Microwave Engineering
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Lecture 27
RF Oscillators

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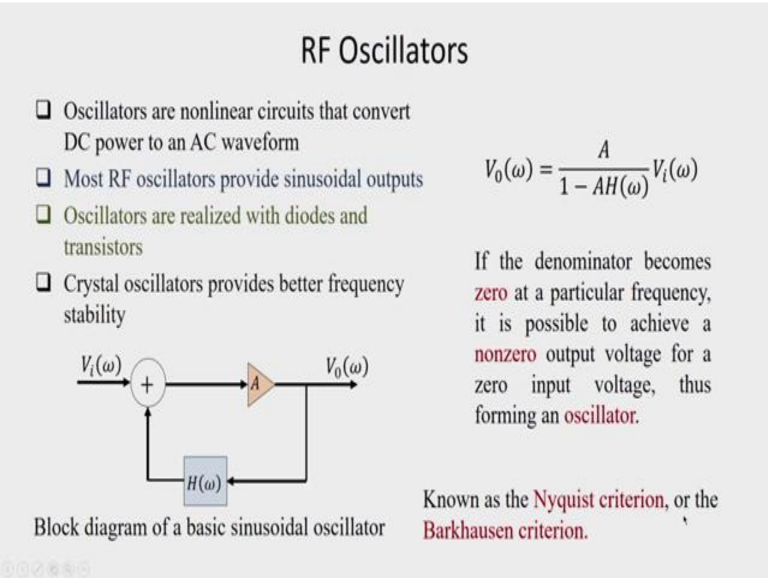
$$V_0(\omega) = \frac{A}{1 - AH(\omega)} V_i(\omega)$$



We start a new topic RF Oscillators. Oscillators are nonlinear circuits that convert DC power to an AC waveform. Most RF oscillators provide sinusoidal outputs. Oscillators are realized using diodes and transistors. Apart from diode and transistor based oscillators, crystal oscillators are also used, which provide better frequency stability.

So, in this lecture, we briefly discuss some of the characteristics of the oscillators. We will start our discussion with some basics of oscillator design, and those concepts should be applicable to oscillators operating in the lower RF frequencies, and then we will discuss some issues related to the design of oscillators for the microwave frequencies.

The figure shows the basic block diagram of a sinusoidal oscillator, here we can see that V output is multiplied by H omega the gain of the feedback path and then it is added to V_i, now this is a positive feedback circuit, so V_i plus Vnaught H this is multiplied by A, and that becomes equal to V_0 So, from there we can write Vnaught omega is equal to A divided by 1 minus AH omega V_i omega.

So, if the denominator becomes 0 at a particular frequency, it is possible to achieve a non-zero output voltage even for 0 input voltage, and thus, the circuit actually forms an oscillator. This condition that 1 minus AH is equal to 0 this is known as Nyquist criterion or Barkhausen criterion.

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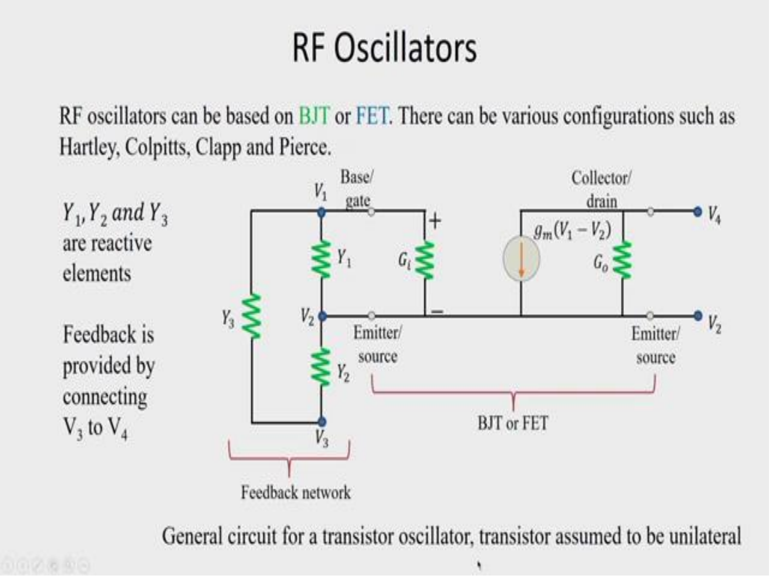

Now, the RF oscillators can be design based on BJT or FET. There can be various configurations such as Hartley, Colpitts, Clapp, and Pierce. So we will discuss a generic block diagram where this active device, this terminal can be the base, this can be collector, and it can be emitted if the device is a BJT. In case of FET this terminal is the gate terminal, this is drain terminal, and this is source terminal.

We had a feedback network which usually comprises of reactive elements which are represented as Y_1 Y_2 and Y_3. Now, feedback is provided by connecting this V_3 and V_4, so here what we do, we first carry out an analysis nodal analysis, so here if you consider this node we can see that V_1 minus V_2 into Y_1, V_1 minus V_2 into G_i and V_1 minus V_3 into Y_3 some of this must be equal to 0 by KCL.

If we consider this node and apply KCL then the currents some of the current given by V_1 minus V_2 into Y_1, V_1 minus V_2 into G_i, V_1 minus V_3 into Y_3, some of this currents must be equal to 0 and we can carry out this analysis for this node voltage node 1 2 3 4 for this first node.

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Writing KCL at the voltage node in the figure, we can write:

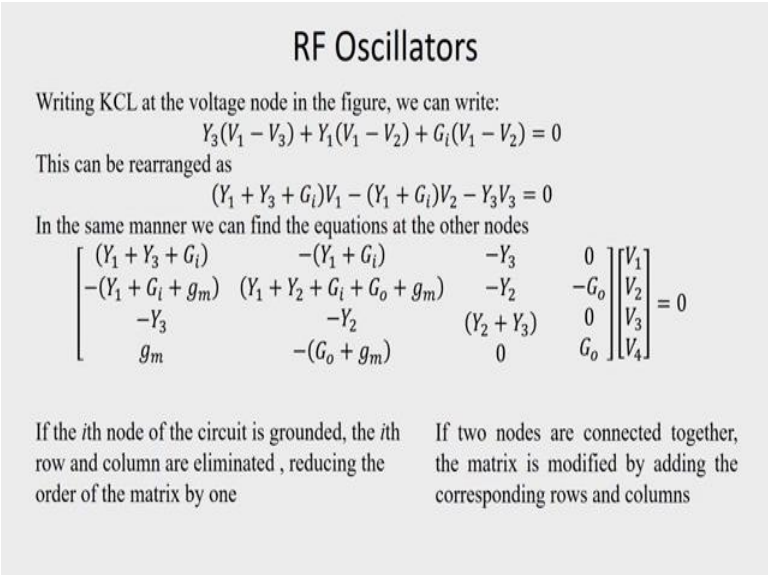
$$Y_3(V_1 - V_3) + Y_1(V_1 - V_2) + G_i(V_1 - V_2) = 0$$

This can be rearranged as

$$(Y_1 + Y_3 + G_i)V_1 - (Y_1 + G_i)V_2 - Y_3V_3 = 0$$

In the same manner we can find the equations at the other nodes

$$\begin{bmatrix} (Y_1 + Y_3 + G_i) & -(Y_1 + G_i) & -Y_3 & 0 \\ -(Y_1 + G_i + g_m) & (Y_1 + Y_2 + G_i + G_o + g_m) & -Y_2 & -G_o \\ -Y_3 & -Y_2 & (Y_2 + Y_3) & 0 \\ g_m & -(G_o + g_m) & 0 & G_o \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = 0$$



As we have seen, Y_3 V_1 minus V_3 plus Y_1 V_1 minus V_2 plus G_i V_1 minus V_2 is equal to 0, so when it is rearranged we can write Y_1 plus Y_3 plus G_1 into V_1 minus Y_1 plus G_i into V_2 minus Y_3 V_3 equal to 0. So, when this analysis is carried out for all other 3 nodes we can write the complete matrix in this form. Now, we know that if the ith node of the circuit is grounded, the ith row and column are eliminated, reducing order of the matrix by one.

And similarly, if two nodes are connected together we have said that in our reference figure we need to connect V_3 and V_4 to provide feedback then the matrix is modified by adding the corresponding rows and columns.

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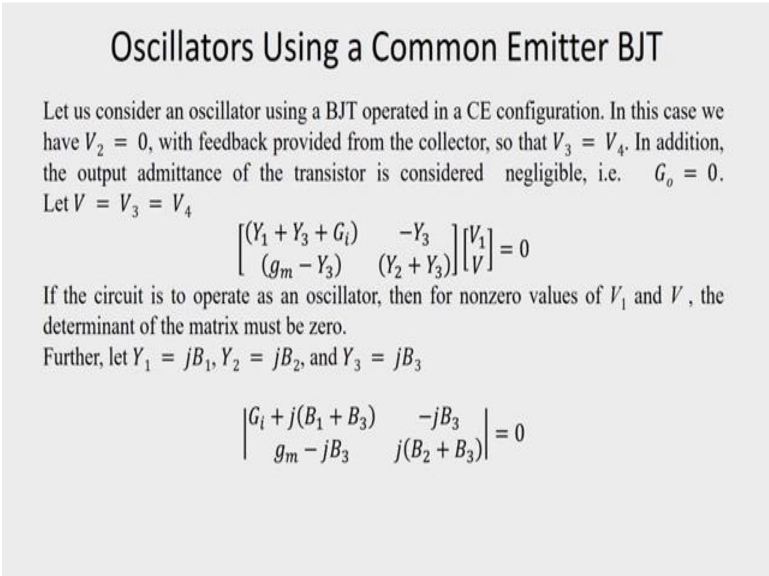
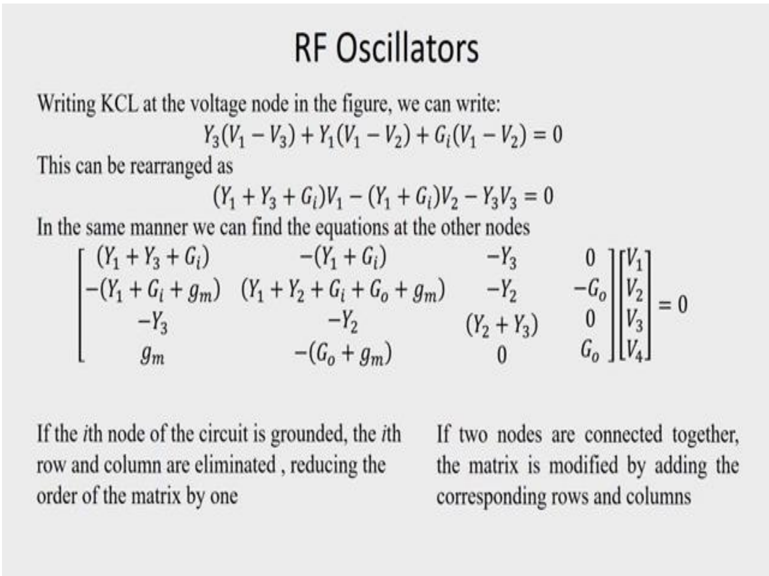
$$\begin{bmatrix} (Y_1 + Y_3 + G_i) & -Y_3 \\ (g_m - Y_3) & (Y_2 + Y_3) \end{bmatrix} \begin{bmatrix} V_1 \\ V \end{bmatrix} = 0$$

$$\begin{vmatrix} G_i + j(B_1 + B_3) & -jB_3 \\ g_m - jB_3 & j(B_2 + B_3) \end{vmatrix} = 0$$





So, let us now consider an oscillator circuit using a common emitter BJT. Now, in this oscillator using BJT will operate the BJT in CE configuration. And in this case, we will have V_2 equal to 0, with the feedback provided from collectors, so V_3 is equal to V_4. And in addition, the output admittance of the transistor is considered negligible, which means we have V naught equal to 0.

And let us represent V equal toV_3 equal to V_4. So, if we now refer to our this matrix when V_2 equal to 0 this second row and this column will be eliminated and when the nodes 3 and 4 are connected together, and also we have Gnaught equal to 0 then if we add this rows and columns essentially this values will not change, Y_3 minus Y_3 Y_2 plus Y_3 they will remain as it is.

And in that process now this matrix will essentially be reduced into a 2 by 2 matrix, please note that we have put V_3 equal to V_4 equal to V. if, this circuit is to operate as an oscillator, then we must have non zero values for V_1 and V and in order to have this the determinant of the matrix must be zero.

As we have said that Y_1, Y_2, Y_3, these are reactive elements let Y_1 be jB_1, Y_2 be jB_2, and Y_3 be jB_3. So, substituting this Y1 Y2 and Y3 here we get this particular determinant has to be 0.

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$$\frac{1}{B_1} + \frac{1}{B_2} + \frac{1}{B_3} = 0$$

$$\frac{1}{B_3} + \left(1 + \frac{g_m}{G_i}\right)\frac{1}{B_2} = 0$$

Let $X_1 = 1/B_1$, $X_2 = 1/B_2$, and $X_3 = 1/B_3$

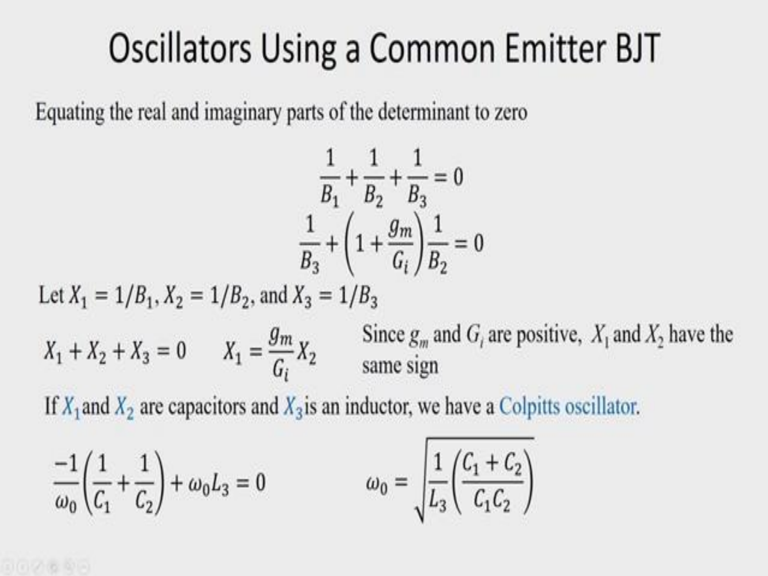
$$X_1 + X_2 + X_3 = 0$$

$$X_1 = \frac{g_m}{G_i} X_2$$

If $X_1$and X_2 are capacitors and $X_3$is an inductor, we have a Colpitts oscillator.

$$\frac{-1}{\omega_0}\left(\frac{1}{C_1} + \frac{1}{C_2}\right) + \omega_0 L_3 = 0$$

$$\omega_0 = \sqrt{\frac{1}{L_3}\left(\frac{C_1 + C_2}{C_1 C_2}\right)}$$



Now, equating the real and imaginary parts to 0 we get the relation 1 by B_1 plus 1 by B_2 plus 1 by B_3 equal to 0 and 1 by B_3 plus 1 plus gm divided by Gi into 1 by B_2 equal to 0. So, this is the 2 relations we obtain, now if we substitute X_1 is equal to 1 by B_1, X_2 is equal to 1 by $B_{2,}$ and X_3 is equal to 1 by B_3, we have X_1 plus X_2 plus X_3 equal to 0.

And also, we get after substitution in the second equation X_1 is equal to g_m by G_i X_2. Now, here gm by $G_{i,}$ this will be a positive quantity, and therefore X_1 and X_2 will be of the same sign. Now, if we choose X_1 and X_2 to be capacitors, in that case, X_3 has to be an inductor because X_1 and X_2 have the same sign and X_3 must have a sign opposite to X_1 and X_2 and this particular configuration when we have X_1 and X_2 are capacitors and X_3 is an inductor this particular configuration is called Colpitts oscillator.

And from this relation now we can write minus 1 by omega naught 1 by C_1 plus 1 by C_2 plus omega naught L_3 equal to 0. So, here omega naught is the frequency of oscillation were this relation is satisfied and solving for omega naught we get the frequency of oscillation which is given by under root 1 by L_3 into C_1 plus C_2 divided by C_1 plus C_2. So, this omega naught is the frequency of oscillation of the circuit, also from this relation X_1 is equal to g_m by G_i X_2.

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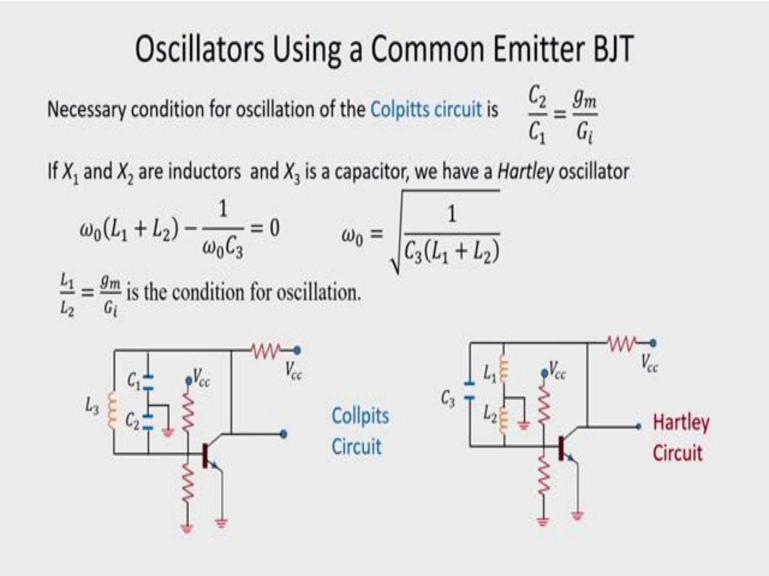
$$\frac{C_2}{C_1} = \frac{g_m}{G_i}$$

$$\omega_0(L_1 + L_2) - \frac{1}{\omega_0 C_3} = 0$$

$$\omega_0 = \sqrt{\frac{1}{C_3(L_1 + L_2)}}$$

$\frac{L_1}{L_2} = \frac{g_m}{G_i}$ is the condition for oscillation.



We can see that the necessary condition for oscillation of the Colpitts circuit is C_2 by C_1 is equal to g_m by G_i. When X_1 X_2 are inductors and X_3 is a capacitor we have a Hartley oscillator and this condition X_1 plus X_2 plus X_3 equal to 0 will now give omega naught L_1 plus omega naught L_2 minus 1 by omega naught C_3 is equal to 0 and omega naught can be found out as under root 1 by C_3 into L_1 plus L_2 again from the relation X_1 is equal to g_m by G_i X_2 we can find that condition for oscillation for the Hartley oscillator circuit is L_1 by L_2 is equal to g_m by G_i.

So, the basic form of Colpitts oscillators is shown here. So, we have a common emitter BJT, and we can see that the feedback is applied from the collector, and we have this Y_1 Y_2 Y_3 represented by C_1 C_2 and L_3. These are the basing registers to ensure that, that register is based in the active region.

Similarly, for the Hartley circuit, we have once again the feedback goes from the collector; this is the basing arrangements, and the reactive elements are L_1 L_2 LC_3. Now, both the circuit configurations provide positive feedback, which is necessary for the operation of an oscillator, and the frequency of oscillation is decided by omega naught for both the circuits and the oscillation frequency can be set by proper design of the inductors and the capacitors.

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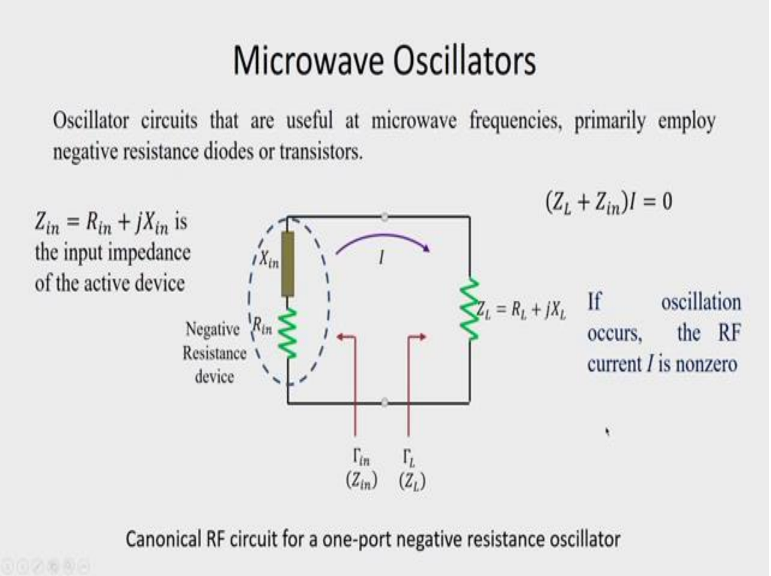
$$(Z_L + Z_{in})I = 0$$



So, transistor-based oscillators what we have discussed this are useful for RF frequencies but when the frequency becomes very high, in the higher microwave frequencies, the oscillators circuits the employ negative solutions diodes and transistors. So, the devices operated in the negative resistance region, we show a generic representation where a canonical RF circuit is shown as 1 port negative resistance oscillator.

And we have a device were this Rin is negative. Now, as we have already discussed while discussing the devices, that negative resistance here implies the generation of RF and RG whereas when the resistance is positive, it dissipates the energy. Now, if you consider this circuit, we find that Z_{in}, which is equal to R_{in} plus jX_{in}, it is the input impedance of the active device.

And since there is no other generator here, we will have Z_L plus Z_{in} into I equal to 0, where I is the loop current. So, if we have oscillation occurring in this circuit then we will have RF current I is non zero.

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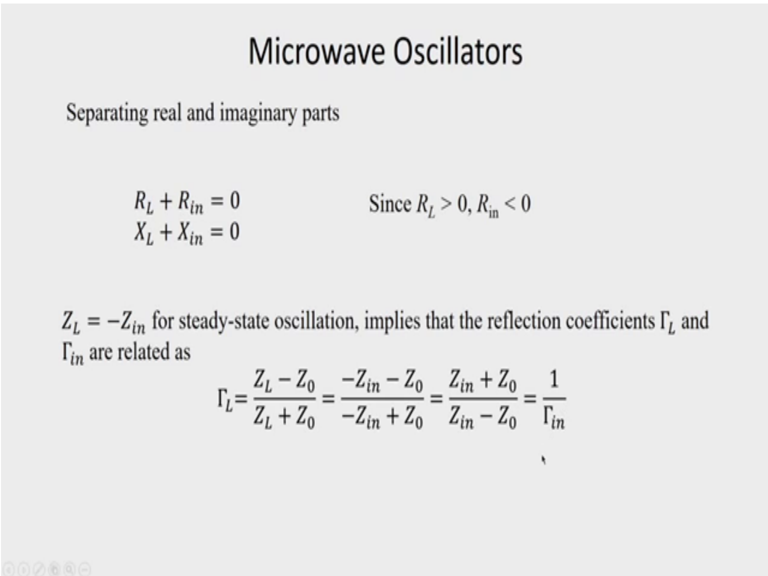
$$R_L + R_{in} = 0$$

$$X_L + X_{in} = 0$$

Since $R_L > 0$, $R_{in} < 0$

$Z_L = -Z_{in}$ for steady-state oscillation, implies that the reflection coefficients Γ_L and Γ_{in} are related as

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{-Z_{in} - Z_0}{-Z_{in} + Z_0} = \frac{Z_{in} + Z_0}{Z_{in} - Z_0} = \frac{1}{\Gamma_{in}}$$



And therefore, we have Z_{in} plus R_L equal to 0, and if we separate the real and imaginary part then we get RL plus Rin equal to 0 and X_L plus X_{in} equal to 0. Since R_L is a passive load and therefore it is greater than 0, so this condition is satisfied only if Rin is less than 0. Now, Z_L is equal to minus Zin for steady-state oscillation, it implies that gamma L which is defined as Z_L minus Z_0 divided by Z_L plus Z_0, can be returned as minus Z_{in} minus Z_0 divided by minus Z_{in}

plus Z_0 and this can be returned as Z_{in} plus Z_0divided by Z_{in} minus Z_0 which is essentially 1 by gamma in.

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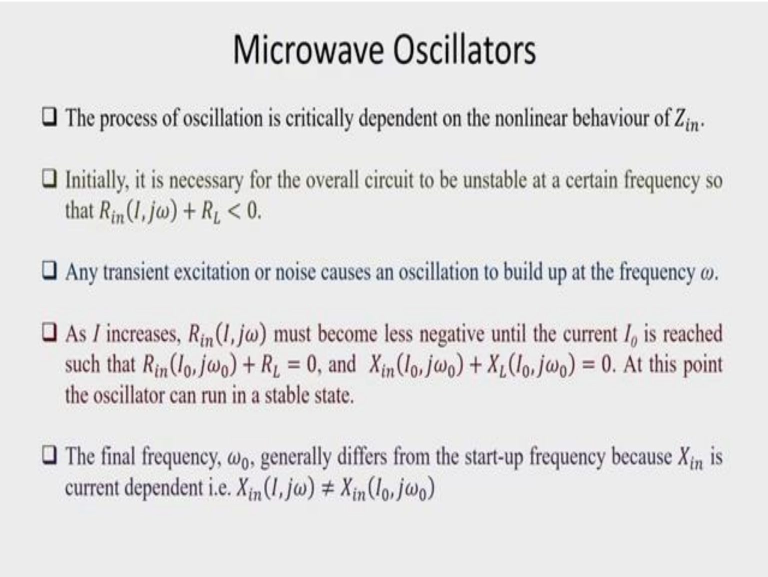

The process of oscillation is critically dependent on the nonlinear behavior of Z_{in}. Initially, it is necessary for overall circuit to be unstable at a certain frequency so that Rin as a function of I and omega plus R_L. This becomes less than 0. Any transient excitation or noise now this is how they start of oscillation is usually described. So, any transient excitation or noise causes an oscillator to build up at the frequency omega.

As I increase R_{in} I, j omega must become less negative until the current I naught is reached such that R_{in} as a function of I naught and omega naught plus R_L is equal to 0 and similarly X_{in} as function Inaught omega naught plus X_l function of I naught omega naught is equal to 0. At this point the oscillator can run in a stable state.

The final frequency omega naught generally differs from the start-up frequency because X_{in} is current dependent, and X_{in} I omega is not same as X_{in} Inaught omega naught. Now, we have seen how oscillation can start and it, and it can become stable at some frequency omega naught.

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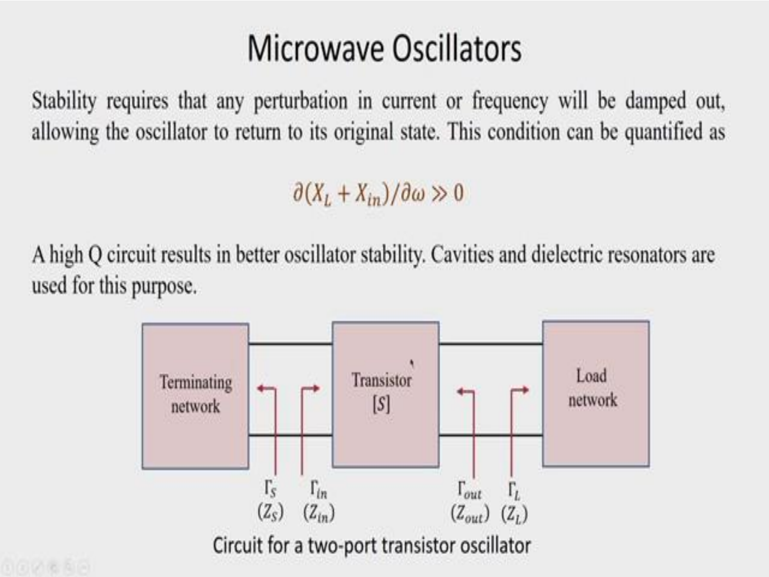
Stability requires that any perturbation in current or frequency will be damped out, allowing the oscillator to return to its original state. This condition can be quantified as

$$\partial(X_L + X_{in})/\partial\omega \gg 0$$

A high Q circuit results in better oscillator stability. Cavities and dielectric resonators are used for this purpose.



Now, stability requires that any perturbation in current or frequency will be damped out, so a small change in the current or the frequency will be damped out, allowing the oscillator to return to the original value. And this condition can be quantified as del of X_L plus X_{in} del of omega much much greater than 0. And essentially this translates into the fact that a high Q circuit results in better oscillator stability.

And that is the reason why cavities and dielectric resonators are used for this purpose. So, when we use a transistor for designing microwave oscillators we have the transistor, and in the input side now we have a terminating network and we also have the load network Z_{in} is the input impedance looking through this transistor ports and corresponding reflection coefficient is gamma in, and gamma S is the reflection coefficient looking into the terminating network. Similarly gamma L is the reflection coefficient looking into the load network, and gamma out is the reflection coefficient that is looking through the output ports the transistor.

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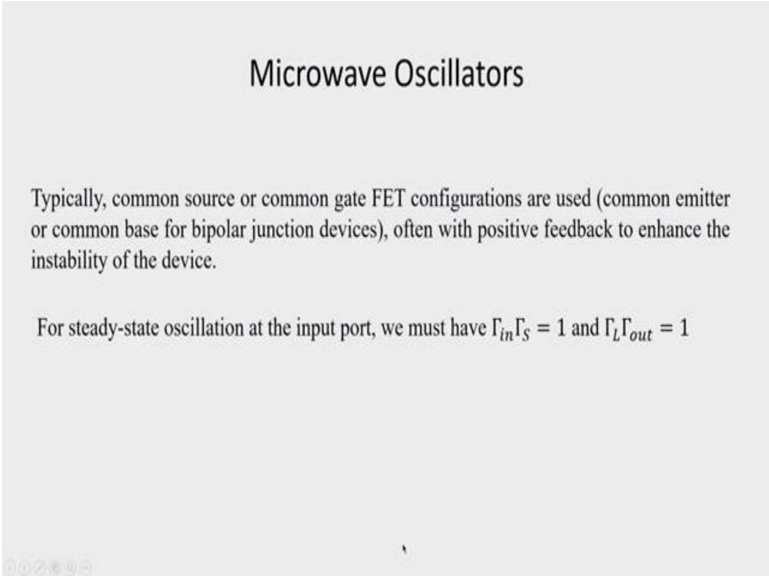

Typically common source or common gate FET configurations are used; in case of BJT it will be common emitter or common base and often with positive feedback to enhance the instability of the device. For steady-state oscillation at the input port, we must have gamma in gamma S is equal to 1, and similarly gamma L gamma out is equal to 1.

This brings us to the end of this module. In this module, we have briefly described the methodologies that are adopted for design of microwave frequency transistor amplifiers. We have seen the particular cases when we go, for we will design for maximum gain when we design for specified gain, and we have also discussed very briefly the (())(28:09) amplifiers and finally the oscillators.

In the next module, we will discuss microwave frequency tubes, which are still very much in use as high power microwave sources. Specialist tubes had to be developed for working in the microwave frequency range we will discuss the conventional tubes such as triode or pentode and then we will discuss specialist microwave tubes such as klystron reflex klystron magnetron and traveling web tube.