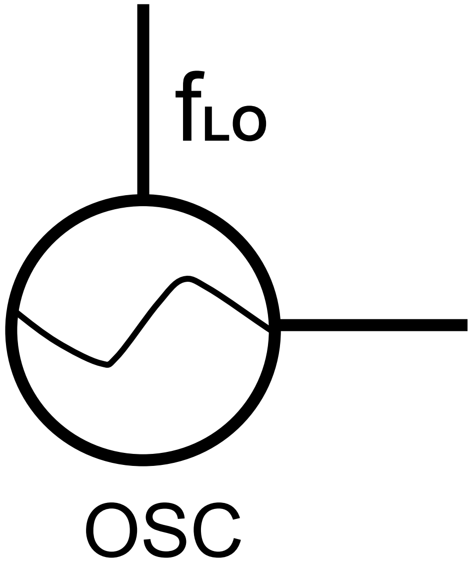
MICROWAVE OSCILLATORS

EE5303 – Part 2



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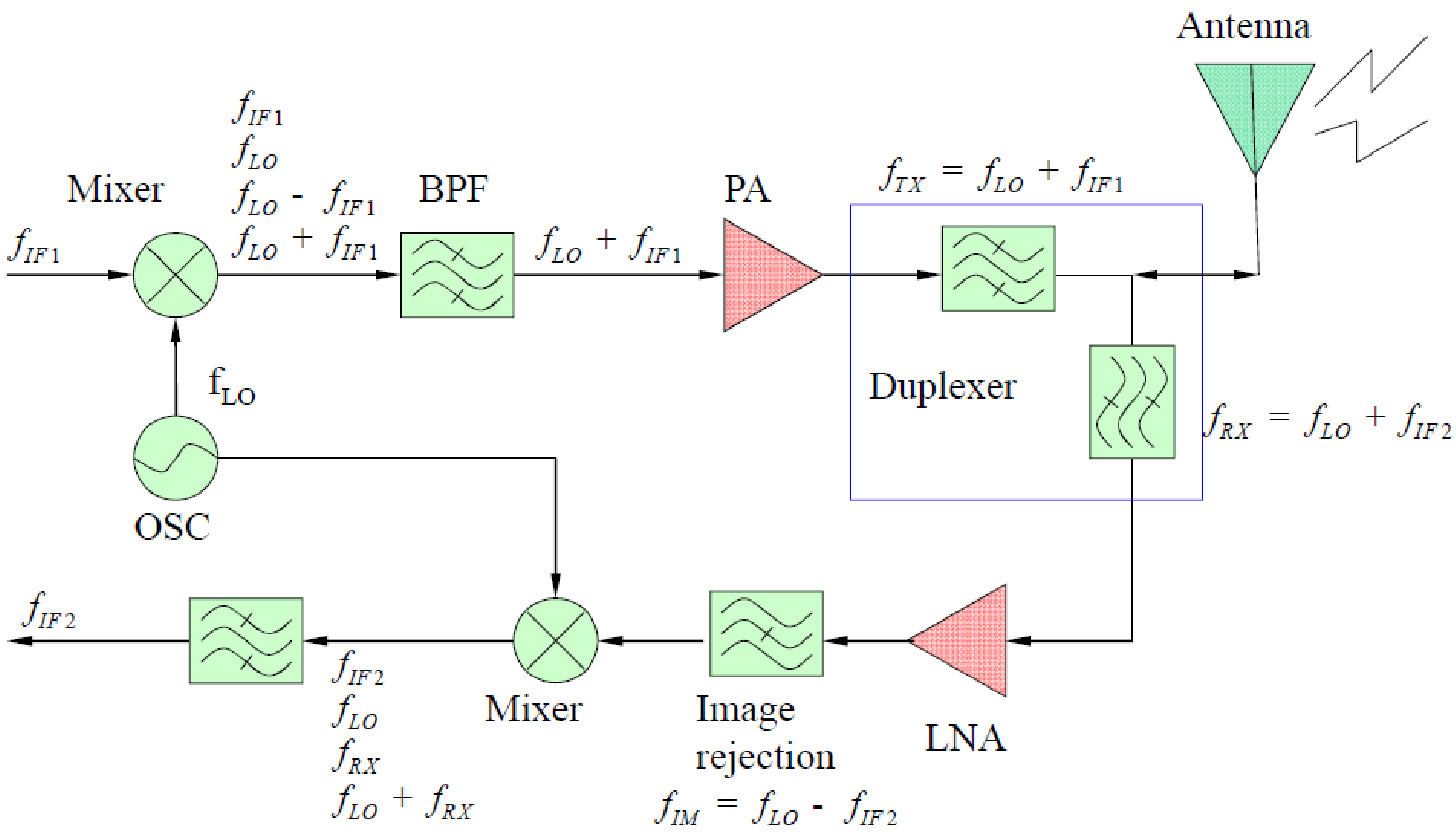
Outline

- ❑ **Introduction of Oscillators**
- ❑ **One-Port Negative Resistance Model**
  - Oscillation Conditions
  - How to design R_L for maximum oscillator power
- ❑ **Two-Port Oscillator Model**
  - Basic Feedback Oscillation Condition
  - **Two-Port Negative Resistance Oscillator**
    - ✓ Terminating and load networks, input & output ports
    - ✓ Oscillation conditions in terms of reflection coefficients
    - ✓ Oscillator design procedures & design examples
- ❑ **Other Design Considerations** (***optional reading)
  - Resonant network in oscillators (e.g., LC resonator)
  - Use of High-Q resonators in oscillators (e.g., DRO)
  - Frequency Tunable Oscillator (e.g., tunable YIG oscillator)
  - An illustration of VCO

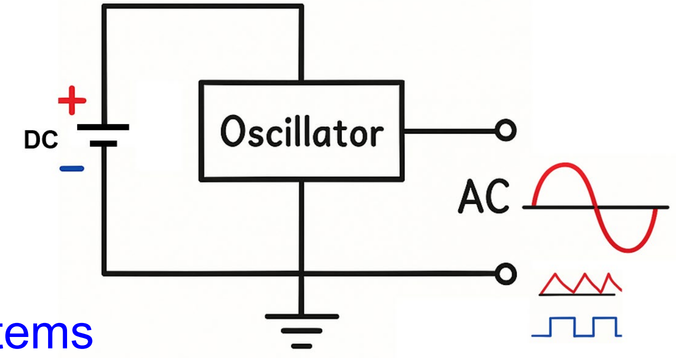
Block Diagram of RF Transceiver



Introduction

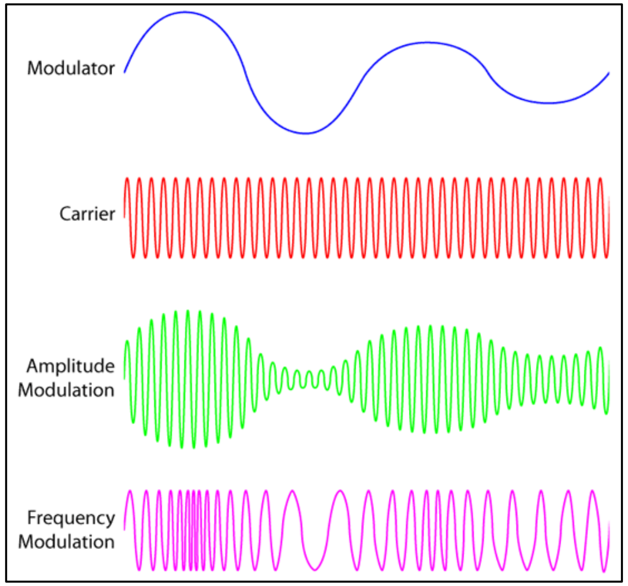
RF/Microwave Oscillator(s)

- Most RF oscillators produce **sinusoidal outputs**, which minimizes undesired harmonics and noise sidebands.
- Those sinusoidal signal from oscillators are
  - either used to drive mixers (i.e., as signal sources for frequency conversion)
  - or, if modulated, to produce frequency modulated signals directly (i.e., for carrier generation)
- Found in all modern wireless communications, radar, and remote sensing systems
- Generally speaking, an oscillator is a **nonlinear** circuit converting DC power to an AC (RF/microwave) waveform



❑ Requirements on performance of Microwave Oscillators

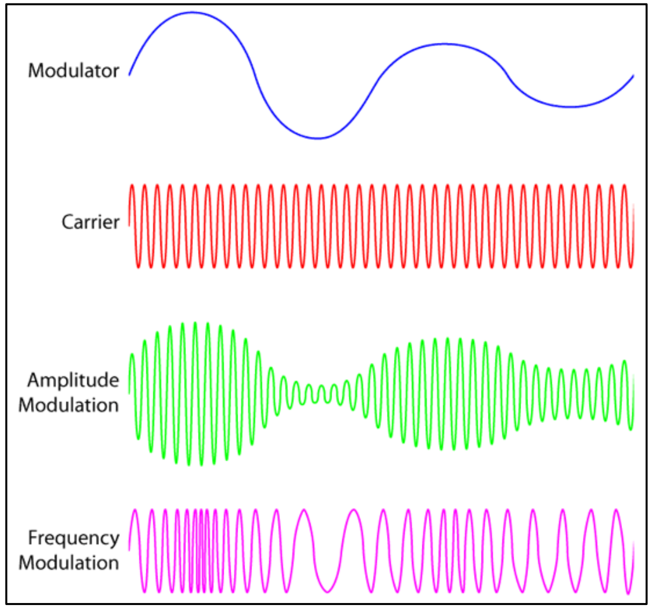
- Steady output and pure sinusoidal signal
- Oscillation frequency stability against variations in temperature, power-supply voltage, and oscillator loading
- Low amplitude-, phase-, and frequency-modulation noise
- Adequate power output for the intended use
- Frequency tuning (mechanical tuning and/or voltage control)
- Capability to be modulated

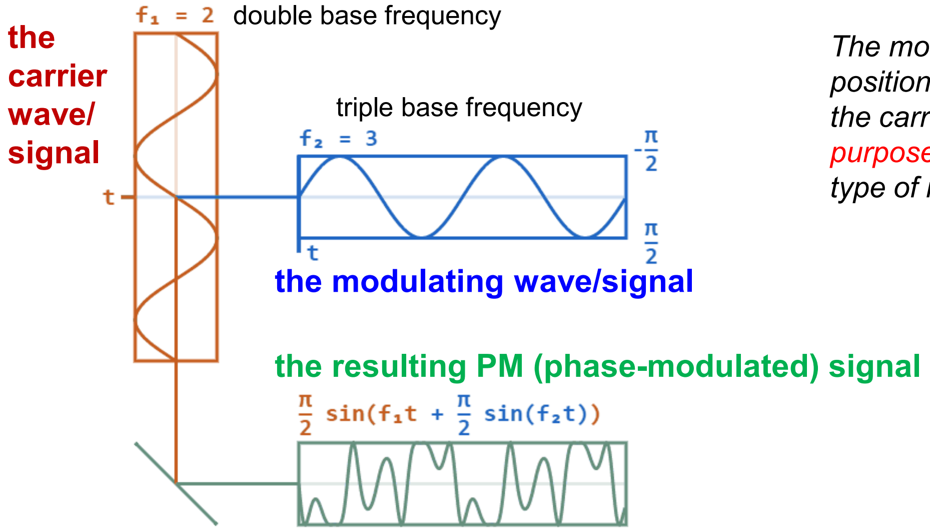


Introduction

RF/Microwave Oscillator(s)

- **Requirements on performance of Microwave Oscillators**
  - Low **amplitude-, phase-, and frequency-modulation** noise





The modulating signal is positioned perpendicular to the carrier signal for the purpose of visualizing this type of modulation

The modulating wave (blue) is modulating the carrier wave (red), resulting the PM (phase-Modulated) signal (green).

$g(t) = \pi/2 \times \sin[2 \times 2\pi t + \pi/2 \times \sin(3 \times 2\pi t)]$

https://en.wikipedia.org/wiki/Phase_modulation

$$v(\mathrm{t}) = v_0 \sin(2\pi f_c t + \theta_0)$$

amplitude-, frequency-, and phase-modulation

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Oscillator: One-Port Negative Resistance Model

- **Basic principle of operation**

The active device:

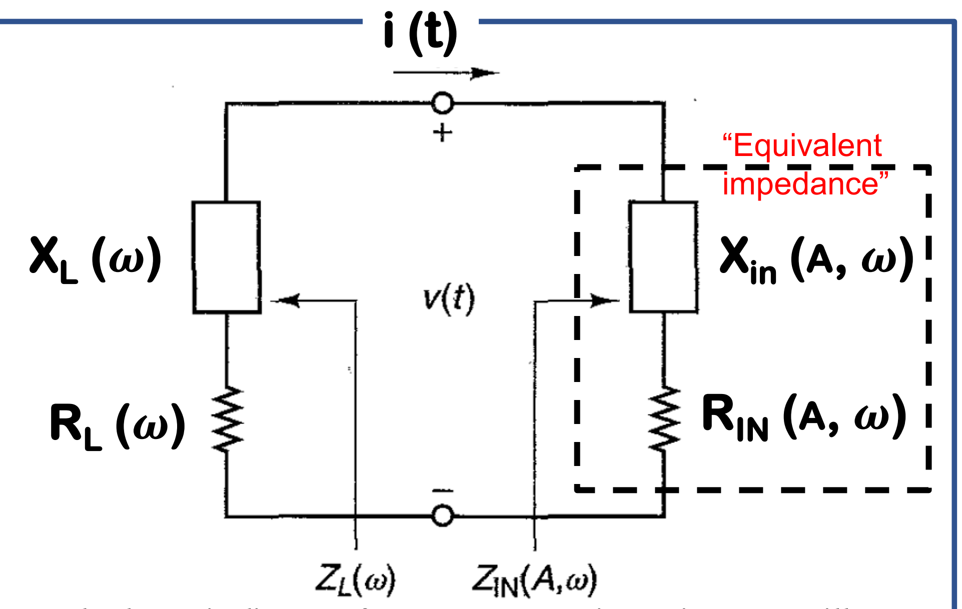
$$Z_{IN}(A,\omega) = R_{IN}(A,\omega) + jX_{IN}(A,\omega)$$

A: amplitude of the RF current i(t) and $R_{IN}(A,\omega) < 0$.

ω is the frequency

The oscillator is constructed by connecting the device to a passive load impedance:

$$Z_L(\omega) = R_L(\omega) + jX_L(\omega)$$



A general schematic diagram for one-port negative resistance oscillators

From Kirchoff's voltage law: $\{\boxed{Z_L(\omega) + Z_{IN}(A,\omega)}\}\ i(t) = 0$

If oscillation is occurring, such that the RF current i(t) is nonzero, with an amplitude $A = A_o$ and frequency $\omega = \omega_o$, the following conditions must be satisfied:

1 $R_L(\omega_o) + R_{IN}(A_o, \omega_o) = 0$ 2 $X_L(\omega_o) + X_{IN}(A_o, \omega_o) = 0$

1 **Since the load is passive, $R_L(\omega_o) > 0$, and the first condition indicates that $R_{IN}(A_o, \omega_o) < 0$.**

Thus, a negative resistance implies an energy source.

2 The second condition controls the frequency of oscillation.

The condition that $Z_L(\omega_o) = -Z_{IN}(A_o,\omega_o)$ for steady-state oscillation, implies that the reflection coefficients Γ_L and Γ_{IN} are related as

$$\Gamma_L = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{-Z_{IN} - Z_o}{-Z_{IN} + Z_o} = \frac{Z_{IN} + Z_o}{Z_{IN} - Z_o} = \frac{1}{\Gamma_{IN}}$$

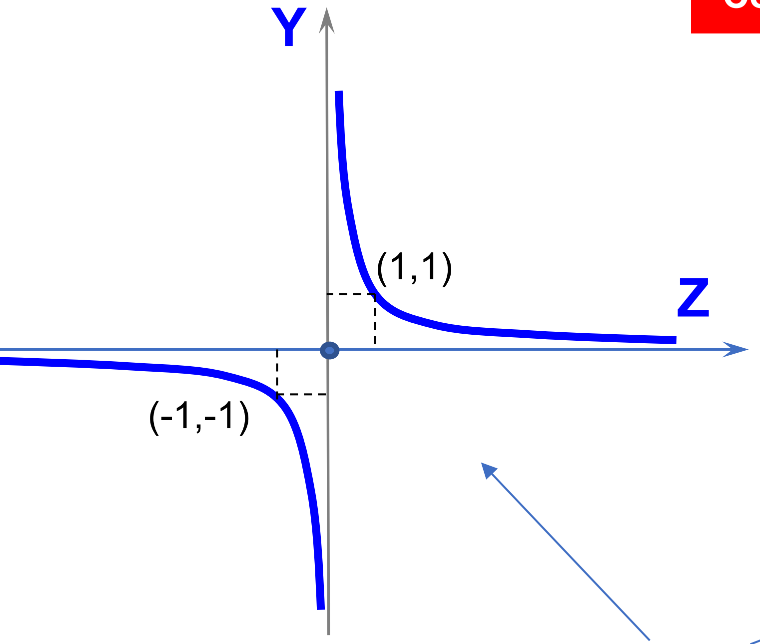
Or

$\boxed{\Gamma_L \Gamma_{IN} = 1}$ **This implies that $\Gamma_{IN} > 1$**

Reciprocal of real numbers & complex variables

Z*Y = 1

If both Z and Y are real numbers



A pictorial interpretation

Impedance (Z)	
Resistance (R)	Reactance (X)

$$Z = R + jX$$

Unit: Ohm, Ω

Capacitors	Inductor
$X_C = \frac{1}{2\pi f C}$	$X_L = 2\pi f L$

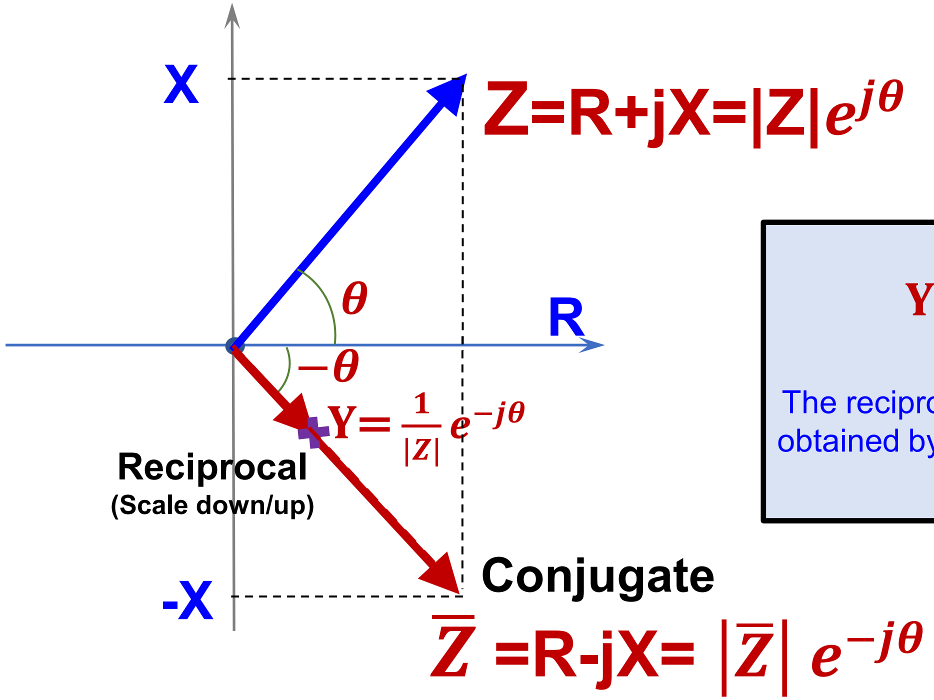
SI Unit: L → Henry (H); C → Farad (F)

Admittance (Y)	
Conductance (G)	Susceptance (B)

$$Y = G + jB$$

Unit: Ω^{-1}, mho, Siemens, S

Z*Y = 1



$$Y=\frac{\bar{Z}}{|Z|^2}=\frac{1}{|Z|}e^{-j\theta}$$

The reciprocal (inverse) of Z (which is Y) is obtained by scale up/down the conjugate of Z (which is $\bar{Z}$) by $|Z|^2$

Conjugate symbol

$$\bar{Z} \rightarrow Z^*$$

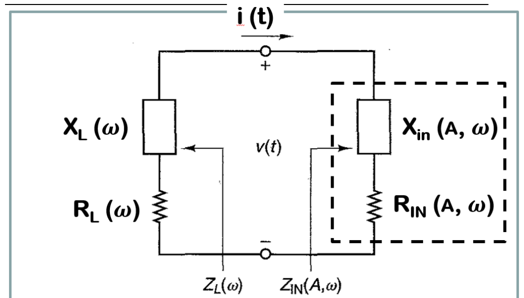
One-Port Negative Resistance Model of Oscillator

The starting & holding of the Oscillation

- The process of oscillation depends on the non-linear behavior of Z_{IN}
- It is necessary for the overall circuit to be unstable at a certain frequency i.e. $R_{IN}(A, \omega) + R_L < 0$
- Any transient excitation or noise will cause the oscillation to build up at the frequency, ω
- As **A** increases, $R_{IN}(A,\omega)$ must become less negative until the current A_0 is reached such that

$$R_{IN}(A_0, \omega) + R_L = 0$$

$$X_{IN}(A_0,\omega) + X_L(\omega) = 0$$



A general schematic diagram for one-port negative resistance oscillators

- Then the oscillator is running in steady state.
- The final frequency, ω_0, generally differs from the startup frequency because X_{IN} is current dependent, so that $X_{IN}(A,\omega) \neq X_{IN}(A_0,\omega_0)$.

$Z_{IN}(A,\omega)$ must be amplitude and frequency dependent

One-Port Negative Resistance Model of Oscillator

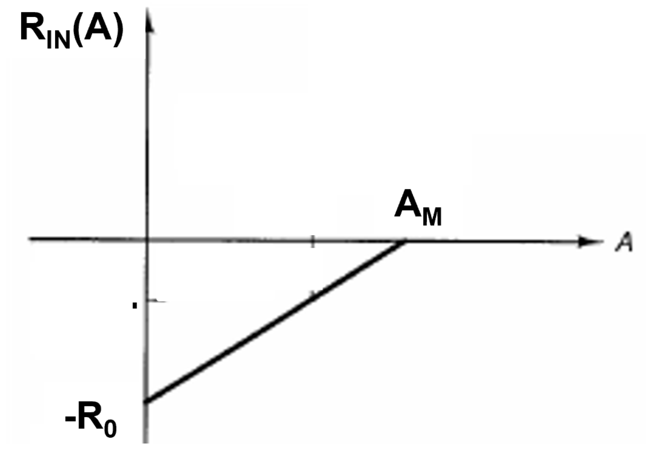
Selecting R_L

A practical way of designing $\mathbf{R_L}$ is to select the value of $\mathbf{R_L}$ for maximum oscillator power.

If the magnitude of the negative resistance is a linearly decreasing function of A, we can express $\mathbf{R_{IN}}$(A) in the form

$$\boxed{R_{IN}(A) = -R_0\left(1 - \frac{A}{A_M}\right)}$$

Where $-\mathbf{R_0}$ is the value of in $\mathbf{R_{IN}}$(A) at A=0, and $\mathbf{A_M}$ is the maximum value of **A**



Linear variation of the negative resistance as a function of the current amplitude

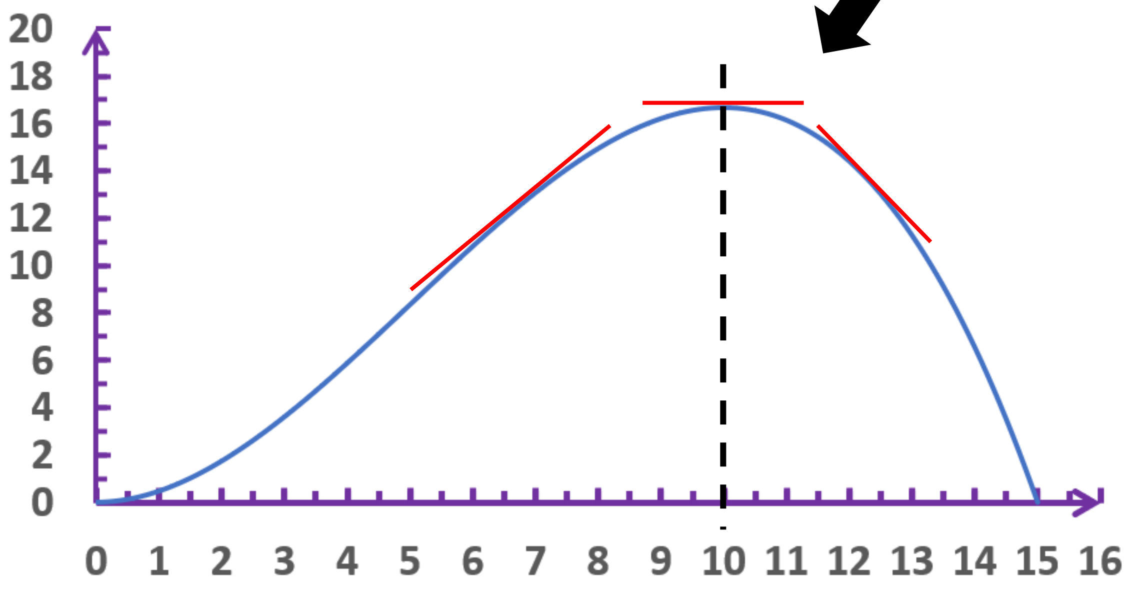
the power delivered to R_L by R_{IN} (for $A < A_M$) is

$$P = \frac{1}{2}\mathrm{Re}[VI^*] = \frac{1}{2}\,|I|^2|R_{IN}(A)| = \frac{1}{2}A^2R_0\left[1 - \frac{A}{A_M}\right]$$

$$\mathbf{P} = \frac{1}{2}A^2R_0\left[1 - \frac{A}{A_M}\right] \Rightarrow \frac{P}{R_0} = 0.5\mathbf{A}^2 - \frac{0.5\mathbf{A}^3}{A_M}$$

"polynomial"

If $A_M = 15, (A < A_M)$



One-Port Negative Resistance Model of Oscillator

$$\boxed{\mathbf{P} = \frac{1}{2}A^2R_0\left[1 - \frac{A}{A_M}\right] = \frac{1}{2}R_0\left[A^2 - \frac{A^3}{A_M}\right]}$$

Hence, the value of A that maximizes the oscillation power is found from

$$\frac{dP}{dA} = \frac{1}{2}R_0\left[2A - \frac{3A^2}{A_M}\right] = 0 \quad \Rightarrow \quad A\left(2 - \frac{3A}{A_M}\right) = 0$$

which gives the desired value of A, denoted by $A_{o,\max}$, that maximizes the power. That is,

$$A_{o,\max} = \frac{2}{3}A_M$$

At $A_{o,\max}$, the value of $R_{IN}(A_{o,\max})$ is

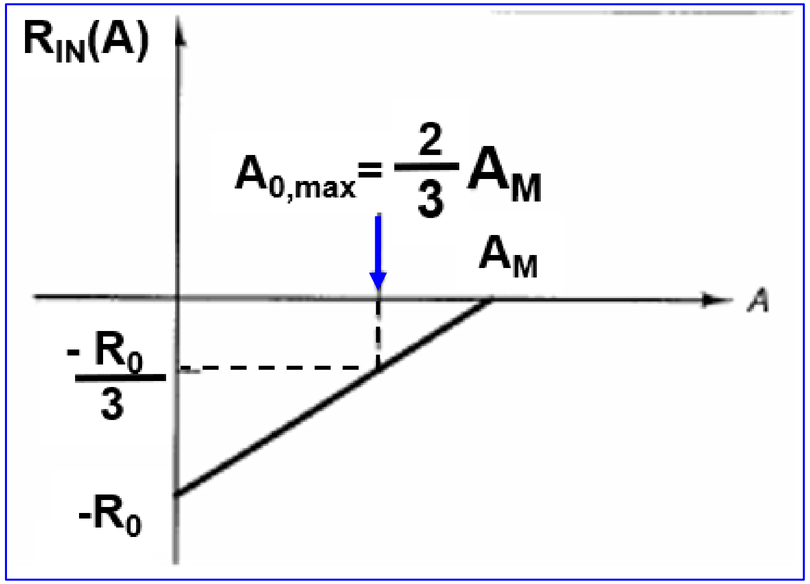
$$R_{IN}(A_{o,\max}) = -\frac{R_0}{3}$$

Hence a convenient value of R_L, which maximized the oscillator power is

$$\boxed{R_L = \frac{R_0}{3}}$$

Note that the above equation is valid when the negative input resistance varies linearly with the amplitude of the current. But in general practical applications, the equation still gives relatively good results.

$$\boxed{R_{IN}(A) = -R_0\left(1 - \frac{A}{A_M}\right)}$$



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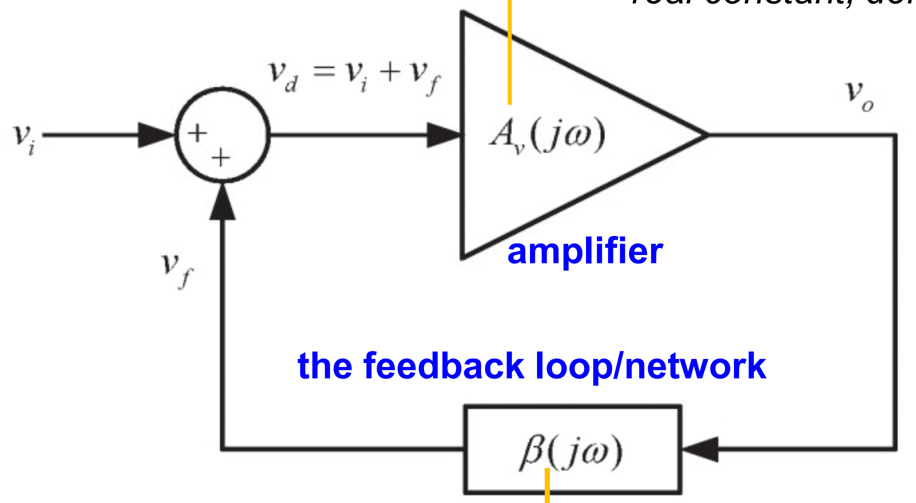
Two-Port Model & Basic Feedback Oscillation Condition

Basic Feedback Oscillator (two port model)

Oscillator = the amplifier plus feedback loop

Amplifier voltage gain (open loop gain) → a complex quantity (in general)
In the mid-band region, it is a real constant, denoted as ***Avo***



Transfer function of the feedback network

$$\beta(j\omega) = \beta_r(\omega) + j\beta_i(\omega)$$

$$v_d = v_i + v_f$$

$$v_o = A_v(j\omega)v_d \qquad v_f = \beta(j\omega)v_o$$

The close-loop voltage gain

$$A_{vf}(j\omega) = \frac{v_o}{v_i} = \frac{A_v(j\omega)}{1 - \beta(j\omega)A_v(j\omega)}$$

For oscillators to occur, an output signal must exist with no input signal applied (i.e., V_i=0). The above equation shows with V_i=0, a finite V_o is possible ONLY when the denominator is zero. That is, when

$$1 - \beta(j\omega)A_v(j\omega) = 0 \implies \boxed{\beta(j\omega)A_v(j\omega) = 1}$$

The loop gain is unity for oscillation to occur→ **Barkhausen criterion**

With $A_v(j\omega) = A_{vo}$

$\beta(j\omega) = \beta_r(\omega) + j\beta_i(\omega)$

$$\beta_r(\omega)A_{vo} + j\beta_i(\omega)A_{vo} = 1$$

Barkhausen criterion in rectangular (real-imaginary) form

$\beta_r(\omega)A_{vo} = 1 \quad \Rightarrow \quad A_{vo} = \dfrac{1}{\beta_r(\omega)}$ (gain condition)

$\beta_i(\omega)A_{vo} = 0 \quad \Rightarrow \quad \beta_i(\omega) = 0$ (frequency of oscillation condition)

Microwave Oscillation

$\Gamma_L(j\omega)$: Load reflection coefficient
$\Gamma_{IN}(j\omega)$: Input reflection coefficient of an active device
a_n: incident wave, a small noise signal generated in the circuit

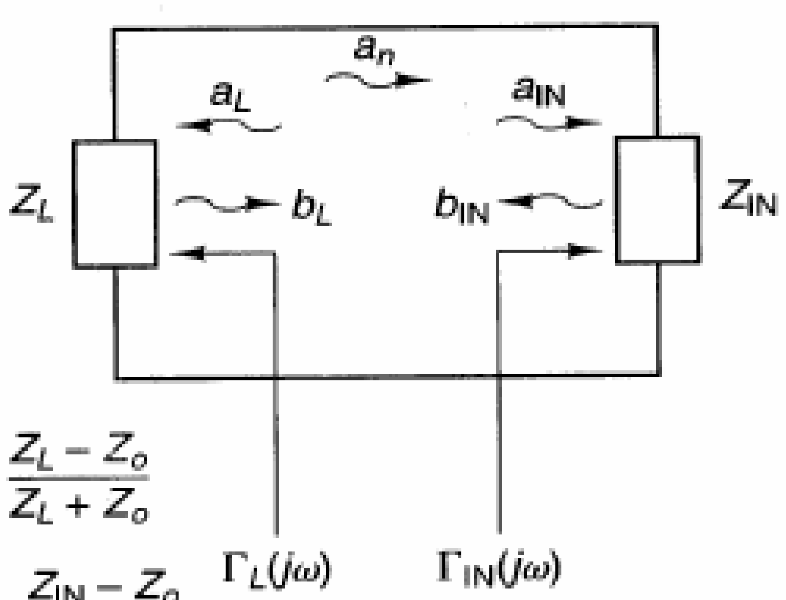
From Signal flow graph

$$a_L = \frac{a_n \Gamma_{IN}(j\omega)}{1-\Gamma_{IN}(j\omega)\Gamma_L(j\omega)}$$

For oscillations, loop gain must be unity, i.e.,

1 $$\boxed{\Gamma_{IN}(j\omega)\Gamma_L(j\omega) = 1}$$

2 **Also, for oscillations, $\boxed{\text{Re}\{Z_{IN}\} \text{ must be negative}}$**



$$\Gamma_L(j\omega) = \frac{Z_L - Z_o}{Z_L + Z_o}$$

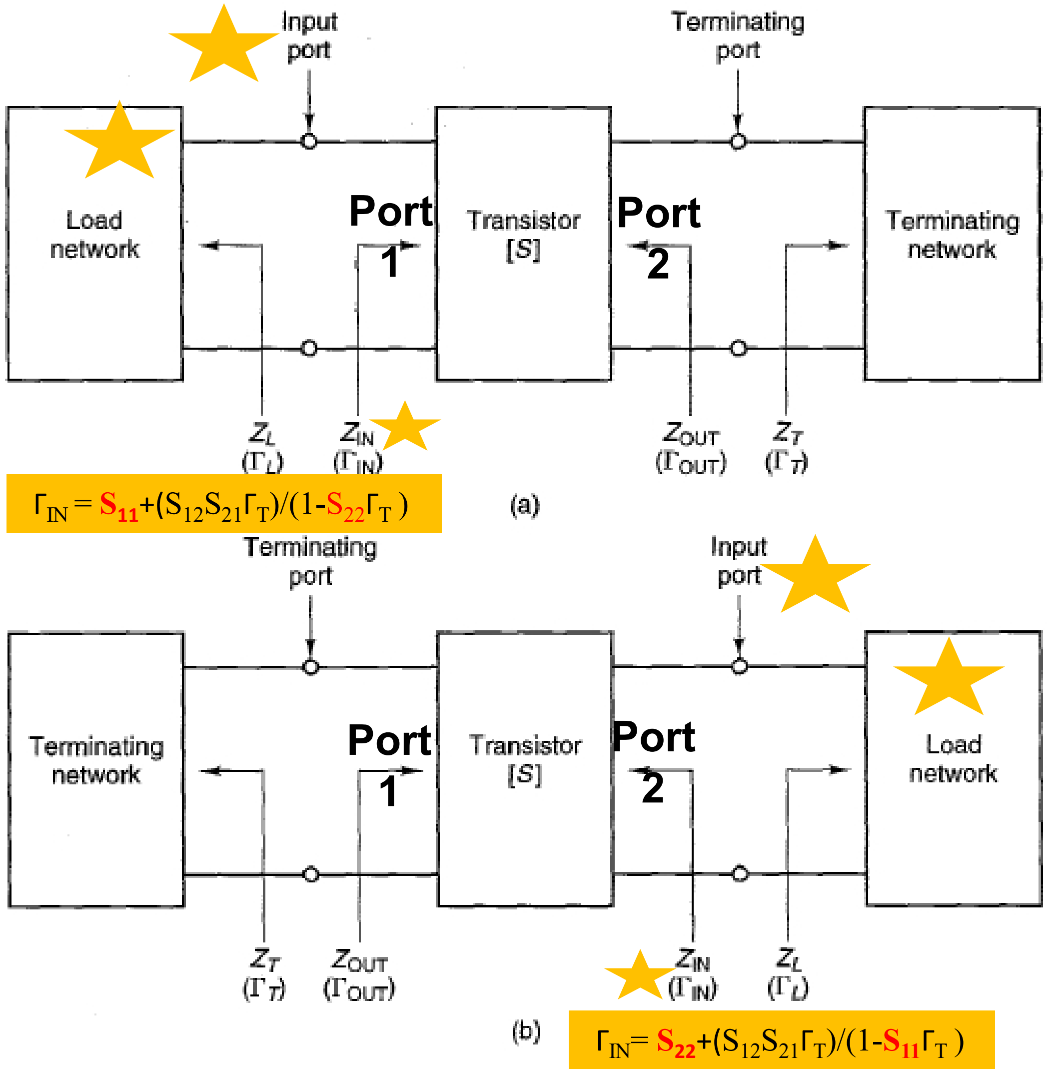
$$\Gamma_{IN}(j\omega) = \frac{Z_{IN} - Z_o}{Z_{IN} + Z_o}$$

Microwave oscillator circuit

Two-Port Negative Resistance Oscillator

“Load-in(put)”
“Term(innating)-out(put)”

“L in”
“T out”



$\Gamma_{IN} = S_{11}+(S_{12}S_{21}\Gamma_T)/(1-S_{22}\Gamma_T)$

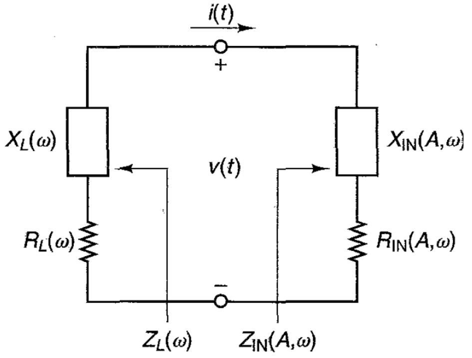
$\Gamma_{IN} = S_{22}+(S_{12}S_{21}\Gamma_T)/(1-S_{11}\Gamma_T)$

Figure 5.3.1 Two-port oscillator model.

Fig. 5.3.1, Microwave Transistor Amplifiers by G. Gonzalez

- The terminating network can be placed at either port of the transistor.
- Once the terminating port is chosen, the other port is referred to as the **input port (which** the load network is connected to).
- The input port (Γ_{in}) of an Oscillator (the transistor) is always opposite the Terminating port (where the terminating network is connected)

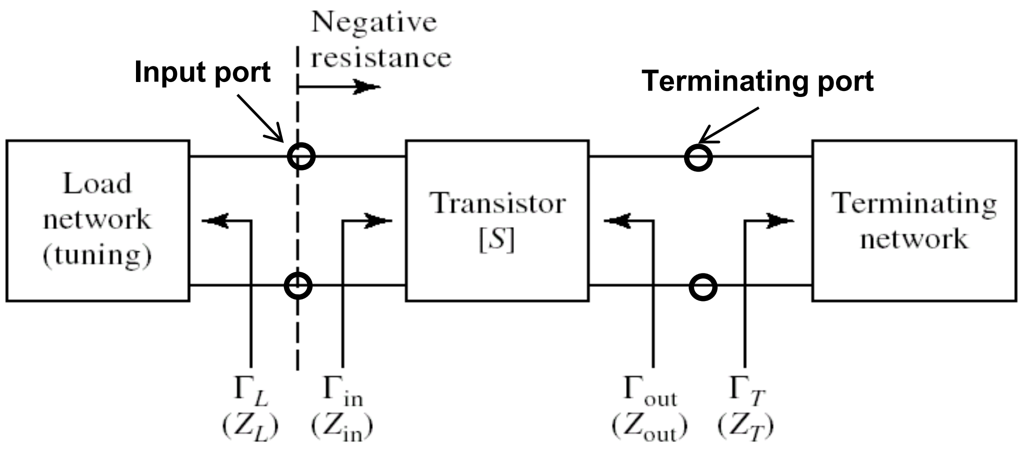
[this notion of the “input port” is consistent with the previous 1-port model, repeated blew]



Note that Gonzlez’s definition of the oscillator input port is opposite to that of Pozar’s.

Two-Port Negative Resistance Oscillator

The “input port” is at the Load network side (i.e, opposite the terminating port); the load matching network is connected to the input port.



- one port is made to resonate (K<1)
- the other port is designed to match the output impedance with the negative resistance Rin

‘Mnemonic’ – RN vs NR
- Load (resonator) network – RN
- Terminating network (negative resistance)-- NR

Steady oscillation conditions

$$R_{IN}(A_o,\omega_o) + R_L(\omega_o) = 0$$

$$X_{IN}(A_o,\omega_o) + X_L(\omega_o) = 0$$

To start the oscillation

$$R_L = R_0/3 \text{ or, in general, } R_L = |R_{IN}(0,\omega)|/3$$

the oscillation conditions

$\boxed{\Gamma_L\Gamma_{in}=1}$ for **the input port**

$\boxed{\Gamma_T\Gamma_{out}=1}$ for **the output port**

“L in”
“T out”

When oscillations occurs between the load network and the transistor, oscillations will simultaneously occur at the output port.

Two-Port Negative Resistance (NR) Oscillator

Design Procedure for 2-port NR oscillator

1. Use a potentially unstable transistor at the frequency of oscillation (K < 1). This may require conversion of the S parameters (say, CE to CB) Also, S parameters may need to be modified to include the effect of feedback elements, if any, to 'increase' the instability, or to change a stable transistor into an unstable one. The above steps can be easily carried out using a microwave CAD package.

2. Design the terminating n/w to make $|\Gamma_{IN}| > 1$. Series or shunt feed back can be used to increase $|\Gamma_{IN}|$.

3. Calculate $Z_{IN} = Z_o \dfrac{1+\Gamma_{IN}}{1-\Gamma_{IN}} = R_{IN} + jX_{IN}$

4. Design the load network to resonate with Z_{IN}, and to maximize the oscillator power, i.e., $X_L(\omega_o) = -X_{IN}(\omega_o)$ and $R_L = R_o / 3 = |R_{IN}| / 3$

5. Implement the terminating network in the required configuration.

Condition 1: Unstable device: K < 1

Condition 2: Oscillating input port : $\Gamma_{IN}\Gamma_L = 1$

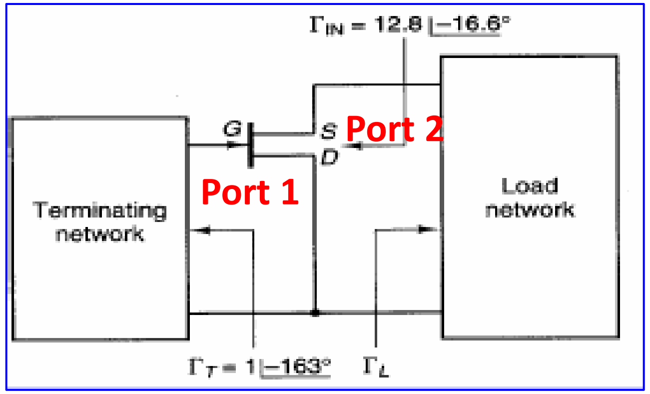
Condition 3: Oscillating output port: $\Gamma_{OUT}\Gamma_T = 1$

Example

Design an 8-GHz GaAs FET oscillator using the reverse channel configuration shown in the figure below. The S parameters of the transistor at 8 GHz are as follows,

$S_{11} = 0.98 \angle 163°$　　$S_{21} = 0.675 \angle -161°$

$S_{12} = 0.39 \angle -54°$　　$S_{22} = 0.465 \angle 120°$



Solution

Step 1: Calculate stability factor K

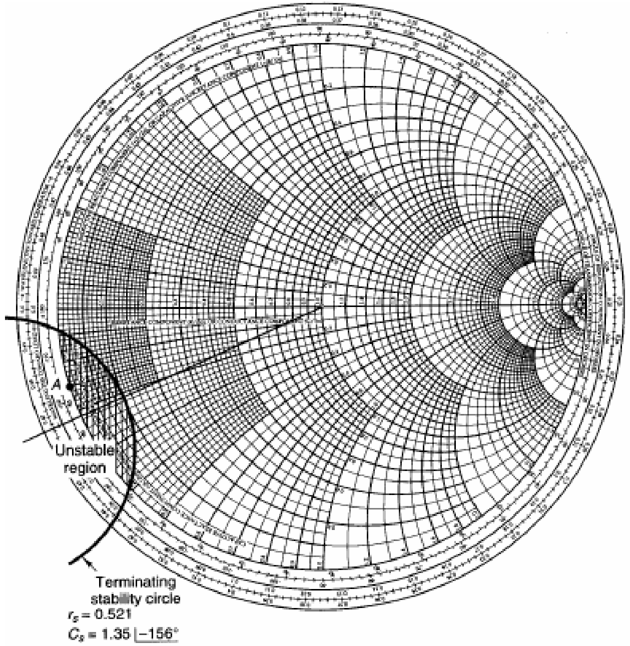
$$\Delta = S_{11} S_{22} - S_{12} S_{21} = 0.672\angle -62°$$

$$K = \frac{1-|S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} = 0.529 < 1$$

Step 2: Design the terminating network to make $|\Gamma_{in}|>1$
Draw the terminating port (or the input) stability circle in the Γ_T plane. From the figure, the gate-to-drain port is the terminating port.

$$r = r_s = \left| \frac{S_{12}S_{21}}{|S_{11}|^2 - |\Delta|^2} \right| = 0.521$$

$$c = c_s = \frac{\left(S_{11} - \Delta S_{22}^*\right)^*}{|S_{11}|^2 - |\Delta|^2} = 1.35\angle -156°$$



The stability circle at the terminating port is shown in Fig. 9.3(b).
Since $|S_{22}| < 1$, the unstable region is as marked in the figure.
If Γ_T is selected to lie in the unstable (or shaded) region,
one will have $|\Gamma_{IN}| > 1$, or in other words, negative resistance in the circuit.

Select Γ_T at point A, i.e., $\Gamma_T = 1\angle -163°$.

The corresponding value of $Z_T = Z_o \frac{1+\Gamma_T}{1-\Gamma_T} = -j\,7.5\ \Omega$ (assuming $Z_o = 50\ \Omega$)

Value of Γ_{IN}:

$$\Gamma_{IN} = S_{22} + \frac{S_{12}S_{21}\Gamma_T}{1-S_{11}\Gamma_T} = \frac{S_{22} - \Delta\Gamma_T}{1-S_{11}\Gamma_T} = 12.822\angle -16.6°$$

Step 3: Calculate Z_{IN}

$$Z_{IN} = Z_o \frac{1+\Gamma_{IN}}{1-\Gamma_{IN}} = -58 - j\,2.6\ \Omega$$

Step 4: Design the load network to resonate with Z_{IN}, and to maximize the oscillator power

$$X_L(\omega_o) = -X_{IN}(\omega_o) \text{ and } R_L = R_o / 3$$

$= |R_{IN}| / 3$

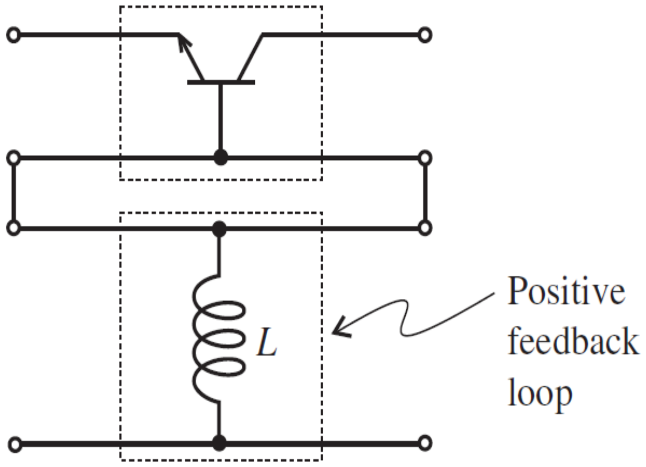
$$Z_L = 19 + j\,2.6\ \Omega \text{ at 8 GHz}$$

Base Inductance Positive Feedback

A reactive feedback element – inductance or capacitor is combined with a transistor. The value of this reactance is selected to ensure that $|S_{11}|$ and $|S_{22}|$ of the transistor/ feedback combination are greater than unity:

Example:

A BJT is operated at 2 GHz and has the following S parameters in common base configuration $S_{11}=1.9\angle 174^0$, $S_{12}=0.013\angle -98^0$, $S_{21}=1.9\angle -28^0$, $S_{22}=1.01\angle -17^0$
Determine how the Rollett factor (k) will be affected by adding the inductance to the base of the transistor



Z matrix of the transistor is

$$\begin{bmatrix} -0.42+j3.43 & -2.17-j0.097 \\ -95.23-j303.06 & -6.88-j321.03 \end{bmatrix}$$

Z matrix of the inductor is

$$\begin{bmatrix} j\omega L & j\omega L \\ j\omega L & j\omega L \end{bmatrix}$$

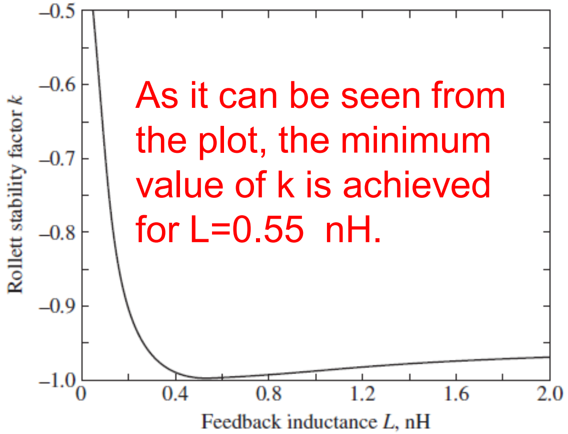
The entire circuit Z matrix will be

$$Z = Z_{tr} + Z_{ind} = \begin{bmatrix} -.42 + j3.43 + j\omega L & -2.17 - j0.097 + j\omega L \\ -95.23 - j303.06 + j\omega L & -6.88 - j321.03 + j\omega L \end{bmatrix}$$

Converting to S matrix and calculating k factor for each value of L at a frequency of 2 GHz

$$K = \frac{1 + |\Delta|^2 - |S_{11}|^2 - |S_{22}|^2}{2|S_{12}S_{21}|}$$

Rollett stability factor (k) as a function of feedback inductance in common-base configuration

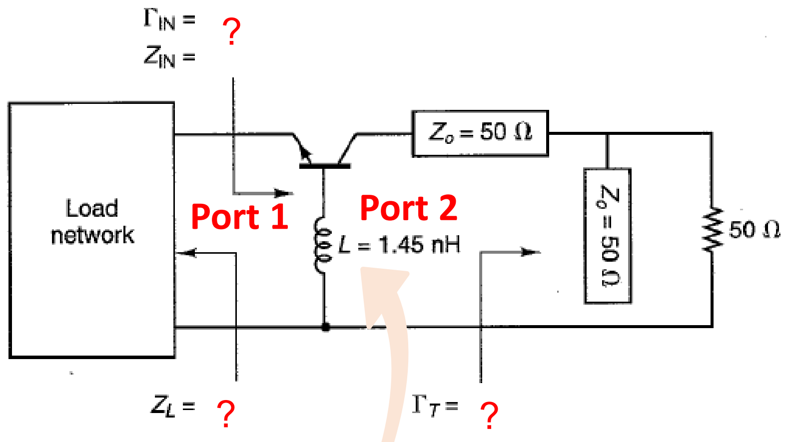


Example

Design a 2.75-GHz BJT oscillator using the common-base configuration. The S parameters of the transistor at 2.75 GHz are:

$S_{11} = 0.9 \angle 150°$ $\quad$ $S_{21} = 1.7 \angle -80°$

$S_{12} = 0.07 \angle 120°$ $\quad$ $S_{22} = 1.08 \angle -56°$



Solution

Step 1: Calculate stability factor K:

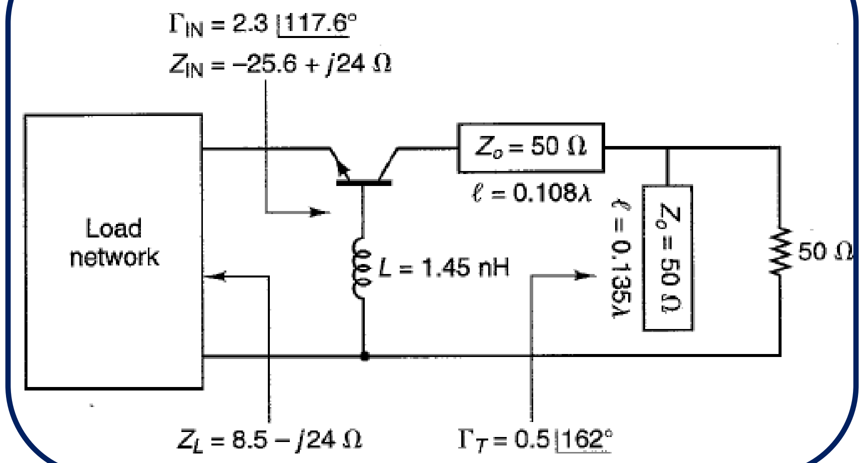
$$\Delta = S_{11} S_{22} - S_{12} S_{21} = 0.91 \angle 100.1°$$

$$K = \frac{1 - |S11|^2 - |S22|^2 + |\Delta|^2}{2|S12\,S21|} = -0.64 < 1$$

The instability can be improved further, i.e., the region of instability in the Smith Chart can be increased, by using external feedback (Fig.

Feedback modifies S parameters. The value of the feedback inductor L is varied (0.5 nH – 15 nH) to produce large values of $|S_{11}|$ and $|S_{22}|$ and to optimize the instability at the input and the output.

Final Answer (cf. next page)



Example

When L = 1.45 nH,

$S_{11} = 1.72 \angle 100°$ $S_{21} = 2.08 \angle -136°$

$S_{12} = 0.712 \angle 94°$ $S_{22} = 1.16 \angle -102°$

$$K = -0.559 < 1$$

Step 2: Design the terminating network to make $|\Gamma_{IN}| > 1$

Choose the collector-ground port for the terminating network (following Fig. 9.1a). Draw the terminating port (or the output) stability circle in the Γ_T plane.

$$r = r_L = \left| \frac{S_{12}S_{21}}{|S_{22}|^2 - |\Delta|^2} \right| = 4.91$$

$$c = c_L = \frac{\left(S_{22} - \Delta S_{11}^*\right)^*}{|S_{22}|^2 - |\Delta|^2} = 5.53\angle 23.1°$$

Choice of Γ_T :

Γ_T should be so selected (within the unstable region) that

i) $|\Gamma_{IN}|$ is large;

ii) for the resulting Γ_{IN} values, it is easily possible to implement a load matching network;

iii) there is some tuning capability.

Γ_{IN} and Γ_T are related as:

$$\Gamma_{IN} = S_{11} + \frac{S_{12}S_{21}\Gamma_T}{1 - S_{22}\Gamma_T} = \frac{S_{11} - \Delta\Gamma_T}{1 - S_{22}\Gamma_T}$$

Fig. 9.4c shows Γ_T vs. Γ_{IN}.

Let $\Gamma_T = 0.5\angle 162°$, so that,

$\Gamma_{IN} = 2.31\angle 117.6°$

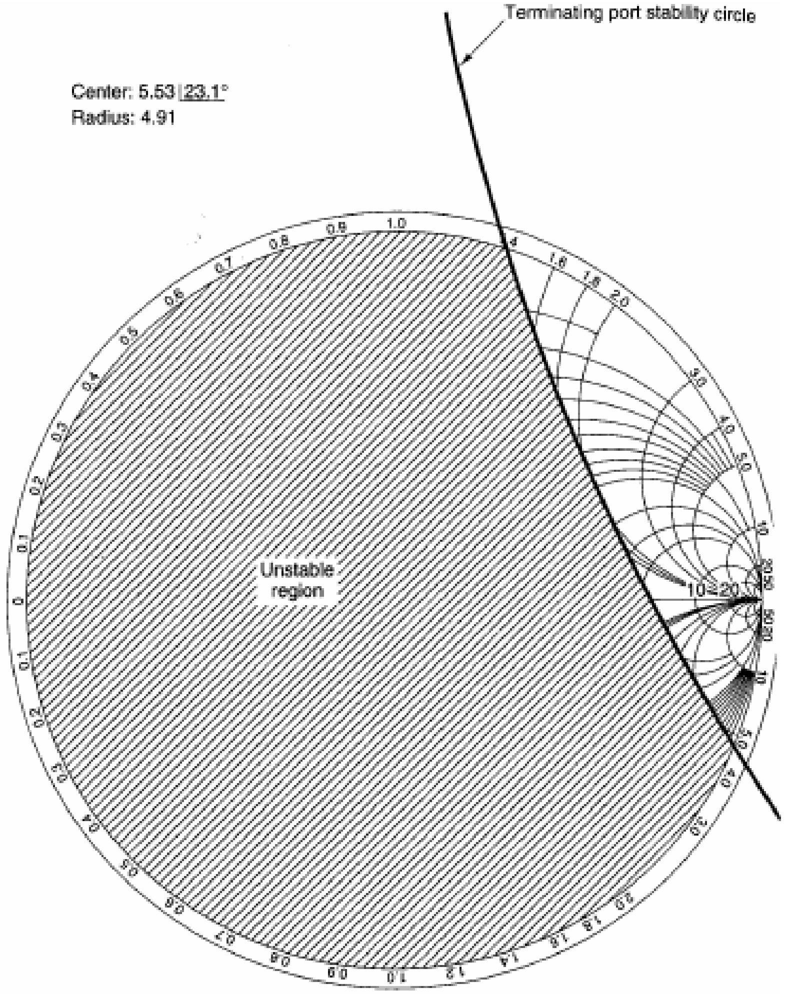
Step 3: Calculate Z_{IN}: $Z_{IN} = Z_o \dfrac{1+\Gamma_{IN}}{1-\Gamma_{IN}} = -25.6 + j\,24\ \Omega$

Step 4: Design the load network to resonate with Z_{IN}, and to maximize the oscillator power

$X_L(\omega_o) = -X_{IN}(\omega_o)$ and $R_L = R_o/3$

$Z_L = 8.53 - j\,24\ \Omega$ at 2.75 GHz

Step 5: Implement the terminating network in the required configuration



- Since |S11|>1, the unstable region is as marked in the figure.
- If Γ_T is selected to lie in the shaded (unstable) region, $|\Gamma_{in}|>1$

Outline

- ❑ **Introduction of Oscillators**
- ❑ **One-Port Negative Resistance Model**
  - Oscillation Conditions
  - How to design R_L for maximum oscillator power
- ❑ **Two-Port Oscillator Model**
  - Basic Feedback Oscillation Condition
  - **Two-Port Negative Resistance Oscillator**
    - ✓ Terminating and load networks, input & output ports
    - ✓ Oscillation conditions in terms of reflection coefficients
    - ✓ Oscillator design procedures & design examples
- ❑ **Other Design Considerations** (***optional reading)
  - Resonant network in oscillators (e.g., LC resonator)
  - Use of High-Q resonators in oscillators (e.g., DRO)
  - Frequency Tunable Oscillator (e.g., tunable YIG oscillator)
  - An illustration of VCO

Resonant Networks in Oscillators

- A resonant network (or resonator) is the frequency-selective element of an oscillator.
- It serves as the frequency-determining and phase-controlling component, providing a frequency-dependent impedance or feedback that satisfies the Barkhausen criterion at one specific frequency.
- By interacting with the active device's negative resistance, it selects and sustains a single, stable oscillation frequency.

> **Frequency stability- Very desirable & corresponds to low phase noise**

> **Resonant circuit – achieve frequency stability; High Q**

Lumped elements:
Q's ≈ a few hundred (used at lower microwave frequencies)

Distributed elements:
Q's ≈ a few hundred (microstrip line stubs, rings, disks)

Cavities:
Q's $> 10^4$ (waveguide or coaxial; bulky, temperature sensitive)

Dielectric resonators:
Q's $\approx 10^3$ (small size; low-cost; excellent temperature stability: increasingly common over micro-wave/millimeter-wave frequencies)

Dielectric loaded cavity resonators:
Q's $\approx 10^2$ (miniature; self-shielding; SMT compatible etc.)

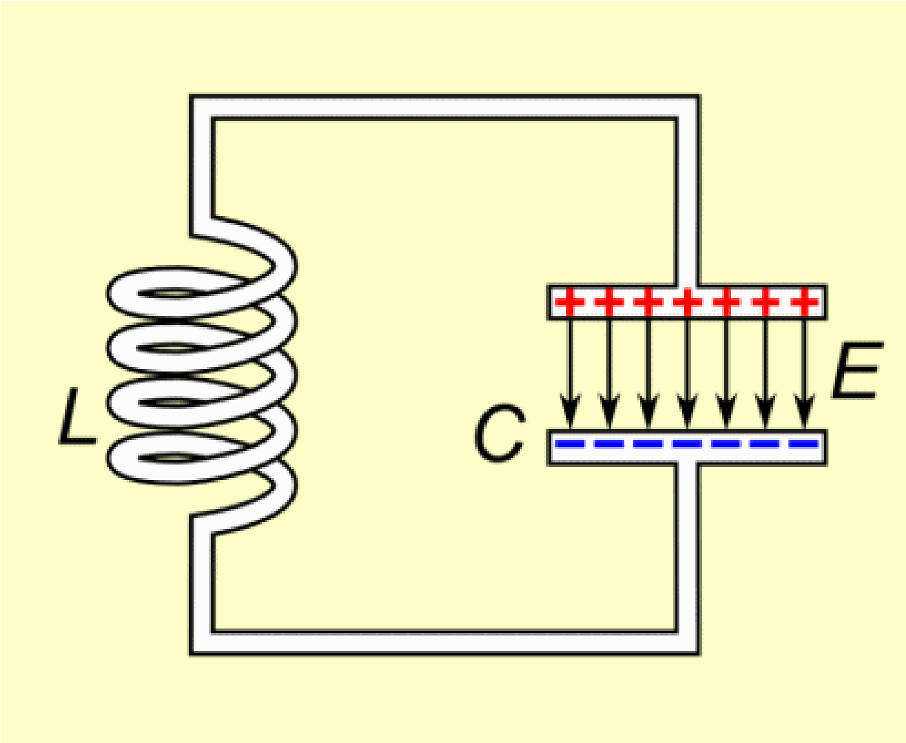
Electronic tuning: YIG; varactor

Recall

1D oscillator model & oscillation condition

1. $R_{IN}(A_o,\omega_o) + R_L(\omega_o) = 0$
   Negative resistance
2. $X_{IN}(A_o,\omega_o) + X_L(\omega_o) = 0$
   Frequency of oscillation

LC (in parallel) Resonator

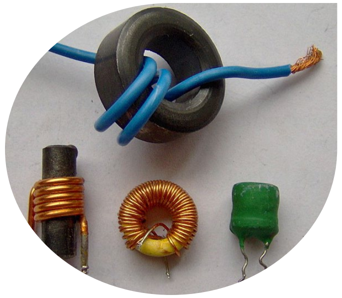


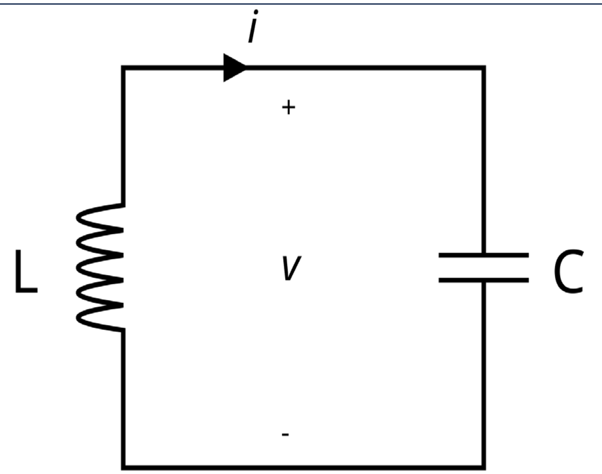
- Animated diagram showing the operation of a tuned circuit (LC circuit).
- The capacitor C stores energy in its electric field *E* and the inductor L stores energy in its magnetic field *B* (*green*).
- In the LC circuit, the charge may oscillate back and forth thousands to billions of times per second (kHz/MHz/GHz).

Source: https://en.wikipedia.org/wiki/LC_circuit

LC (in parallel) circuit diagram

inductor

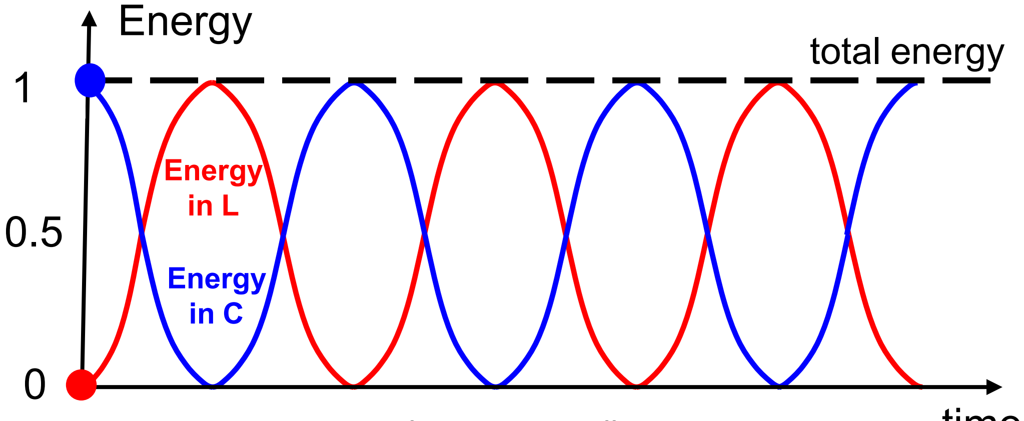




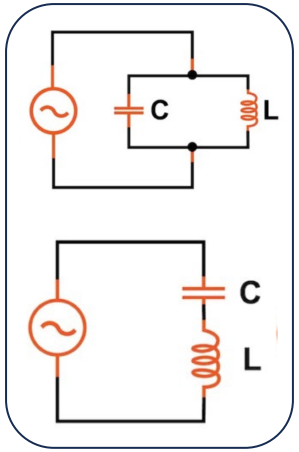
capacitor

The resonant frequency of the LC circuit

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$



Energy exchange in an oscillating LC circuit



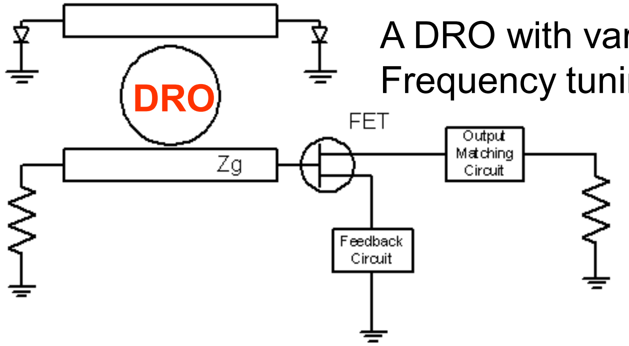
DRO & Frequency Tunable Oscillator

Other design considerations

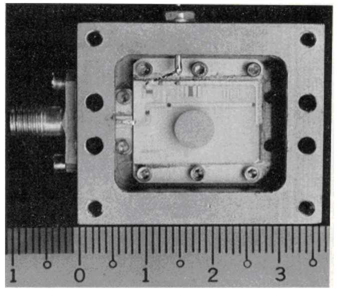
- **Use of a high-Q resonator:**
  For frequency stability & low noise
- **Oscillator pushing:**
  Frequency variation with DC bias voltage
- **Oscillator pulling:**
  Frequency variation with changes in the load
- **Active device required to:**
  - Have a negative resistance to generate power
  - Be nonlinear to start oscillations and reach a steady state

Dielectric resonator oscillator (DRO)

Use of High-Q resonators
For frequency stability and low noise



A DRO with varactors for Frequency tuning

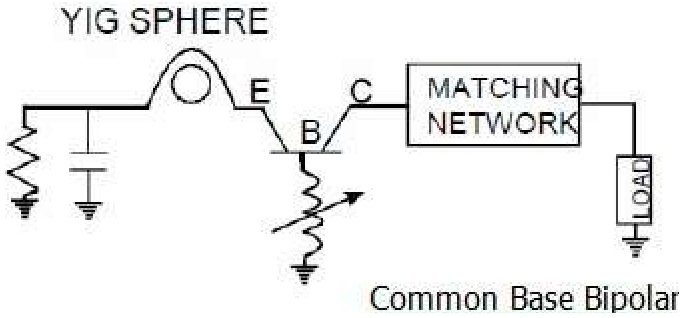


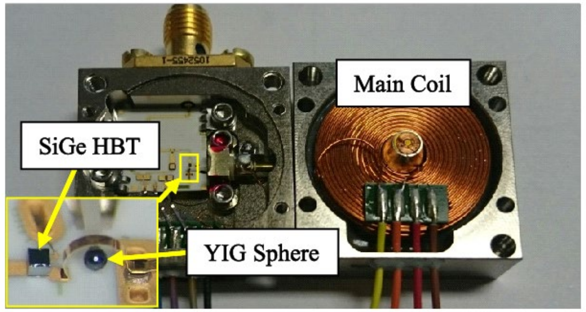
Photograph of a 10GHz DRO Oscillator

Tunable YIG oscillator

(YIG = **Yttrium Iron Garnet is** a ferrite material which resonates at microwave frequencies when inserted into a DC magnetic field)

Frequency Tunable Oscillator





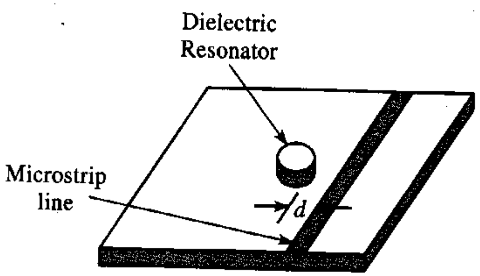
ultra-low-phase noise tunable YIG oscillator (6–12 GHz)

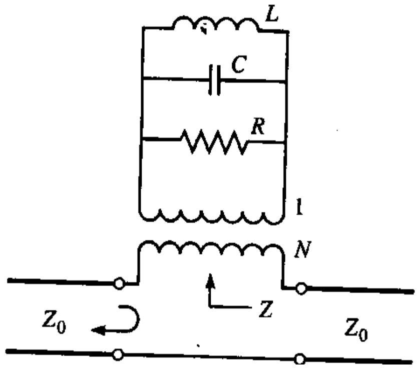
Dielectric Resonator Oscillators

DRO's

- DRO's have unloaded Q as high as several thousand.
- They are compact & easily integrated with the planar circuitry
- DR has excellent temperature stability as they are made from ceramic materials.
- A dielectric resonator is coupled to an oscillator by placing it in close proximity to a microstrip line
- The strength is determined by the spacing, *d* between resonator & microstrip line
- The resonator is modeled as a parallel RLC circuit and the coupling is modeled by turns ratio, N of the transformer.

$$Z = \frac{N^2 R}{1 + j2Q\Delta\omega/\omega_0}$$





Where $Q = R/\omega_0 L$ is the unloaded Q

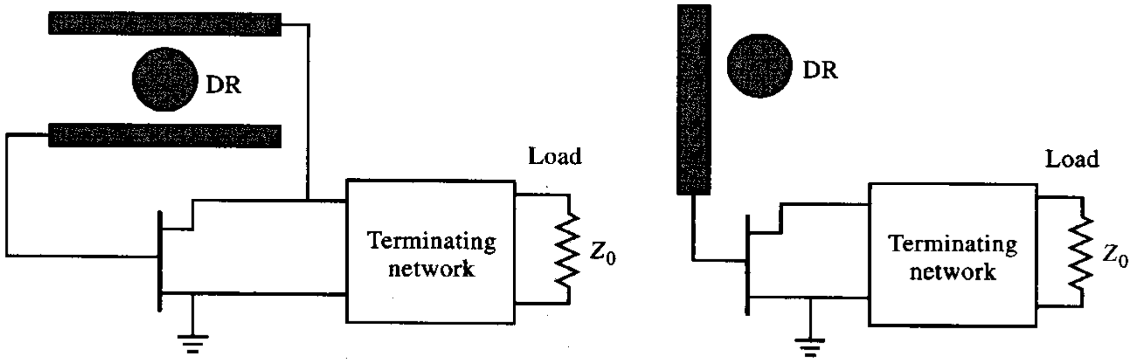
$\omega_0 = 1/\sqrt{LC}$ is the resonant frequency

Dielectric Resonator Oscillators

- The reflection coefficient seen on the terminated microstrip transmission line looking toward the resonator is

$$\Gamma = \frac{(Z_0 + N^2 R) - Z_0}{(Z_0 + N^2 R) + Z_0} = \frac{N^2 R}{2Z_0 + N^2 R}$$

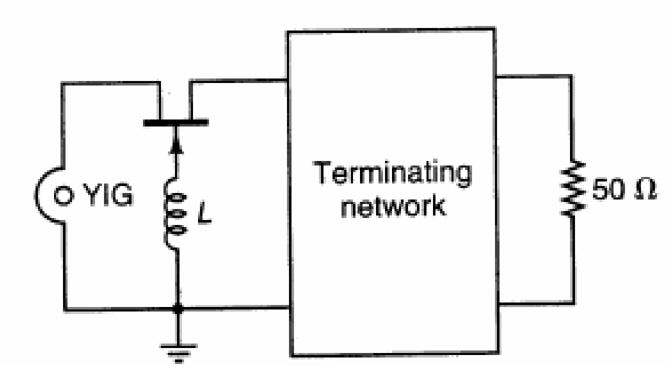
- The oscillator configuration may be common source (emitter), common gate (gate) and common drain (collector).
- A dielectric resonator can be incorporated into the circuit to provide frequency stability using parallel or series feedback

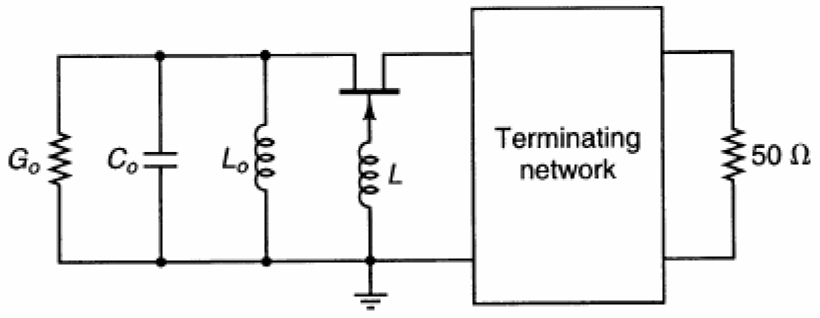


Frequency Tunable Oscillator

YIG Oscillator

- YIG Yttrium Iron Garnet ($Y_3Fe_5O_{12}$) is a magnetic crystal material with a frequency of oscillation proportional to applied bias magnetic field
- YIG provides a high Q resonance circuit in which tuning over a frequency range can be accomplished.
- Tuning is achieved by positioning the YIG crystal in a magnetic field (provided by solenoid) and than vary the DC current through solenoid
- This changes in the magnetic field is applied to YIG and frequency of oscillation also varies.
- Resonant frequency can vary from 500 MHz – 50 GHz.





Frequency Tunable Oscillator

Varactor Tuned Oscillator

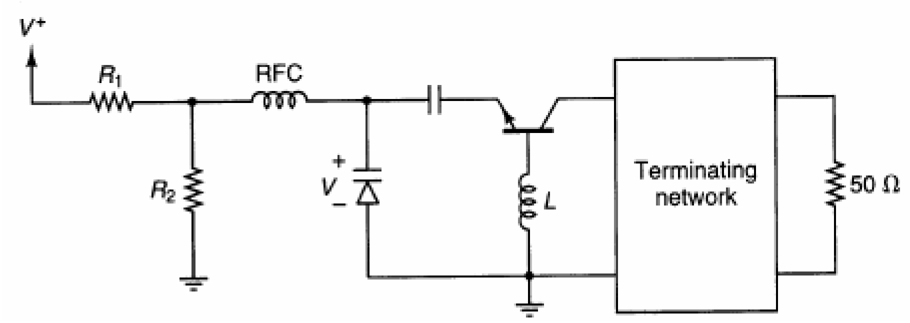
- Varactor tuned oscillator uses varactor diode for frequency tuning.
- The pn junction capacitance under reverse bias conditions are used by proper choice of diode doping profile.

$$C_j = \frac{C_{j0}}{\left(1 - \frac{V_a}{V_{bi}}\right)^S}$$

C_{j0}: Junction capacitance at zero bias voltage; Va: applied voltage across junction;

V_{bi}: the built in voltage (contact potential) & S=1/m+2 is doping distribution

- Varactor diodes are made up of GaAs or silicon, GaAs provides higher Q.
- Varactor tuned oscillators have higher tuning speed compared to YIG
- The control of the frequency is by applied voltage, so varactor tuned oscillators are also called voltage controlled oscillator.



Comparison

Characteristic	Varactor	YIG
Tuning speed	nanosecond	Millisecond
Tuning power	microwatt	watt
Tuning linearity	2% - 10%	<2%
Tuning bandwidth	Multi-octave	Multi-octave
Loaded Q	5 - 50	500 - 5000

Typical Specifications

Parameter	High-Q or Cavity-Tuned (e.g., YIG)	Low-Q or Varactor-Tuned VCO
Frequency	2–4 GHz	2–4 GHz
Power	+10 dBm	+10 dBm
Power variation versus f	±2 dB	±2 dB
Temperature stability versus f	±10 ppm/°C	±500 ppm/°C
Power versus temperature (−30 to 60°C)	±2 dB	±2 dB
Modulation sensitivity	10–20 MHz/mA	50–200 MHz/V
FM noise	−110 dBc/Hz at 100 kHz	−100 dBc/Hz at 100 kHz
AM noise	−140 dBc/Hz at 100 kHz	−140 dBc/Hz at 100 kHz
FM noise floor	−150 dBc/Hz at 100 MHz	−150 dBc/Hz at 100 MHz
All harmonics	−20 dBc	−20 dBc
Short-term post Tuning drift	±2 MHz 1 μs	±2 MHz 1–100 μs
Long-term post Tuning drift	±2 MHz 5–30 s	±2 MHz 5–30 s
Pulling of f for all phases of 12-dB return loss	±1 MHz	±20 MHz
Pushing of f with change of bias voltage	5 MHz/V	5 MHz/V

An example of Voltage-Controlled Oscillator (VCO)

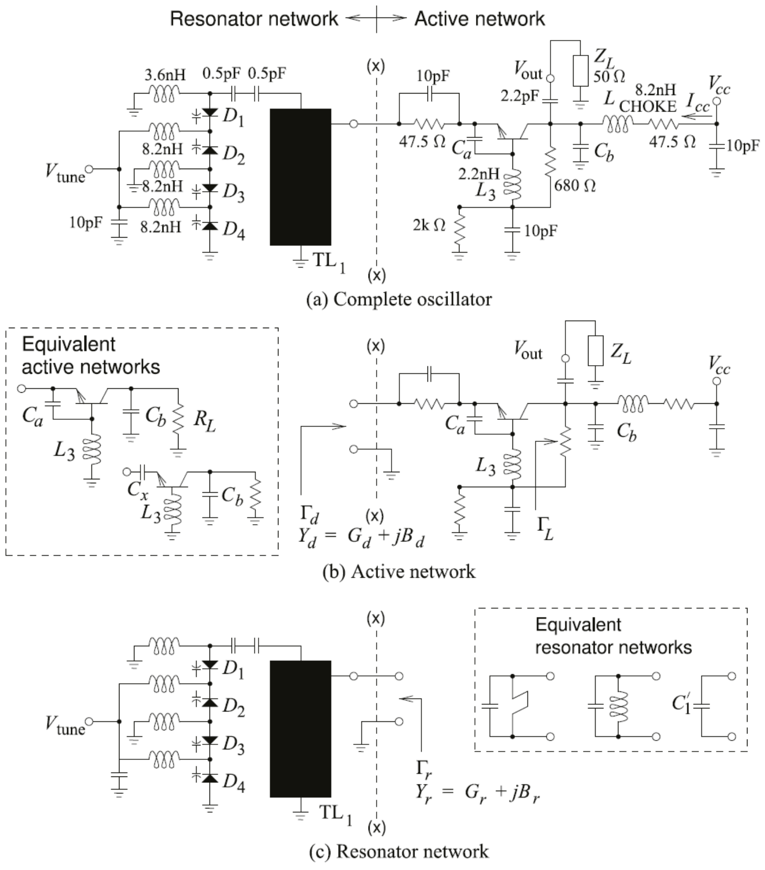


Figure 5-19: A 5 GHz common-base SiGe BJT oscillator: (a) oscillator showing the interface (x-x) between the resonator network (also called a tank circuit) and the device; (b) active network; and (c) resonator network. The element labeled TL_1 is a low impedance microstrip line. Capacitors C_a and C_b compensate for the frequency-dependent feedback provided by the base inductance. The choke inductor, $L_{CHOKE} = 8.2$ nH, presents an RF open circuit and is part of the bias circuit. $V_{CC} = 30$ V and $I_{CC} = 30$ mA. Each varactor diode (D_1–D_4) is model JDS2S71E. The transistor is a Si BJT model NE894M13, which is designed for oscillator applications above 3 GHz.

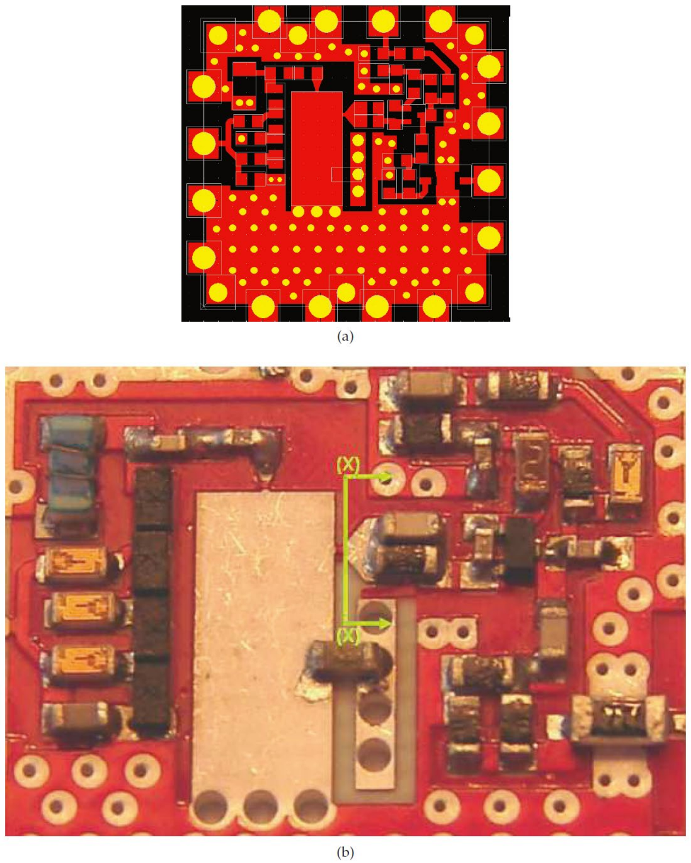


Figure 5-21: C-band VCO circuit: (a) layout showing metalization and vias to ground planes (in yellow); and (b) populated circuit board with the resonator network to the left of the cutaway line (x-x) separated from the active circuit to the right.

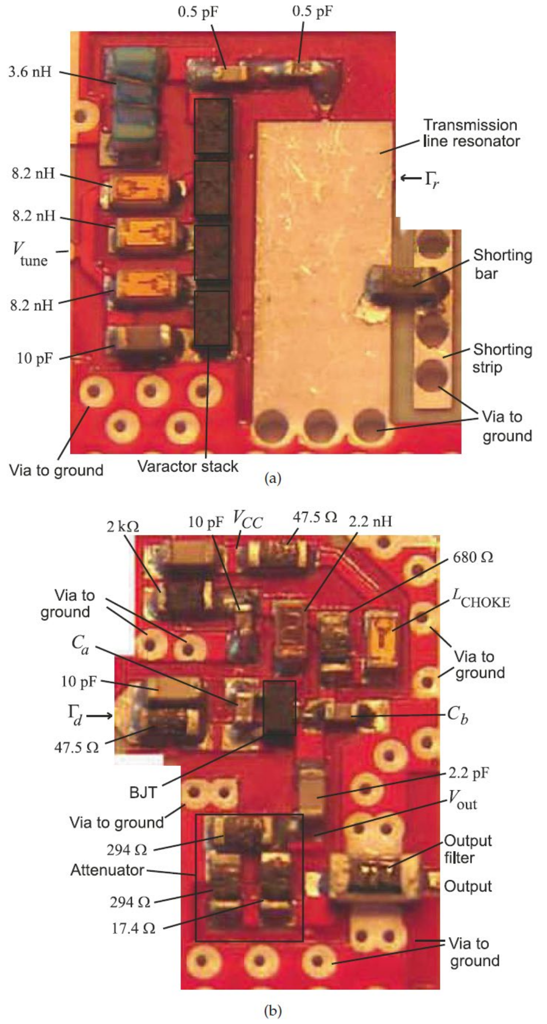


Figure 5-22: C-band VCO circuit: (a) annotated resonator network; and (b) annotated active network. The Pi attenuator (with 294 Ω resistors in the shunt legs and a 17.4 Ω series resistor) is between V_{out} and the 50 Ω bandpass filter.

From Michael Steer's Book, Vol. 5, more detail in p.176-190


Thank You!