$\gamma = \frac{|A_p|}{|A_d|} = \frac{1 + k^2Q^2}{2kQ}$$

$$\gamma = \frac{|A_p|}{|A_d|} = \frac{1 + k^2Q^2}{2kQ}$$

Using quadratic simplification and choosing positive sign we get,

$$kQ = \gamma + \sqrt{\gamma^2 - 1}$$

The bandwidth between the frequencies at which the gain is $|A_d|$ is the useful bandwidth of the double tuned amplifier. It is given as,

$$BW = 2\delta' = \sqrt{2} (f_2 - f_1)$$

At 3 dB bandwidth,

$$\gamma = \sqrt{2}$$

$$\therefore \quad kQ = \gamma + \sqrt{\gamma^2 + 1} = \sqrt{2} + \sqrt{2^2 + 1} = 2.414$$

$$\therefore \quad 3 \text{ dB BW} = 2\delta' = \sqrt{2} (f_2 - f_1)$$

$$= \sqrt{2} \left[ f_r \left(1 - \frac{1}{2Q} \sqrt{k^2Q^2 - 1}\right) - f_r \left(1 - \frac{1}{2Q} \sqrt{k^2Q^2 - 1}\right) \right]$$

$$= \sqrt{2} \left[ \frac{f_r \sqrt{k^2Q^2 - 1}}{Q} \right]$$

$$= \sqrt{2} \left[ \frac{f_r \sqrt{(2.414)^2 - 1}}{Q} \right] = \frac{3.1f_r}{Q}$$
We know that, the 3 dB bandwidth for single tuned amplifier is $2 f_r/Q$. Therefore, the 3 dB bandwidth provided by double tuned amplifier ($3.1f_r/Q$) is substantially greater than the 3 dB bandwidth of single tuned amplifier.

Compared with a single tuned amplifier, the double tuned amplifier
1. Possesses a flatter response having steeper sides.
2. Provides larger 3 dB bandwidth.
3. Provides large gain-bandwidth product.

2. **Describe the principles involved in stagger tuned amplifier (Nov/Dec-05)**

The double tuned amplifier gives greater 3dB bandwidth having steeper sides and flat top. But alignment of double tuned amplifier is difficult. To overcome this problem two single tuned cascaded amplifiers having certain bandwidth are taken and their resonant frequencies are so adjusted that they are separated by an amount equal to the bandwidth of each stage. Since resonant frequencies are displaced or staggered, they are known as stagger tuned amplifiers. The advantage of stagger tuned amplifier is to have a better flat, wideband characteristics in contrast with a very sharp, rejective, narrow band characteristics of synchronously tuned circuits (tuned to same resonant frequencies). Fig. 3.23 shows the relationship of amplification characteristics of individual stages in a staggered pair to the overall amplification of the two stages.

![Figure 3.23](image1)

**Fig. 3.23**

![Figure 3.24](image2)

**Fig. 3.24 Response of individually tuned and staggered tuned pair**
The overall response of the two-stage staggered tuned pair is compared in Fig. 3.24 with the corresponding individual single tuned stages having the same resonant circuits. Looking at Fig. 3.24, it can be seen that staggering reduces the total amplification of the centre frequency to 0.5 of the peak amplification of the individual stage and at the centre frequency each stage has an amplification that is 0.707 of the peak amplification of the individual stage. Thus the equivalent voltage amplification per stage of the staggered pair is 0.707 times as great as when the same two stages are used without staggering. However, the half power (3 dB) bandwidth of the staggered pair is $\sqrt{2}$ times as great as the half power (3 dB) bandwidth of an individual single tuned stage. Hence the equivalent gain bandwidth product per stage of a staggered tuned pair is $0.707 \times \sqrt{2} = 1.00$ times that of the individual single tuned stages.

The stagger tuned idea can easily be extended to more stages. In case of three stage staggering, the first tuning circuit is tuned to a frequency lower than centre frequency while the third circuit is tuned to higher frequency than centre frequency. The middle tuned circuit is tuned at exact centre frequency.

**Analysis of stagger tuned amplifier:**

**Analysis**

From equation (14) of section 3.4 we can write the gain of the single tuned amplifier as,

$$\frac{A_v}{A_v \text{ (at resonance)}} = \frac{1}{1 + 2jQ_{\text{eff}} \delta} = \frac{1}{1 + jX} \text{ where } X = 2Q_{\text{eff}} \delta$$

Since in stagger tuned amplifiers the two single tuned cascaded amplifiers with separate resonant frequencies are used, we can assume that the one stage is tuned to the frequency $f_r + \delta$ and other stage is tuned to the frequency $f_r - \delta$. Therefore we have,

$$f_{r1} = f_r + \delta$$

and

$$f_{r2} = f_r - \delta$$

According to these tuned frequencies the selectivity functions can be given as,

$$\frac{A_v}{A_v \text{ (at resonance)}_1} = \frac{1}{1 + j(X+1)}$$

and

$$\frac{A_v}{A_v \text{ (at resonance)}_2} = \frac{1}{1 + j(X-1)}$$

The overall gain of these two stages is the product of individual gains of the two stages.
3. Large signal tuned amplifiers:

The output efficiency of an amplifier increases as the operation shifts from class A to class C through class AB and class B. As the output power of a radio transmitter is high and efficiency is prime concern, class B and class C amplifiers are used at the output stages in transmitter.

The operation of class B and class C amplifiers are non-linear since the amplifying elements remain cut-off during a part of the input signal cycle. The non-linearity generates harmonics of the single frequency at the output of the amplifier. In the push-pull arrangement where the bandwidth requirement is no limited, these harmonics can be eliminated or reduced. When a narrow bandwidth is desired, a resonant circuit is employed in class B and class C tuned RF power amplifiers to eliminate the harmonics.

\[
\frac{A_v}{A_v \text{ (at resonance)}_{\text{cascaded}}} = \frac{1}{1+j(X+1)} \times \frac{1}{1+j(X-1)} = \frac{1}{2+2jX-X^2} = \frac{1}{(2-X^2)+(2jX)}
\]

\[
\frac{A_v}{A_v \text{ (at resonance)}_{\text{cascaded}}} = \frac{1}{\sqrt{(2-X^2)^2+(2X)^2}} = \frac{1}{\sqrt{4-4X^2+X^4+4X^2}} = \frac{1}{\sqrt{4+X^4}}
\]

Substituting the value of \( X \) we get,

\[
\frac{A_v}{A_v \text{ (at resonance)}_{\text{cascaded}}} = \frac{1}{\sqrt{4+(2Q_{\text{eff}} \cdot \delta)^4}} = \frac{1}{\sqrt{4+16Q_{\text{eff}}^4 \delta^4}} = \frac{1}{2\sqrt{1+4Q_{\text{eff}}^4 \delta^4}}
\]
Class B tuned amplifier:

It works with a single transistor by sending half sinusoidal current pulses to the load. The transistor is biased at the edge of the conduction. Even though the input is half sinusoidal, the load voltage is sinusoidal because a high Q RLC tank shunts harmonics to ground. The negative half is delivered by the RLC tank. The Q factor of the tank needs to be large enough to do this. This is analogous to pushing someone on a swing. We only need to push in one direction, and the reactive energy stored will swing the person back in the reverse direction.

Class C tuned amplifier:

The amplifier is said to be class C amplifier, if the Q point and the input signal are selected such that the output signal is obtained for less than a half cycle, for a full input cycle. Due to such a selection of the Q point, transistor remains active, for less than a half cycle. Hence only that much part is reproduced at the output. For remaining cycle of the input cycle, the transistor remains cut-off and no signal is produced at the output.
From the figure, it is apparent that the total angle during which current flows is less than $180^\circ$. This angle is called the conduction angle, $\theta_c$.

The above shows the class C tuned amplifier. Here a parallel resonant circuit acts as a load impedance. As collector current flows for less than half a cycle, the collector current consists of a series of pulses with the harmonics of the input signal. A parallel tuned circuit acting as a load impedance is tuned to the input frequency. Therefore, it filters the harmonic frequencies and produce a sine wave output voltage consisting of fundamental component of the input signal.

4. **Frequency response of tuned amplifier:**

   To amplify the selective range of frequencies, the resistive load, $R_c$ is replaced by a tuned circuit. The tuned circuit is capable of amplifying a signal over a narrow band of frequencies centered at $f_r$, the amplifiers with such a tuned circuit as a load are known as tuned amplifier.
The above figure shows the tuned parallel LC circuit which resonates at a particular frequency. The resonant frequency and the impedance of tuned circuit is given as,

\[ f_r = \frac{1}{2\pi\sqrt{LC}} \quad \ldots (1) \]

and \[ Z_r = \frac{L}{CR} \quad \ldots (2) \]

The response of tuned amplifiers is maximum at resonant frequency and it falls sharply for frequencies below and above the resonant frequency.

In the figure 3 dB bandwidth is denoted as B nad 30 dB bandwidth is denoted as S. the ratio of 30 dB bandwidth (S) to the 3 dB bandwidth (B) is known as skirt selectivity.

At resonance, inductive and capacitive effects of tuned circuit cancel each other. As a result, circuit is like resistive and \( \cos \varphi = 1 \) i.e. voltage and current are in phase. For frequencies above resonance circuit is like capacitive and for frequencies below resonance it is like inductive. Since tuned circuit is purely resistive at resonance it can be used as a load for amplifier.
5. **Coil losses in tuned amplifiers:**

The tuned circuit consists of a coil. Practically, coil is not purely inductive. It consists of few losses and they are represented in the form of leakage resistance in series with the inductor. The total loss of the coil is comprised of copper loss, eddy current loss and hysteresis loss. The copper loss at low frequencies is equivalent to the d.c. resistance of the coil. Copper loss is inversely proportional to the frequency. Therefore, as frequency increases, the copper loss decreases. Eddy current loss in iron and copper coil are due to currents flowing within the copper or core cased by induction. The result of eddy currents is a loss due to heating within the inductors copper or core. Eddy current losses are directly proportional to the frequency. Hysteresis loss is proportional to the area enclosed by the hysteresis loop and to the rate at which this loop is transversed. It is a function of signal level and increases with frequency. Hysteresis loss is however independent of frequency.

![Fig. 3.3 Inductor with leakage resistance](image)

The total losses in the coil or inductor is represented by inductance in series with leakage resistance of the coil.

6. **Define Quality factor. Obtain the quality factor for a parallel resonant circuit. Derive the loaded and unloaded Q.**

**Quality factor:**

Quality factor (Q) is important characteristics of an inductor. The Q is the ratio of reactance to resistance and therefore it is unitless. It is the measure of how 'pure' or 'real' an inductor is (i.e. the inductor contains only reactance). The higher the Q of an inductor the fewer losses there are in the inductor. The Q factor also can be defined as the measure of efficiency with which inductor can store the energy. The dissipation factor (D) that can be referred to as the total loss within a component is defined as 1/Q. The Fig. 3.4 shows the quality factor equations for series and parallel circuits and its relation with dissipation factor.

![Fig. 3.4 Quality factor equations](image)

Quality factor equation $Q = \frac{1}{D} = \frac{\omega L_s}{R_s} = \frac{R_p}{\omega L_p}$
Loaded and unloaded Q:

Unloaded Q is the ratio of stored energy to dissipated energy in a reactor or resonator. The unloaded Q or $Q_U$ of an inductor or capacitor is $X/R_o$, where $X$ represents the reactance and $R_o$ represents the series resistance. The loaded Q or $Q_L$ of a resonator is determined by how tightly the resonator is coupled to its terminations.

Let us consider the tuned load circuit as shown in the Fig. 3.5. Here, $L$ and $C$ represents tank circuit. The internal circuit losses of inductor are represented by $R_o$ and $R_c$ represents the coupled in load. For this circuit, we can write

$$R_o = \frac{\omega_o L}{Q_U} \quad \text{and} \quad R_c = \frac{\omega_o L}{Q_L}$$

where $Q_U$ is unloaded Q and $Q_L$ is loaded Q.

The circuit efficiency for the above tank circuit is given as,

$$\eta = \frac{I^2 R_c}{I^2 (R_c + R_o)} = \frac{Q_U}{Q_U + Q_L} \times 100 \%$$

From above equation it can be easily realized that for high overall power efficiency, the coupled-in load $R_c$ should be large in comparison to the internal circuit losses represented by $R_o$ of the inductor.

The quality factor $Q_L$ determines the 3 dB bandwidth for the resonant circuit. The 3 dB bandwidth for resonant circuit is given as,

$$BW = \frac{f_r}{Q_L}$$

where $f_r$ represents the centre frequency of a resonator and $BW$ represents the bandwidth.

If $Q$ is large, bandwidth is small and circuit will be highly selective. For small $Q$ values bandwidth is high and selectivity of the circuit is lost, as shown in the Fig. 3.6.
Thus in tuned amplifier Q is kept as high as possible to get the better selectivity. Such tuned amplifiers are used in communication or broadcast receivers where it is necessary to amplify only selected band of frequencies.

7. Requirements of tuned amplifiers:

The basic requirements of tuned amplifiers are;

• The amplifier should provide selectivity of resonant frequency over a very narrow band.
• The signal should be amplified equally well at all frequencies in the selected narrow band.
• The tuned circuit should be so mounted that it can be easily tuned. If there are more than one circuit to be tuned, there should be an arrangement to tune all circuit simultaneously.
• The amplifier must provide the simplicity in tuning of the amplifier components to the desired frequency over a considerable range or band of frequencies.
8. Effect of cascading single tuned amplifier on bandwidth:

In order to obtain a high overall gain, several identical stages of tuned amplifiers can be used in cascade. The overall gain is the product of the voltage gains of the individual stages. Let us see the effect of cascading of stages on bandwidth.

Consider \( n \) stages of single tuned direct coupled amplifiers connected in cascade. We know that the relative gain of a single tuned amplifier with respect to the gain at resonant frequency \( f_r \) is given from equation (14) of section 3.4.

\[
\left| \frac{A_V}{A_{V, \text{at resonance}}} \right| = \frac{1}{\sqrt{1 + (2\delta Q_{\text{eff}})^2}}
\]

Therefore, the relative gain of \( n \) stage cascaded amplifier becomes

\[
\left| \frac{A_V}{A_{V, \text{at resonance}}} \right|^n = \left[ \frac{1}{\sqrt{1 + (2\delta Q_{\text{eff}})^2}} \right]^n = \frac{1}{\left[1 + (2\delta Q_{\text{eff}})^2\right]^\frac{n}{2}}
\]

The 3 dB frequencies for the \( n \) stage cascaded amplifier can be found by equating

\[
\left| \frac{A_V}{A_{V, \text{at resonance}}} \right|^n = \frac{1}{\sqrt{2}}
\]

\[
\left[1 + (2\delta Q_{\text{eff}})^2\right]^\frac{n}{2} = 2^\frac{1}{2}
\]

\[
\left[1 + (2\delta Q_{\text{eff}})^2\right]^n = 2
\]

\[
1 + (2\delta Q_{\text{eff}})^2 = 2^\frac{1}{n}
\]

\[
2\delta Q_{\text{eff}} = \pm \sqrt{2^\frac{1}{n} - 1}
\]
Substituting for $\delta$, the fractional frequency variation, i.e.

$$
\delta = \frac{\omega - \omega_r}{\omega_r} = \frac{f - f_r}{f_r}
$$

\[\therefore \quad 2 \left( \frac{f - f_r}{f_r} \right) Q_{\text{eff}} = \pm \sqrt{2^n - 1} \]

\[\therefore \quad 2 (f - f_r) Q_{\text{eff}} = \pm f_r \sqrt{2^n - 1} \]

\[\therefore \quad f - f_r = \pm \frac{f_r}{2 Q_{\text{eff}}} \sqrt{2^n - 1} \]

Let us assume $f_1$ and $f_2$ are the lower 3 dB and upper 3 dB frequencies, respectively. Then we have

$$
f_2 - f_r = + \frac{f_r}{2 Q_{\text{eff}}} \sqrt{2^n - 1} \quad \text{and similarly,} \quad f_r - f_1 = + \frac{f_r}{2 Q_{\text{eff}}} \sqrt{2^n - 1}
$$

$$
f_2 - f_r = + \frac{f_r}{2 Q_{\text{eff}}} \sqrt{2^n - 1} \quad \text{and similarly,} \quad f_r - f_1 = + \frac{f_r}{2 Q_{\text{eff}}} \sqrt{2^n - 1}
$$

The bandwidth of $n$ stage identical amplifier is given as,

$$
BW_n = f_2 - f_1 = (f_2 - f_r) + (f_r - f_1)
$$

$$
= \frac{f_r}{2 Q_{\text{eff}}} \sqrt{2^n - 1} + \frac{f_r}{2 Q_{\text{eff}}} \sqrt{2^n - 1}
$$

$$
= \frac{f_r}{Q_{\text{eff}}} \sqrt{2^n - 1}
$$

$$
= BW_1 \sqrt{2^n - 1} \quad \ldots (1)
$$

where $BW_1$ is the bandwidth of single stage and $BW_n$ is the bandwidth of $n$ stages.
9. Effect of cascading single tuned amplifier on bandwidth:

When a number of identical double tuned amplifier stages are cascaded in cascade, the overall bandwidth of the system is thereby narrowed and the steepness of the sides of the response is increased, just as when single tuned stages are cascaded. The quantitative relation between the 3 dB bandwidth of n identical double tuned critically coupled stages compared with the bandwidth $\Delta_2$ of such a system can be shown to be 3 dB bandwidth for

\[ n \text{ identical stages double tuned amplifiers} = \Delta_2 \times \left( \frac{1}{2n} - 1 \right)^{\frac{1}{4}} \]

where \( \Delta_2 = \text{3 dB bandwidth of single stage double tuned amplifier} \)