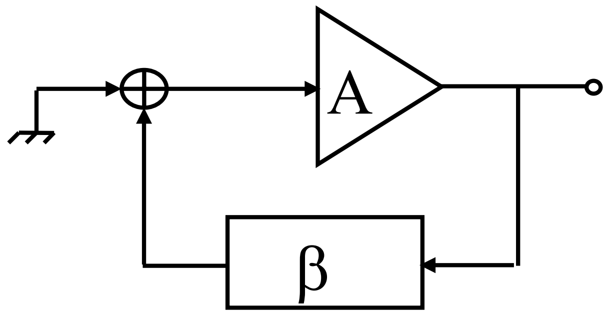
Microwave Oscillators Design

Oscillators Classification

- **Feedback Oscillators**



Oscillation Condition:

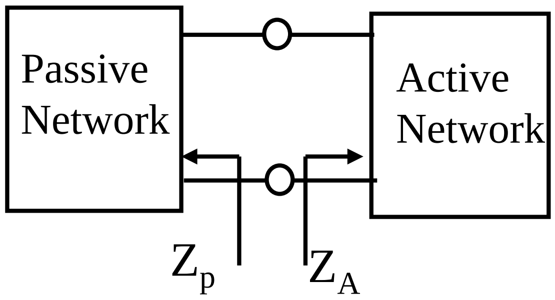
$$\text{Gloop} = A \cdot \beta(j\omega_0) = 1$$

$$\downarrow$$

$$|\text{Gloop}(j\omega_0)| = 1, \ \angle \text{Gloop}(j\omega_0) = 2n\pi$$

- **<u>Negative resistance oscillators</u>**

Most used at microwave frequencies



$$Z_A = R_A + j \ X_A(\omega), \quad Z_p = R_p + j \ X_p(\omega)$$

Oscillation Condition :

$$R_A = -R_p, \qquad X_A(\omega_0) + X_p(\omega_0) = 0$$

Characteristic Parameters

- Generated power at output
- Shape of the signal generated
- Amplitude/Phase stability
- Sensitivity of the oscillation frequency to the circuit components and to the bias sources
- Dependence of amplitude and frequency on the external loads (*load pulling*)
- Initial start-up

Main parameters definition

- Stability of the oscillation frequency: it is referred as *Indirect Stability Coefficient* S_F:

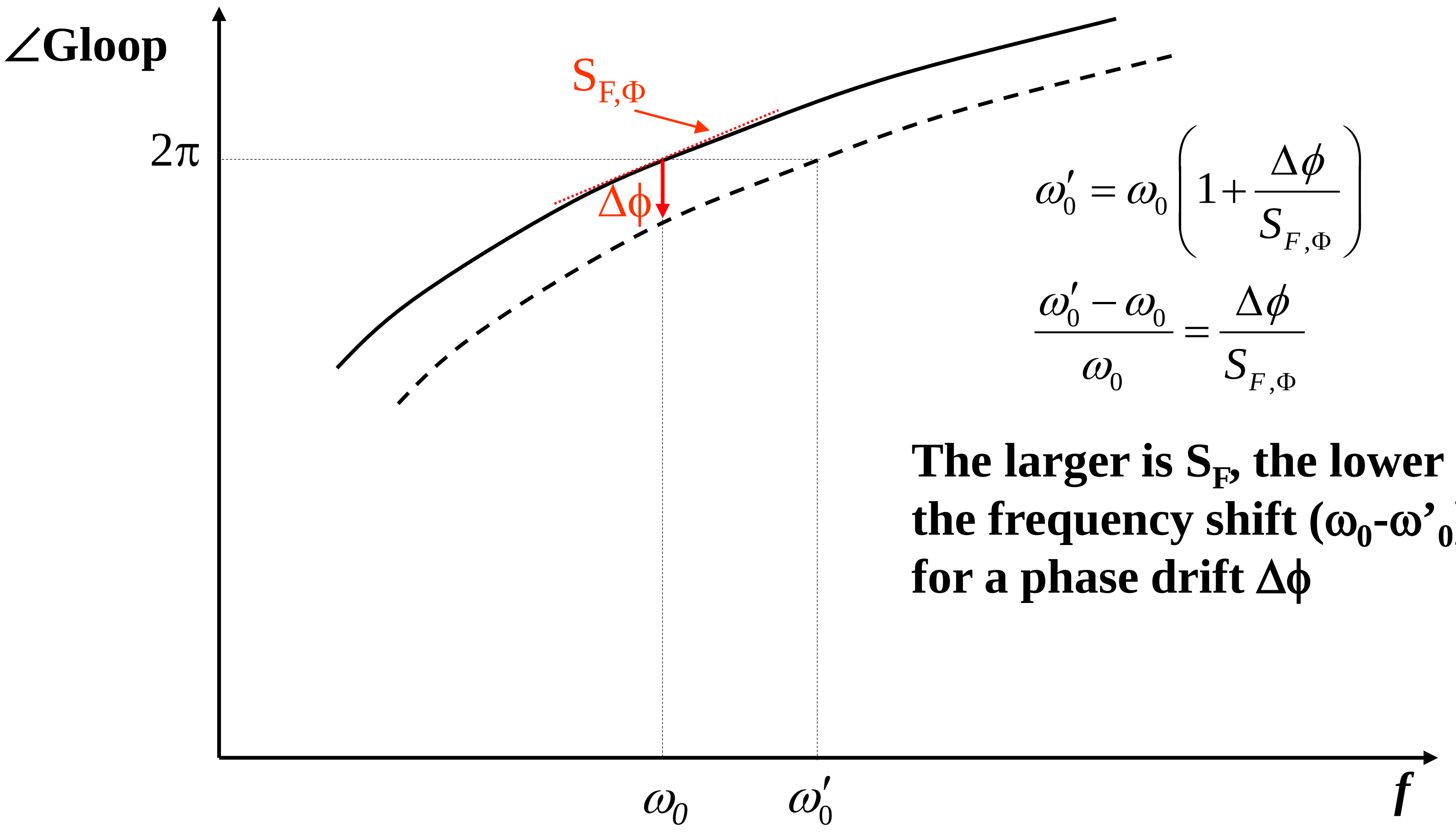
$$S_{F,\Phi} = \omega_o \left| \frac{d\Phi_{Gloop}}{d\omega} \right|_{\omega=\omega_0} \qquad S_{F,X} = \omega_o \left| \frac{d\left[X_A(\omega) + X_p(\omega)\right]}{d\omega} \right|_{\omega=\omega_0}$$

  A change $\Delta\Phi$ of the *Gloop phase* (or ΔX of overall reactance) produces a variation of the oscillation radian frequency given by: $\Delta\omega = \omega_0 \, \Delta\phi / S_{F,\Phi}$

- Harmonic distortion: it is an index of how close is the produced waveshape to the ideal sinusoid. It defines numerically the amplitude of the harmonic referred to the fundamental (ω_o).

- Phase and Amplitude Noise: it defines the random fluctuations of amplitude and phase of the generated signal. While the noise amplitude can be removed (or limited) with a suitable circuitry, the phase noise can not be removed from the output signal and is the most important drawback introduced by the oscillators in communication systems

Graphical representation of indirect stability

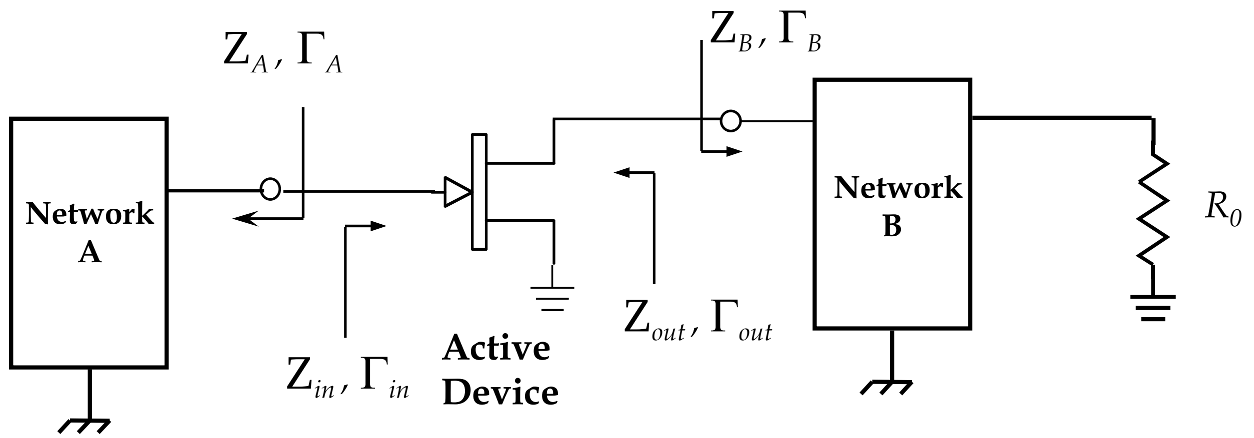


$$\omega_0' = \omega_0 \left(1 + \frac{\Delta\phi}{S_{F,\Phi}}\right)$$

$$\frac{\omega_0' - \omega_0}{\omega_0} = \frac{\Delta\phi}{S_{F,\Phi}}$$

The larger is S_F, the lower is the frequency shift (ω_0-ω'_0) for a phase drift Δϕ

General configuration of a microwave oscillator

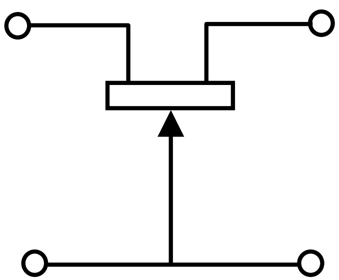


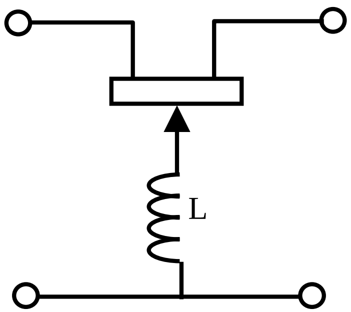
In order to produce a sinusoidal signal, it is necessary that a negative resistance is observed at input and output of the active device (that is an input/output reflection coefficient with magnitude larger that one). As a consequence, the active device must be potentially instable (K<1), so, given Γ_A and Γ_B , we must have (at the oscillation frequency):

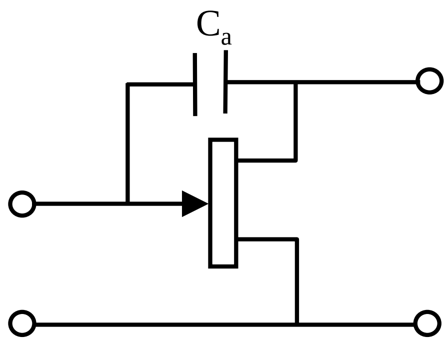
$$|\Gamma_{in}| > 1 \quad , \quad |\Gamma_{out}| > 1$$

Increase the instability of active devices

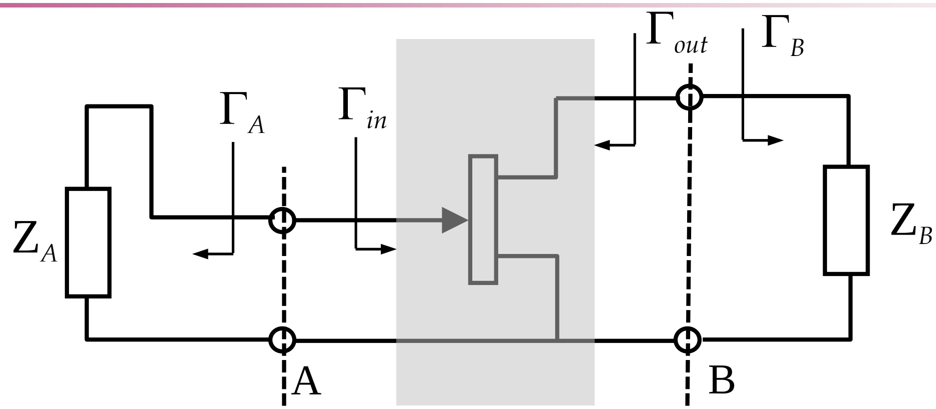
To increment the instability we must decrease the K parameter of the device. This can be obtained by changing the reference terminal or by introducing positive feedback:







Oscillation Conditions (regime)



$$\Gamma_{in}(j\omega_0)\cdot\Gamma_A(j\omega_0)=1 \Rightarrow (Z_{in}+Z_A)=0 \quad \text{or} \quad (Y_{in}+Y_A)=0$$

$$\Gamma_{out}(j\omega_0)\cdot\Gamma_B(j\omega_0)=1 \Rightarrow (Z_{out}+Z_B)=0 \quad \text{or} \quad (Y_{out}+Y_B)=0$$

These condition apply in steady-state, i.e. when the output voltage amplitude is stabilized; it can be shown that in this condition only one of the equations above is required (the other is implied).

Oscillation Conditions (start-up)

To guarantee the start of the oscillation the poles must be in the right-hand plane, then:

$$\left|\Gamma_{in}(j\omega_0)\cdot\Gamma_A(j\omega_0)\right|>1 \quad \Rightarrow \quad \mathrm{Re}\left(Z_{in}+Z_A\right)<0 \quad \text{or} \quad \mathrm{Re}\left(Y_{in}+Y_A\right)<0$$

$$\left|\Gamma_{out}(j\omega_0)\cdot\Gamma_B(j\omega_0)\right|>1 \quad \Rightarrow \quad \mathrm{Re}\left(Z_{out}+Z_B\right)<0 \quad \text{or} \quad \mathrm{Re}\left(Y_{out}+Y_B\right)<0$$

In this case both conditions must be verified in order to guarantee the oscillation start-up.

After the start-up the oscillation grows and the poles must move towards the left-hand plane (it is produced by the non-linearity of the active device).
Once the poles reach the imaginary axis the oscillation remains with constant amplitude and the transient is concluded.

Frequency of oscillation

The oscillation frequency is determined by the regime condition. Combining with the start-up requirement:

$$\left|\Gamma_{in}\left(j\omega_0\right)\cdot\Gamma_A\left(j\omega_0\right)\right|>1,\quad \left|\Gamma_{out}\left(j\omega_0\right)\cdot\Gamma_B\left(j\omega_0\right)\right|>1$$

$$\angle\left(\Gamma_{in}\left(j\omega_0\right)\cdot\Gamma_A\left(j\omega_0\right)\right)=0$$

To increase the oscillation stability, only the phase of Γ_A should determine ω_0. This is obtained by imposing the slope of $\angle\Gamma_A(\omega_0)$ much large than that of $\Gamma_{in}(\omega_0)$ (by using resonating components for which $|\Gamma_A|\approx 1$). Note that once ω_0 is imposed at section A, it is also verified (at regime) at section B.

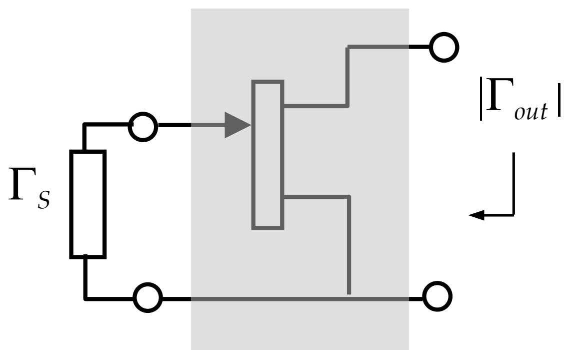
If the impedances are considered the equations become:

$$R_{in}\left(j\omega_0\right)+R_A\left(j\omega_0\right)<0,\quad R_{out}\left(j\omega_0\right)+R_B\left(j\omega_0\right)<0$$

$$X_{in}\left(j\omega_0\right)+X_A\left(j\omega_0\right)=0$$

Mapping Circles

Smith Chart is useful also for oscillators design. Specifically, we can draw on the Γ_s plane the locus of points where the value of $|\Gamma_{out}|$ has been assigned.
This locus is a circle with the following center and radius:



$$|\Gamma_{out}| = \left| s_{22} + \frac{\Gamma_S \cdot s_{12} \cdot s_{21}}{(1 - \Gamma_S \cdot s_{11})} \right| = cost$$

$$C_s = \frac{s_{22}\Delta^* - |\Gamma_{out}|^2 \cdot s_{11}^*}{|\Delta|^2 - |\Gamma_{out}|^2 \cdot |s_{11}|^2}$$

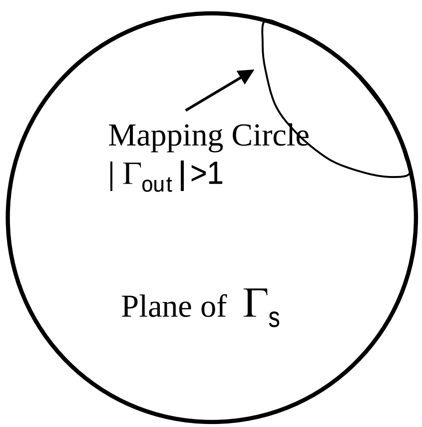
$$r_s = \frac{|s_{12}s_{21}| \cdot |\Gamma_{out}|}{|\Delta|^2 - |\Gamma_{out}|^2 \cdot |s_{11}|^2}$$

General design procedure (1)

The design goal is to get Γ_A e Γ_B allowing the start of oscillation. The active device is characterized by the scattering parameters **S** at the oscillation frequency f_0.
Usually $|\Gamma_A|=1$ is imposed (in order to have the network A made of reactive components). Γ_A (phase) and Γ_B (magnitude and phase) are therefore the unknowns of the design

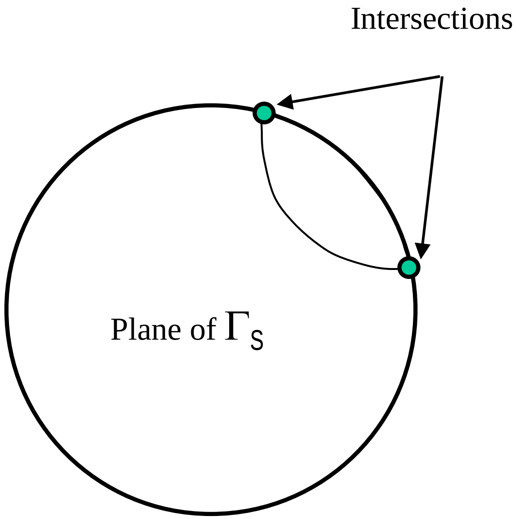
Evaluation of $\angle\Gamma_A$

- $|\Gamma_{out}| > 1$ is assigned (compatibly with the used active device). The relative mapping circle is drawn on the Smith Chart



General design procedure (2)

- The intersections of the mapping circle with the one delimiting the Smith Chart ($|\Gamma_s|=1$) are identified; if there are not intersections, a different value of $|\Gamma_{out}|$ must be assigned and another mapping circle drawn on the chart

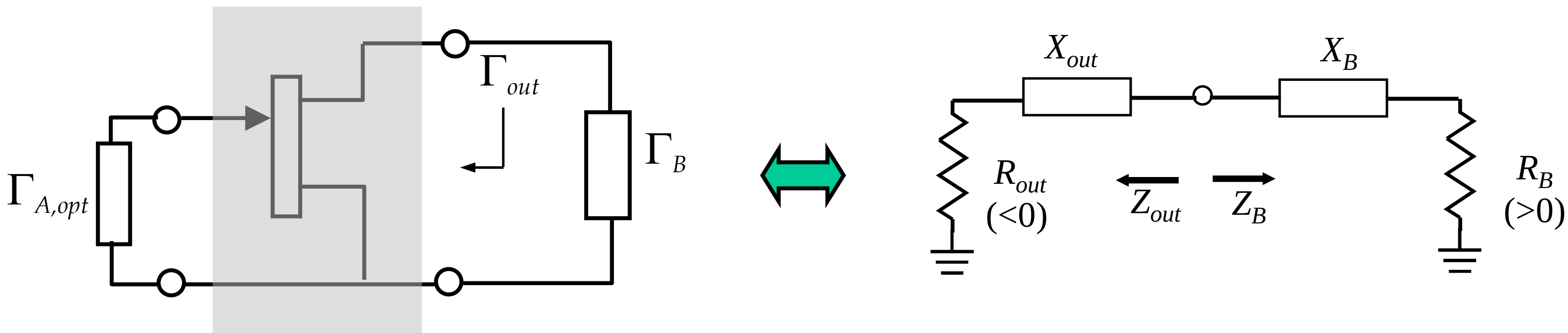


- One of the intersection points is selected: $\Gamma_s = \Gamma_{A,opt}$; network A is then synthesized as a reactive 1-port network presenting $\Gamma_{A,opt}$ at input

General design procedure (3)

- From $\Gamma_{A,opt}$ the ouput Γ is computed: $\Gamma_{out} = s_{22} + \frac{s_{21}s_{12}\Gamma_{A,opt}}{1 - s_{11}\Gamma_{A,opt}}$

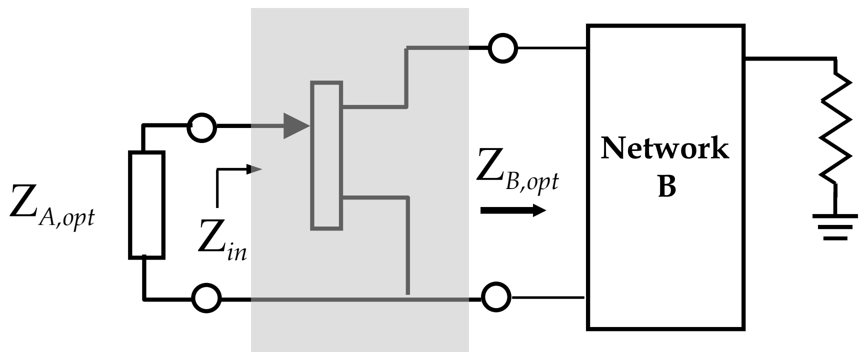
  Z_{out} (o Y_{out}) is then evaluated from Γ_{out}; this impedance (admittance) has a negative real part



- $Z_{B,opt}$ (o $Y_{B,opt}$) is computed by imposing the following condition (start of oscillation): $Z_{B,opt}=|R_{out}|/3-jX_{out}$ or $Y_{B,opt}=|G_{out}|/3-jB_{out}$
- This produces an overall impedance (admittance) real and negative

General design procedure (4)

- Z_{in} and Y_{in} are computed from $Z_{B,opt}$ (o $Y_{B,opt}$); one of the conditions $(R_{in}+R_{A,opt})<0$ or $(G_{in}+G_{A,opt})<0$ must be confirmed; otherwise a different value of $Z_{B,opt}$ (or $|\Gamma_{out}|$) must be selected and the design procedure repeated again



Note:

$(R_{in}+R_{A,opt})<0$ is equivalent to:

$$|\Gamma_{in}\cdot\Gamma_{A,opt}|>1$$

- $\Gamma_{B,opt}$ is finally evaluated from $Z_{B,opt}$ (o $Y_{B,opt}$) and the network B is synthesized by imposing the impedance transformation from the load

Notes on the design choices

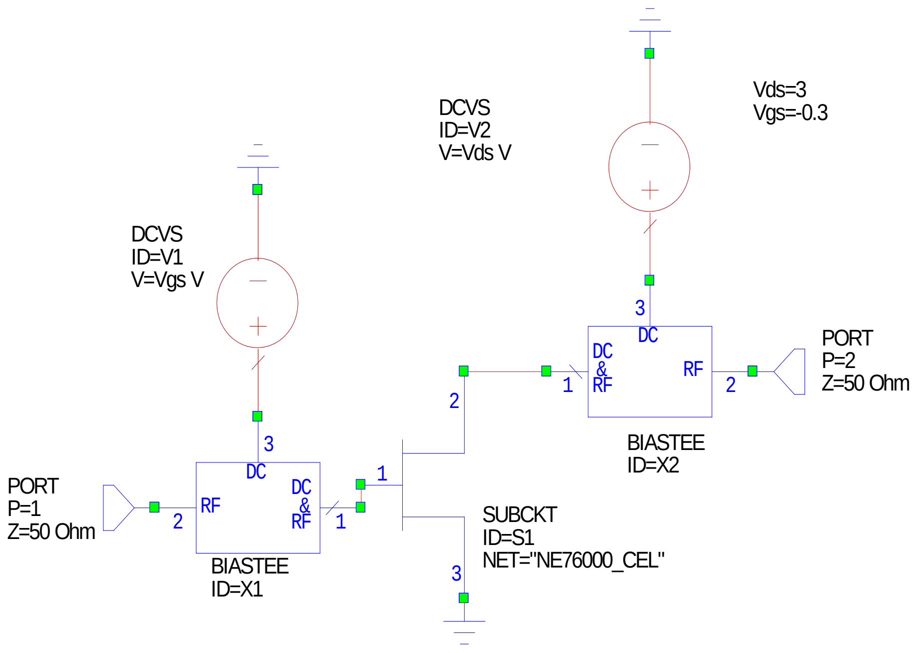
Besides the start of oscillations, the choice of ($\Gamma_{A,opt}$, $\Gamma_{B,opt}$) must take into account all the other figure of merit of the oscillator (delivered power to load, harmonic distortion, load pulling ...).

Here are some general guidelines for the design:

- The loaded Q of the output network must be at least 10 (to suppress the harmonics)
- The reactance (or the susceptance) of one of the networks (A, B) should have a large derivative respect to the frequency for increasing the stability
- To limit the harmonic distortion, the active device should be biased in class A
- To increase the output power and efficiency the active device should be biased in class B or C

Design example: Oscillator at 6 GHz

Biased Active device:
MESFET GaAs



S Parameters at 6 GHz:

S_{11}= 0.88458∠-73.509°

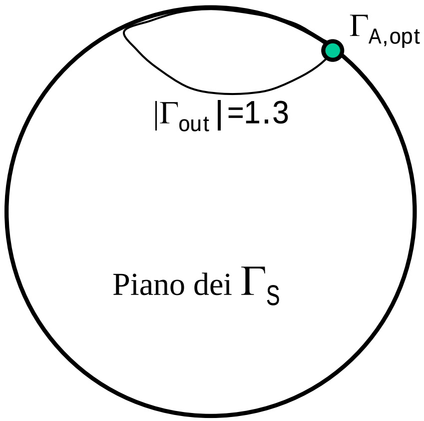
S_{21}= 3.1203 ∠ 119.76°

S_{12}= 0.1152 ∠ 48.699°

S_{22}= 0.56291 ∠ -46.665°

Stability Coeffcient: 0.227

Evaluation of $\Gamma_{A,opt}$ and $\Gamma_{B,opt}$



We assign $|\Gamma_{out}|=1.3$.

From the intersections of the mapping circle with $|\Gamma_s|=1$ we select $\mathbf{\Gamma_{A,opt}=1 \angle 62.28°}$.

We compute $\Gamma_{out} = 1.318 \angle -164.16°$

From Γ_{out} we obtain Y_{out}= -0.0733+j0.0716 mho.

The start of oscillation is then imposed:

$Y_{B,opt}$=0.0733/3-j0.0716= 0.0244-j0.0716

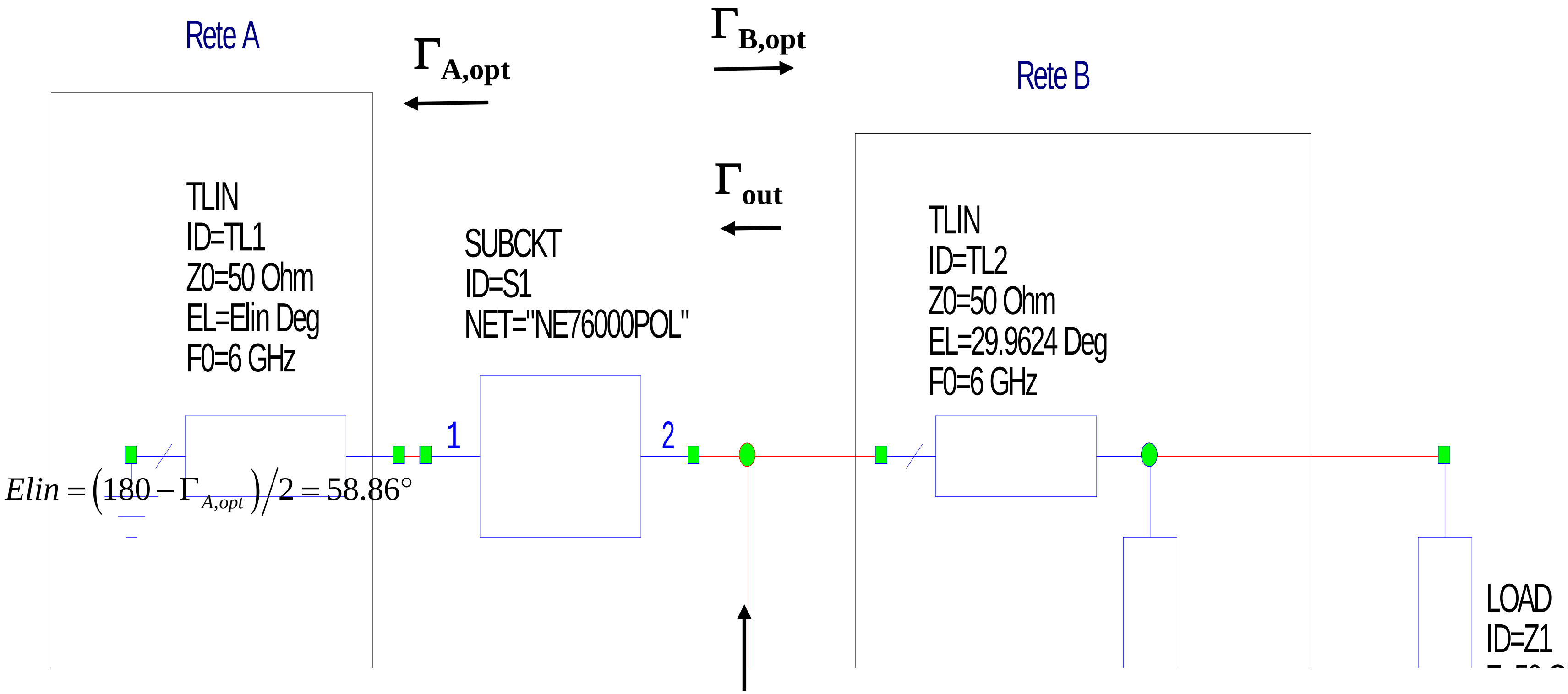
$$\mathbf{\Gamma_{B,opt}=0.851 \angle 151.717°}.$$

<u>Verification of the condition on</u> Γ_{in-}:

Γ_{in}, is computed from $\Gamma_{B,opt}$: $\mathbf{\Gamma_{in}=1.046 \angle -62°}$.

Being $|\Gamma_{in}|$ >1 the condition is met.

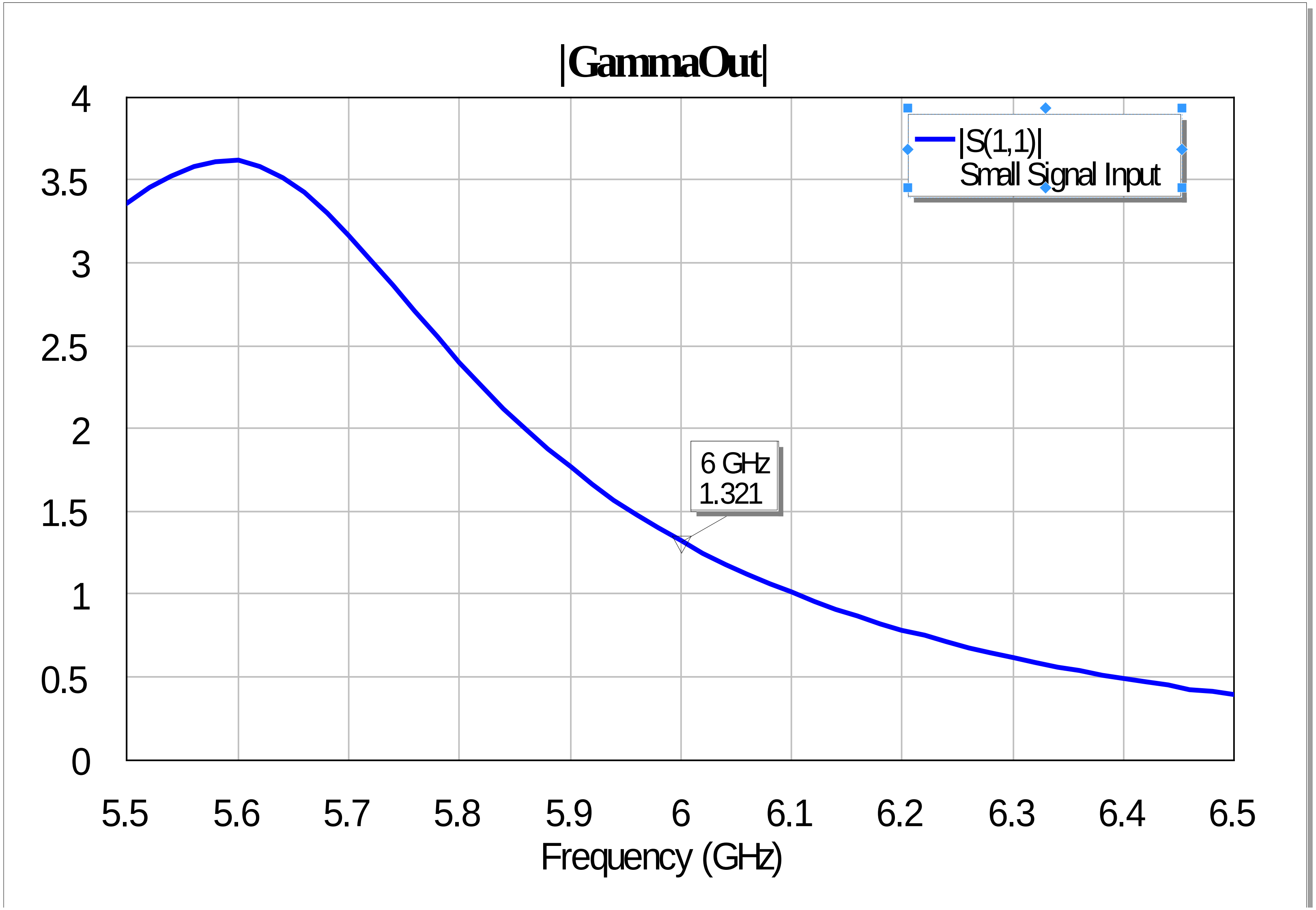
Linear simulation



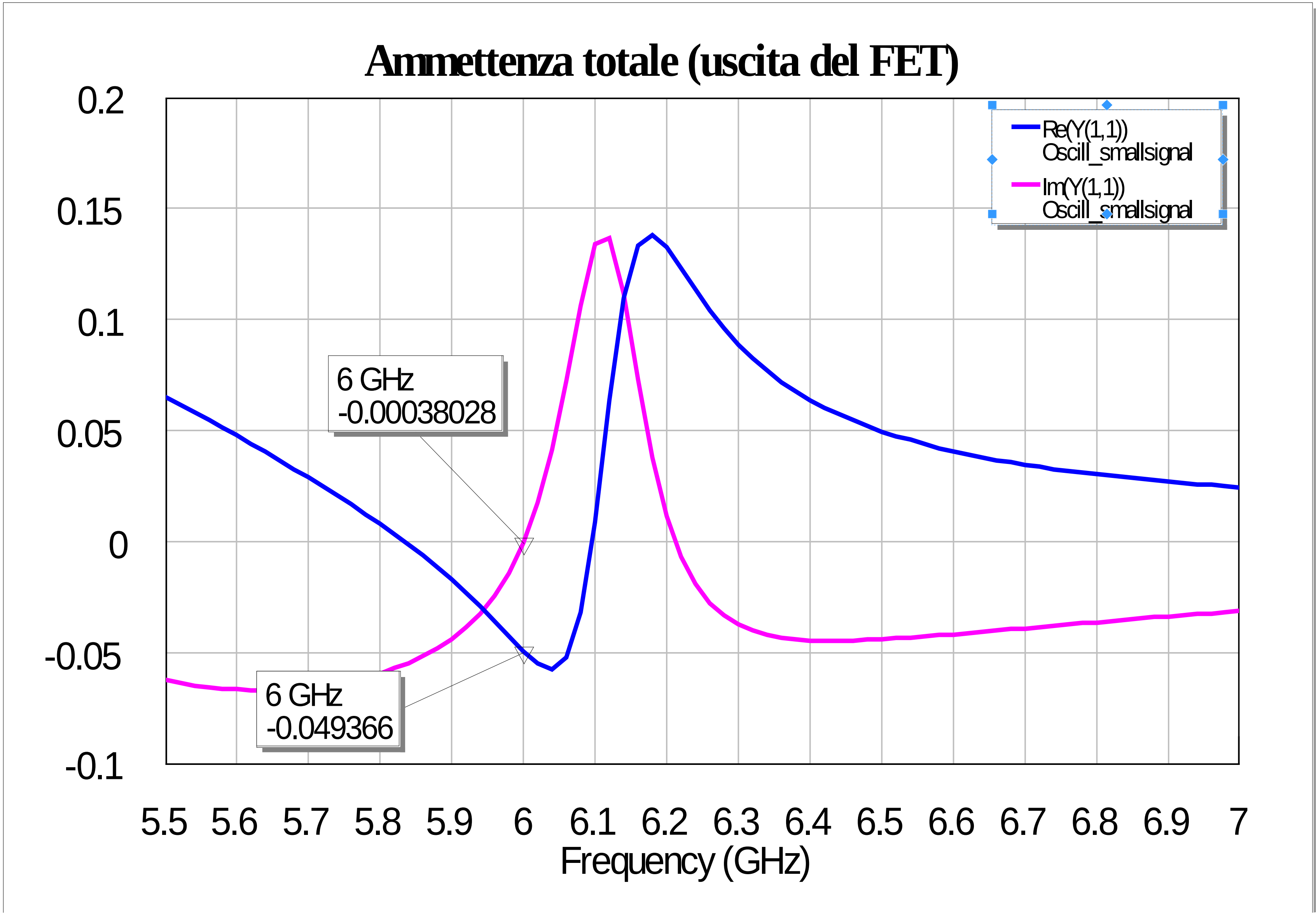
$$Elin = \left(180 - \Gamma_{A,opt}\right)/2 = 58.86°$$

$$\mathbf{Y_{tot} = Y_{out} + Y_{B,opt}}$$

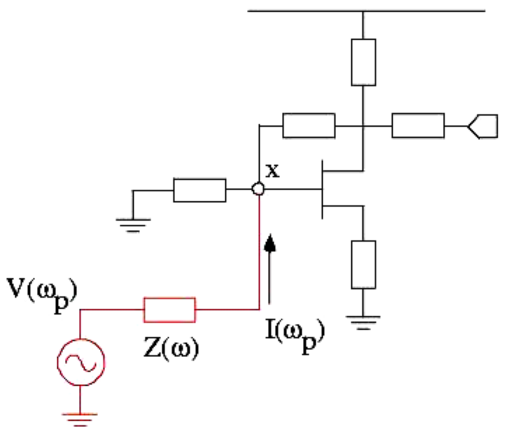
Magnitude of Γ_{out}



Total admittance at output Y_{tot}



Large Signal Analysis in MWO (Harmonic Balance)



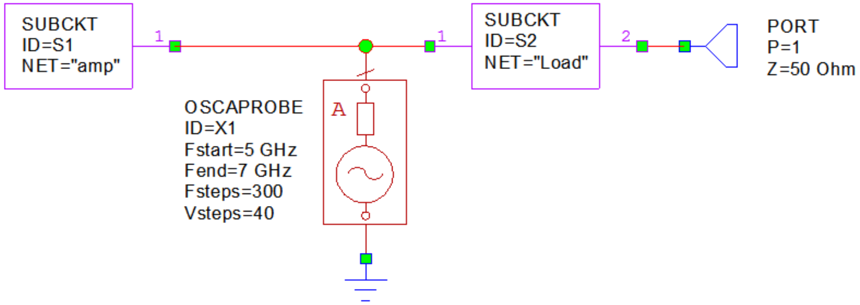
Connect a source $V_s(\omega_p)$ to an arbitrary node of the oscillator circuit. Assume the following source impedance:

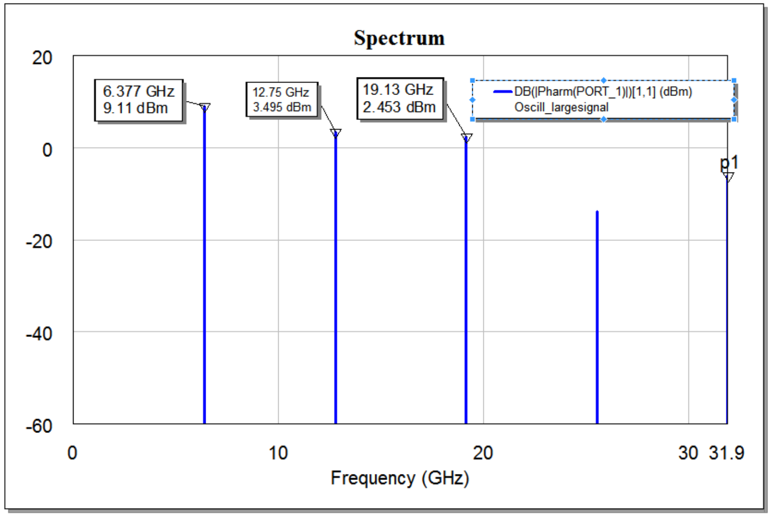
$$Z(\omega) = \begin{cases} 0 & \text{for } \omega = \omega_p \\ \infty & \text{for } \omega \neq \omega_p \end{cases}$$

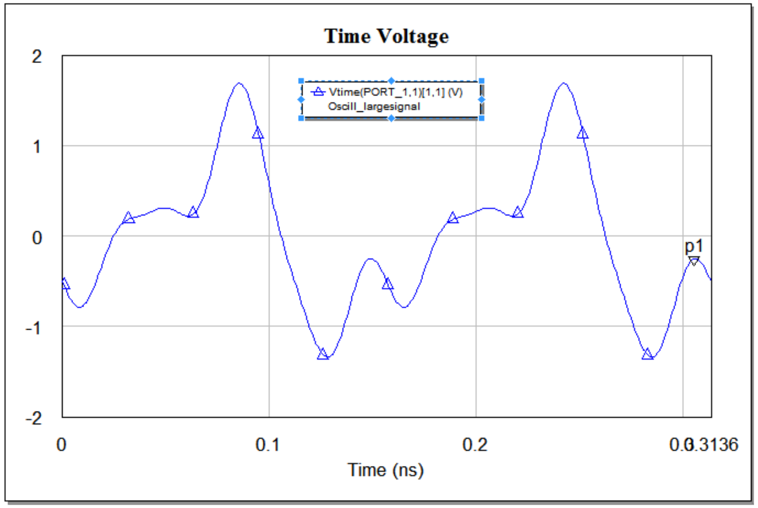
If the circuit oscillates and V_s coincides with V_x (magnitude and phase at ω_p) the current of the source (at ω_p) must be zero.
The steady-state solution can be then found following these steps:

- Connect the probe source (OSCAPROBE) to a convenient node
- Numerically search the frequency ω_p and the phasor amplitude $V_s(\omega_p)$ that determine $I(\omega_p)$ =0 (analysis is performed with harmonic balance, assuming the fundamental tone ω_p with *n* harmonics)

Example







<u>Oscillation frequency:</u>

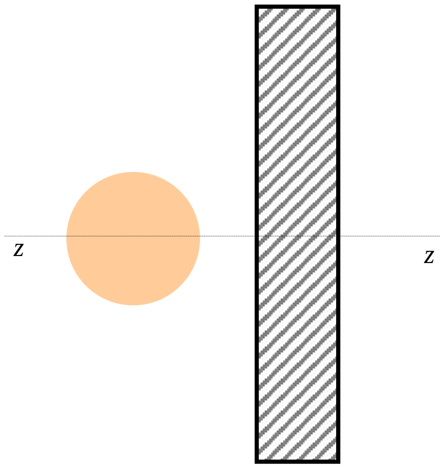
6.377 GHz

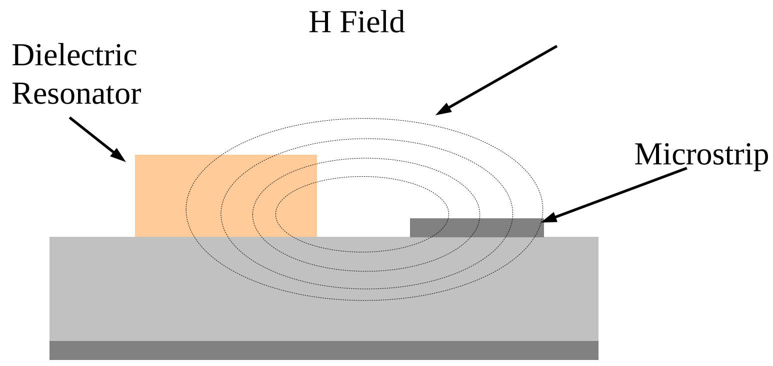
<u>Output Power at fundamental</u>

9.11 dBm

Dielectric Resonator Oscillators

DR and microstrip coupling:

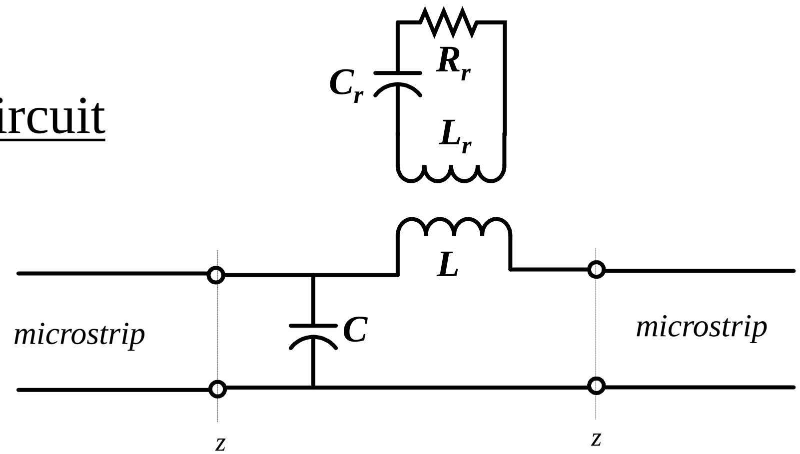




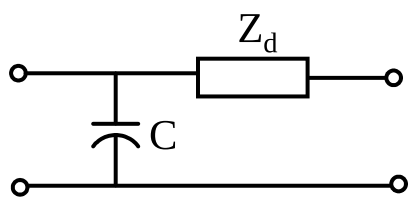
Equivalent Circuit

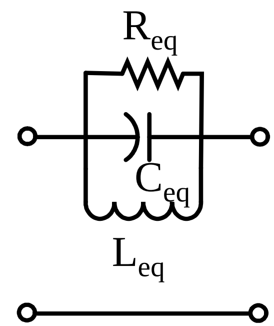
$$\omega_0 = \frac{1}{\sqrt{L_r C_r}}$$

$$Q_0 = \frac{\omega_0 L_r}{R_r} \simeq \frac{1}{\tan\delta}$$



DR Equivalent Parameters

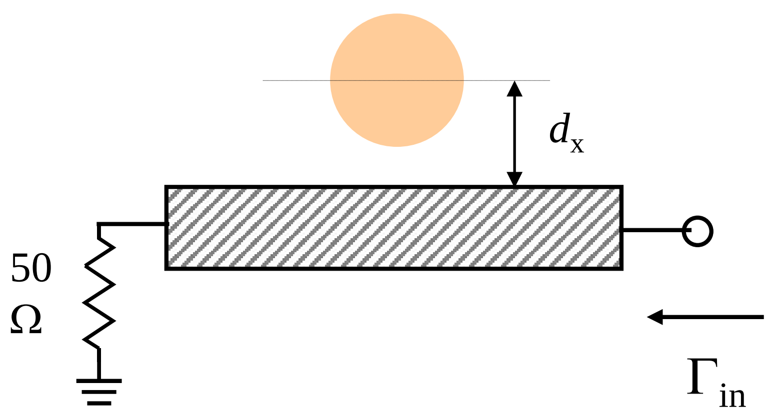


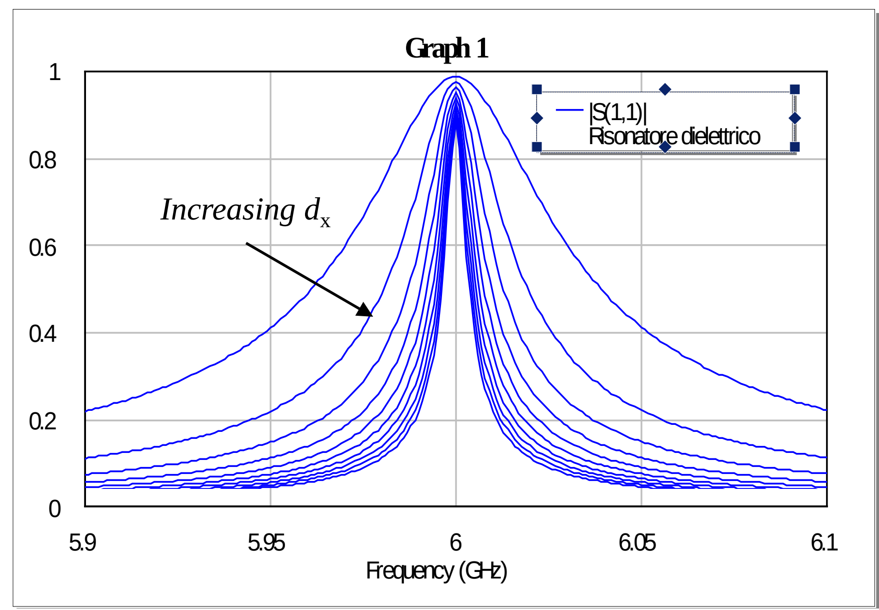


$$L_{eq} \simeq \frac{L_M^2}{L_r}, \qquad \omega_0 = \frac{1}{\sqrt{L_{eq}C_{eq}}} = \frac{1}{\sqrt{L_r C_r}}$$

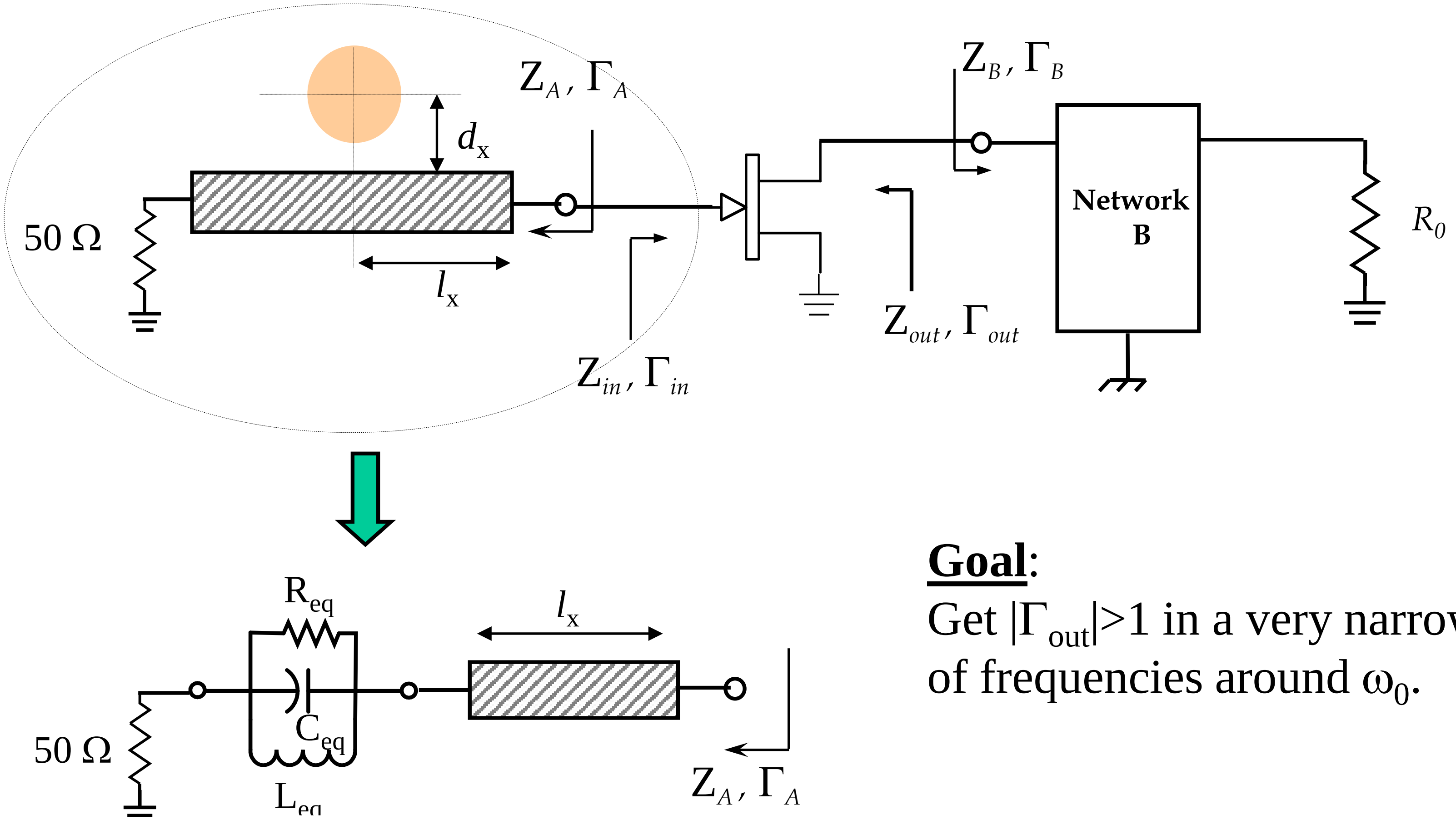
$$R_{eq} \simeq \omega_0 Q_0 \frac{L_M^2}{L_r}$$

$$Z_d \cong \frac{L_M^2}{L_r} \frac{\omega_0 Q_0}{1 + j\dfrac{2Q_0 \Delta\omega}{\omega_0}}$$





DR Oscillator Topology



Goal:
Get $|\Gamma_{out}|>1$ in a very narrow range of frequencies around ω_0.

Design example: DRO at 5 GHz

Scattering Parameters at 5 GHZ

S11 (Mag, Phase deg) 0.91153 , -62.664

S12 (Mag, Phase deg) 0.10188 , 54.396

S21 (dB, Phase deg) 10.3521 , 128.6

S22 (Mag, Phase deg) 0.58373 , -40.011

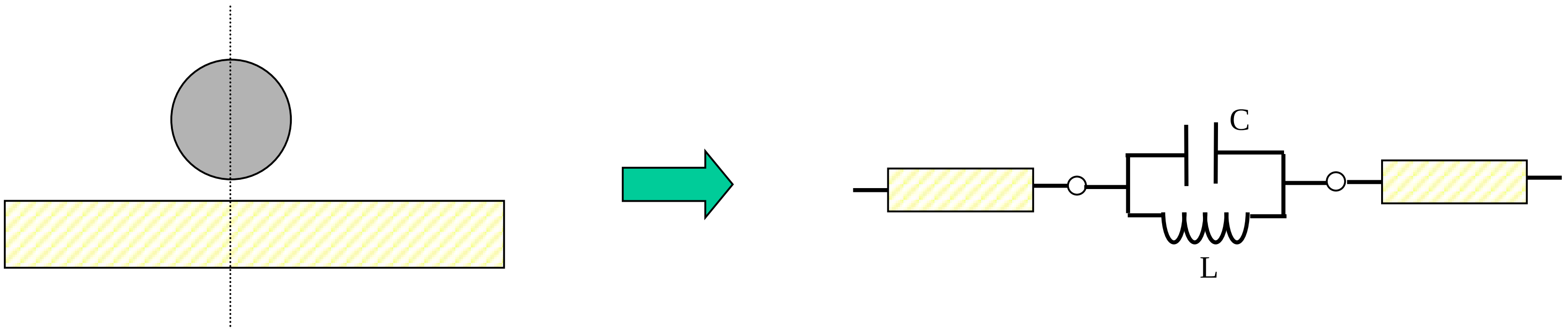
Potentially INSTABLE

Maximum Stable Gain (dB): 15.0952

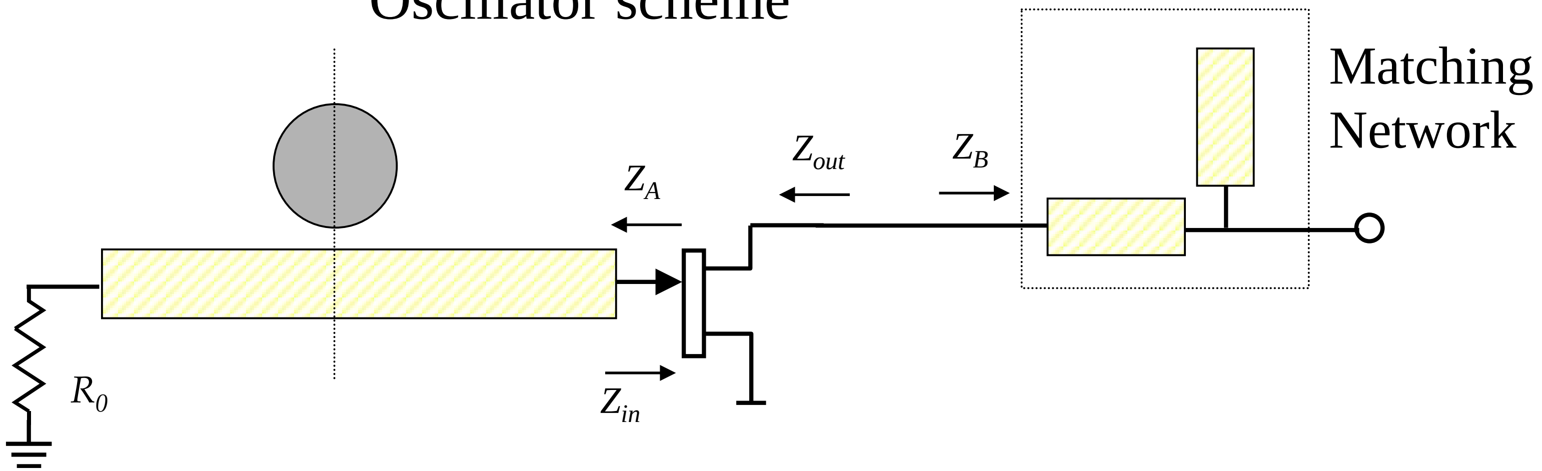
Stability Coefficient K: 0.19018

Topology

DR coupled to microstrip:

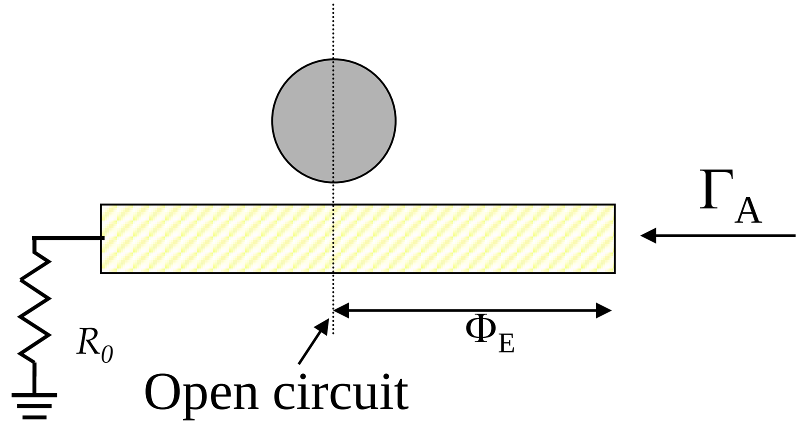


Oscillator scheme



Dimensioning

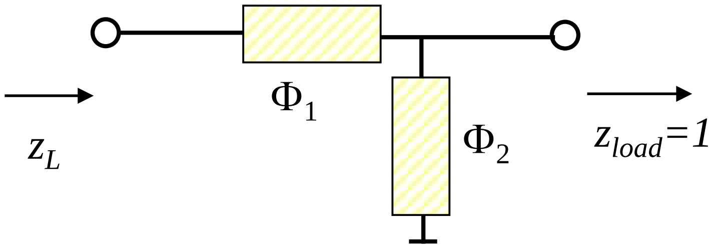
We select $\Gamma_A = 1 \angle 100°$, determining $z_{out} = -0.805 - j4$.
Imposing $z_L = 0.27 + j4$, we get $r_{in} < 0$ (-0.03) →
Oscillation conditions verified



<u>Microstrip dimensioning:</u>

$\Phi_E = 130°$

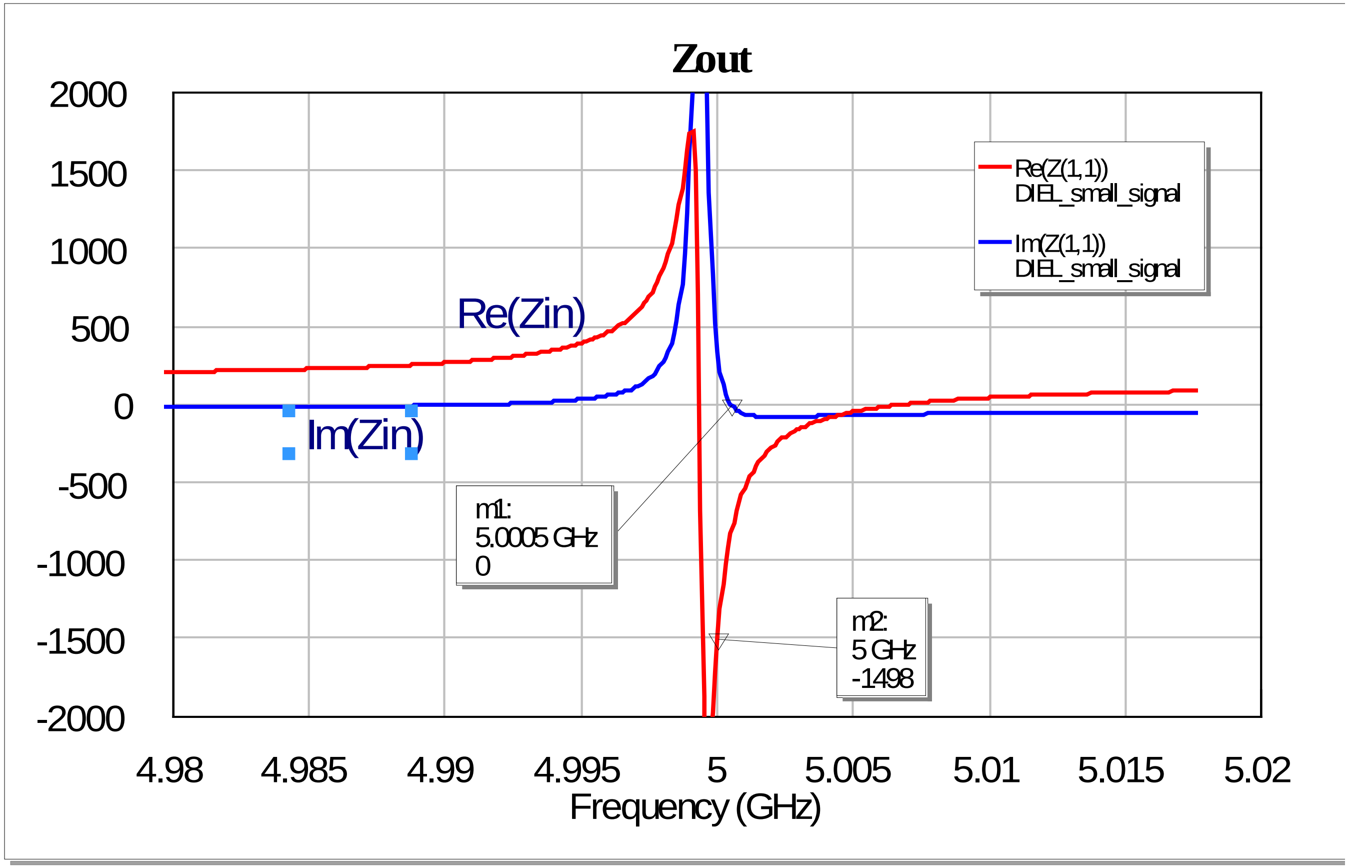
<u>Ouput network:</u>



$\Phi_1 = 68.85°$
$\Phi_2 = 97.3°$ (b=-7.8)

Verification (small signal)

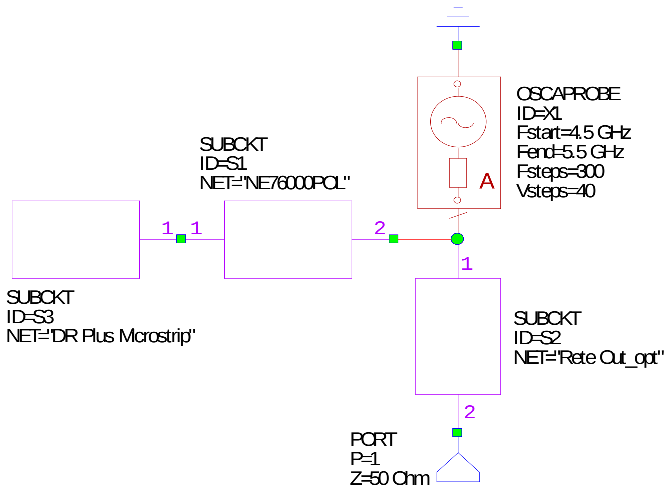
Z_{out} vs. frequency:

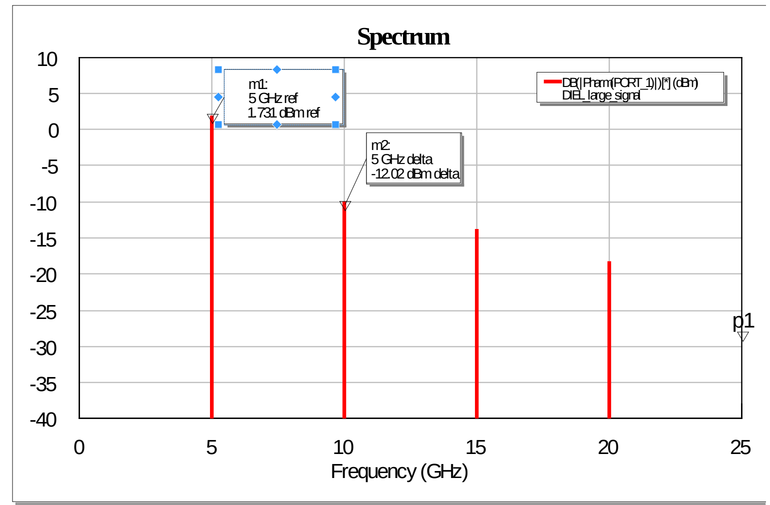


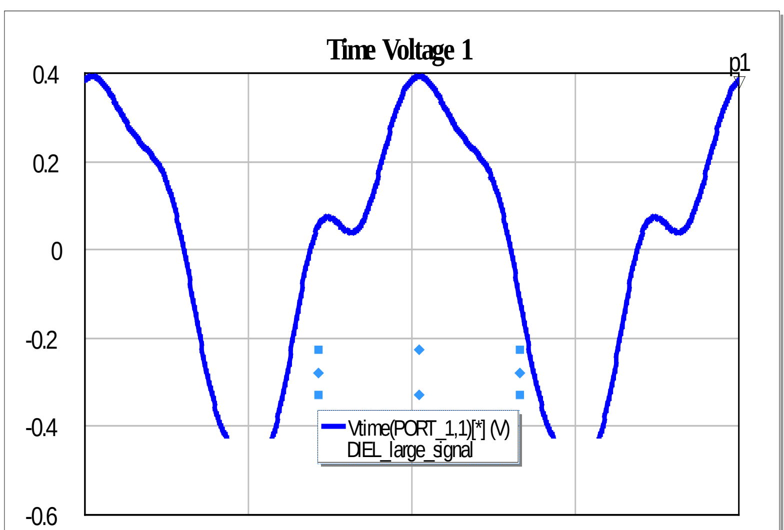
C_{DRO}=100 pF

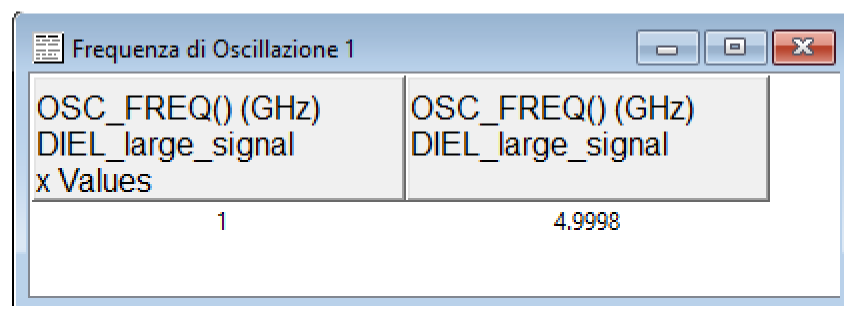
L_{DRO}= 0.01 nH

Verification (large signal)



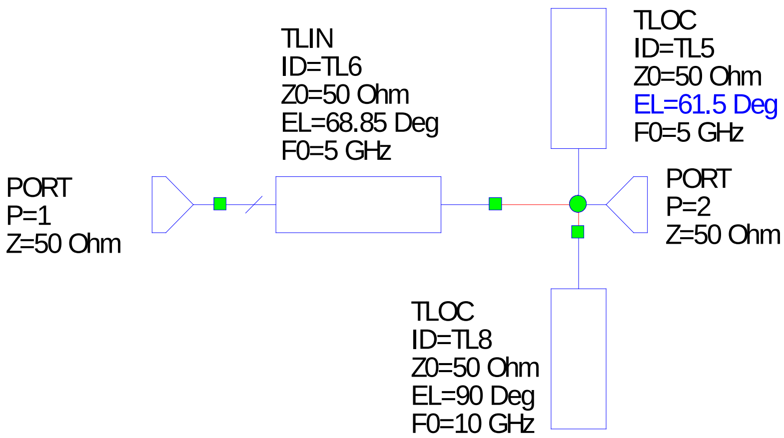


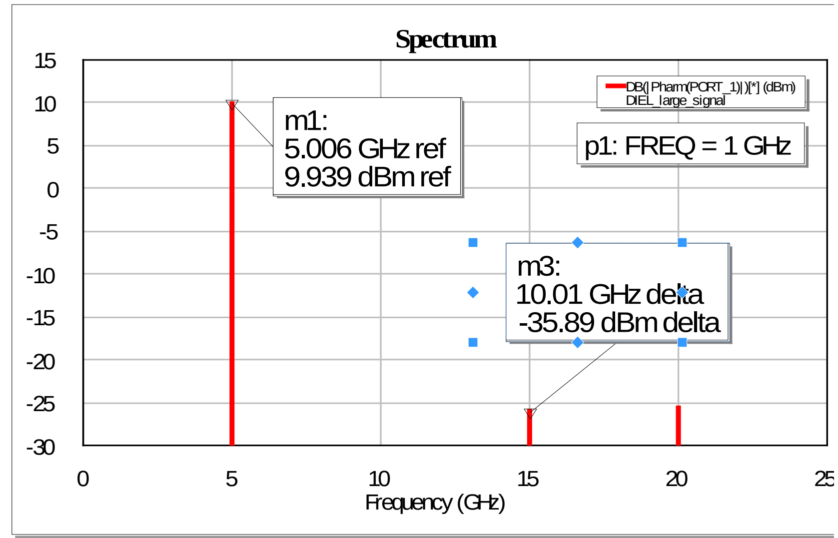


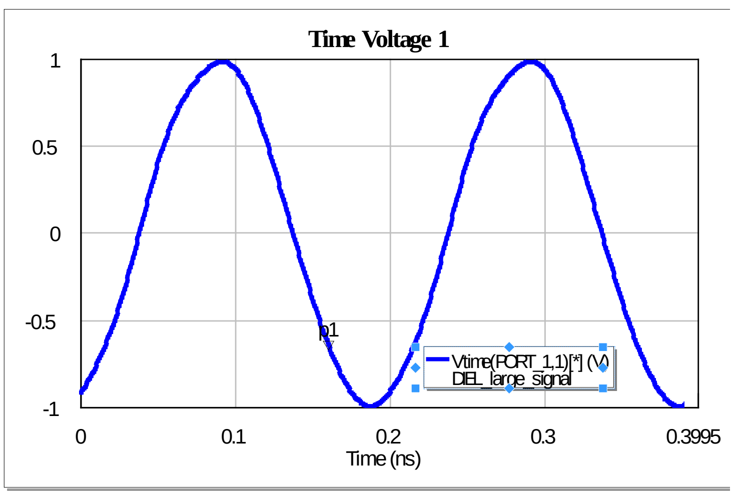


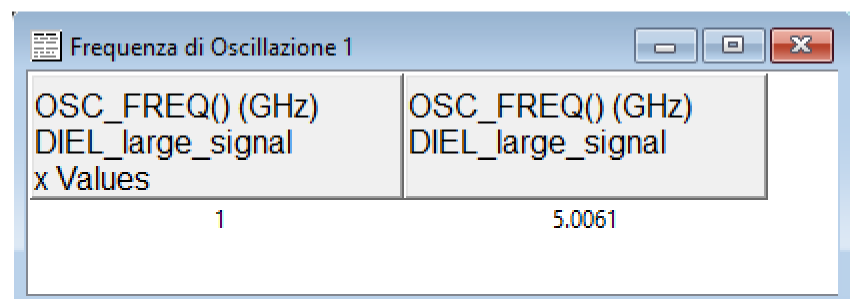
OSC_FREQ() (GHz) DIEL_large_signal x Values	OSC_FREQ() (GHz) DIEL_large_signal
1	4.9998

Improve spectral purity and Pout



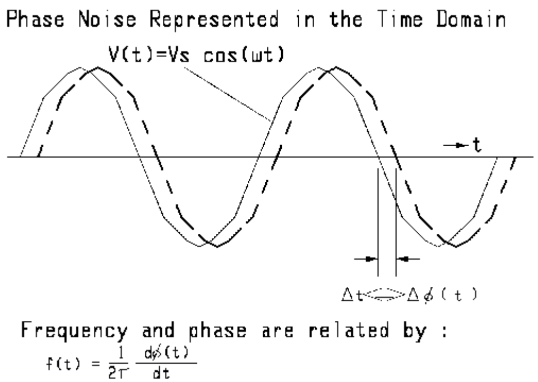




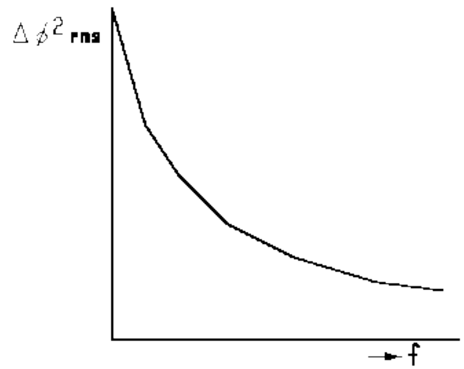


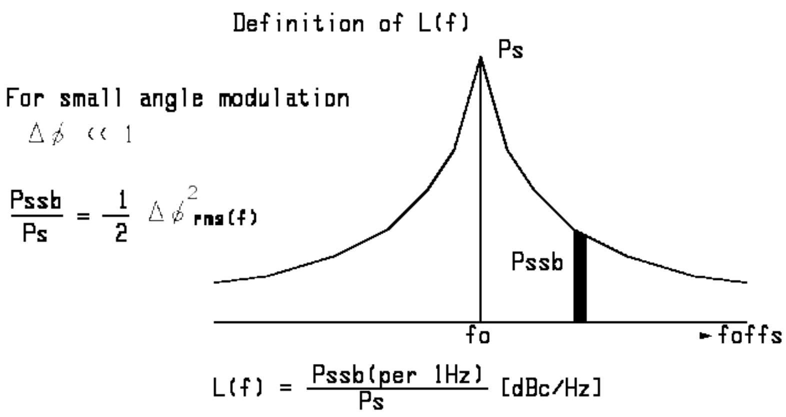
Noise in oscillators

The existence of noise in electric circuits determines fluctuations of the instantaneous phase of the generated signal.



Power Spectrum of phase fluctuations

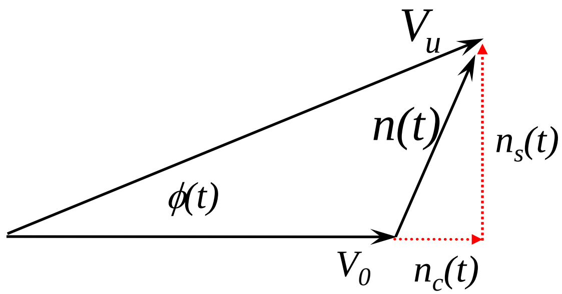




This fluctuation can be assumed as a modulation of the sinusoid produced by noise; the resultant spectral density L(f) depends on the power spectrum of the fluctuations ($\Delta\Phi^2$).

It is found that L(f) has the same shape of $\Delta\Phi^2$ (for small modulation angle)

Phasorial description of noise + oscillation



$n_s(t) \ll V_u, \qquad V_u \cong V_0$

n(t) is a phasor with random magnitude and phase.

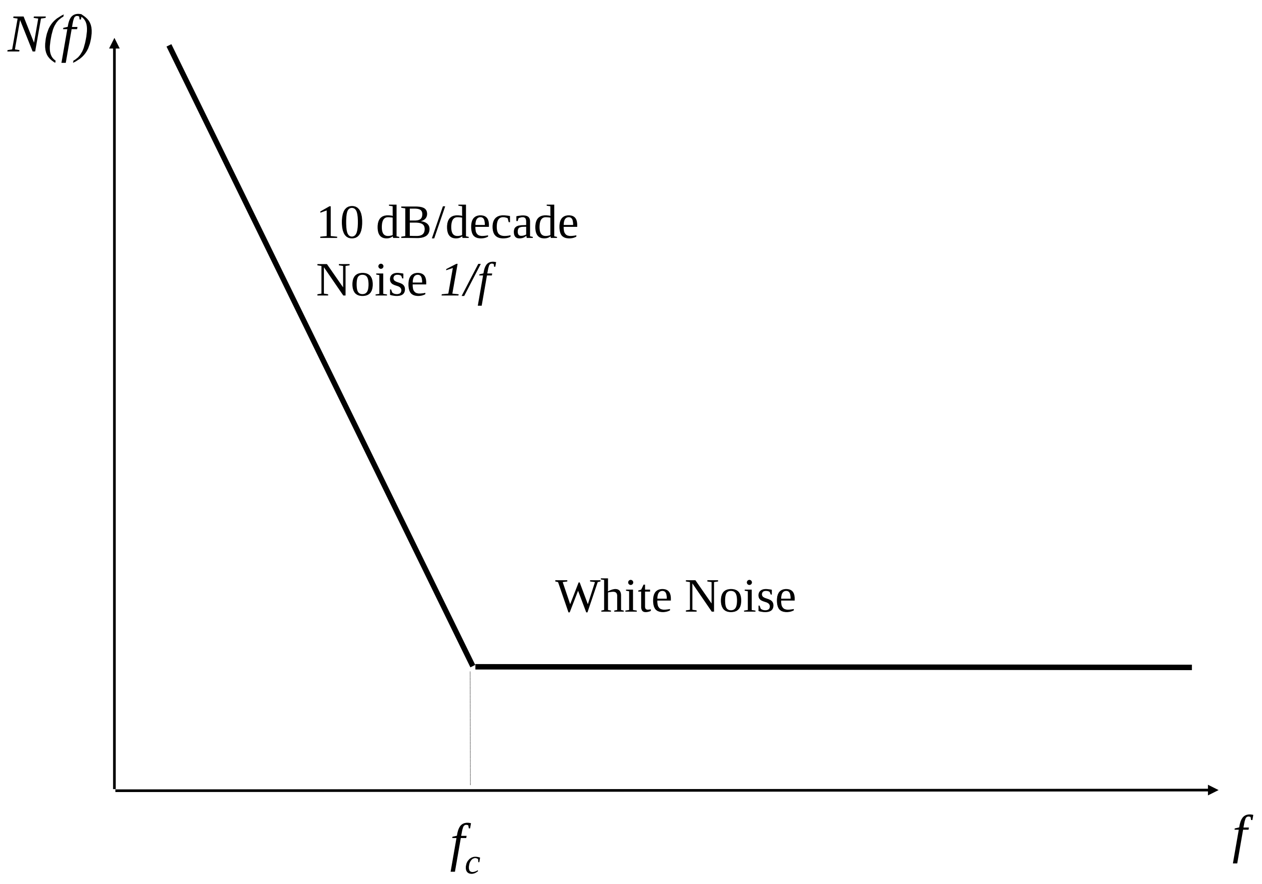
$n_c(t)$ and $n_s(t)$ are the in phase and quadrature components. Half of the overall power density is associated to each of them

$$\phi(t) = \sin^{-1}\left(\frac{n_s(t)}{V_u}\right) \cong \frac{n_s(t)}{V_u} \cong \frac{n_s(t)}{V_0}$$

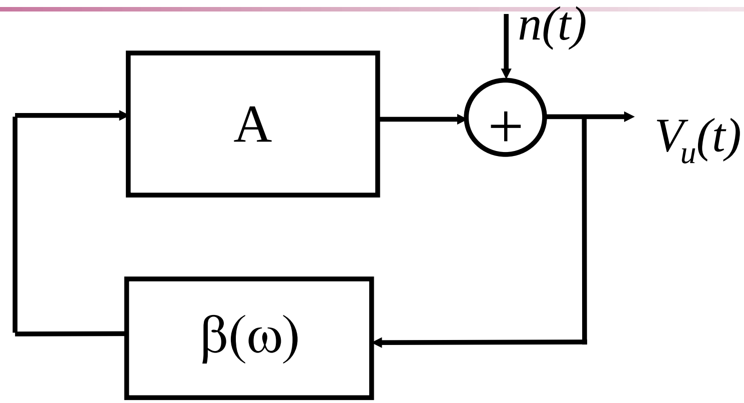
The spectrum of the phase fluctuations is proportional to the spectrum of added noise:

$$S_\phi(f) = \frac{N(f)}{2P_o}$$

Typical Noise Spectrum



Noise generated inside the feedback loop



Noise is not simply summed to the output signal (it is instead injected into the feedback loop). The noise frequency components close to the oscillation frequency are "amplified" by the positive feedback.

Ultimately, a broadening of the ideal spectral line characterizing the ideal oscillator is produced; the width of the spectrum depends on both the noise and the Gloop.

Leeson's Model for the Phase Noise

This model relates the power spectrum of the phase fluctuations with the noise spectrum and the indirect stability of the oscillator:

$$S_\phi \propto \left(\frac{f_0}{S_F}\right)^2 \frac{N(f_\Delta)}{2(f_\Delta)^2}$$

$N(f_\Delta)$ is the power spectrum of the noise; f_Δ is the deviation with respect the oscillation frequency f_0; S_F is the indirect stability.
For what said before, the spectrum of the signal generated by the oscillator around f_0 has the same shape of S_ϕ.

<u>The model is accurate for small values of f_Δ</u>

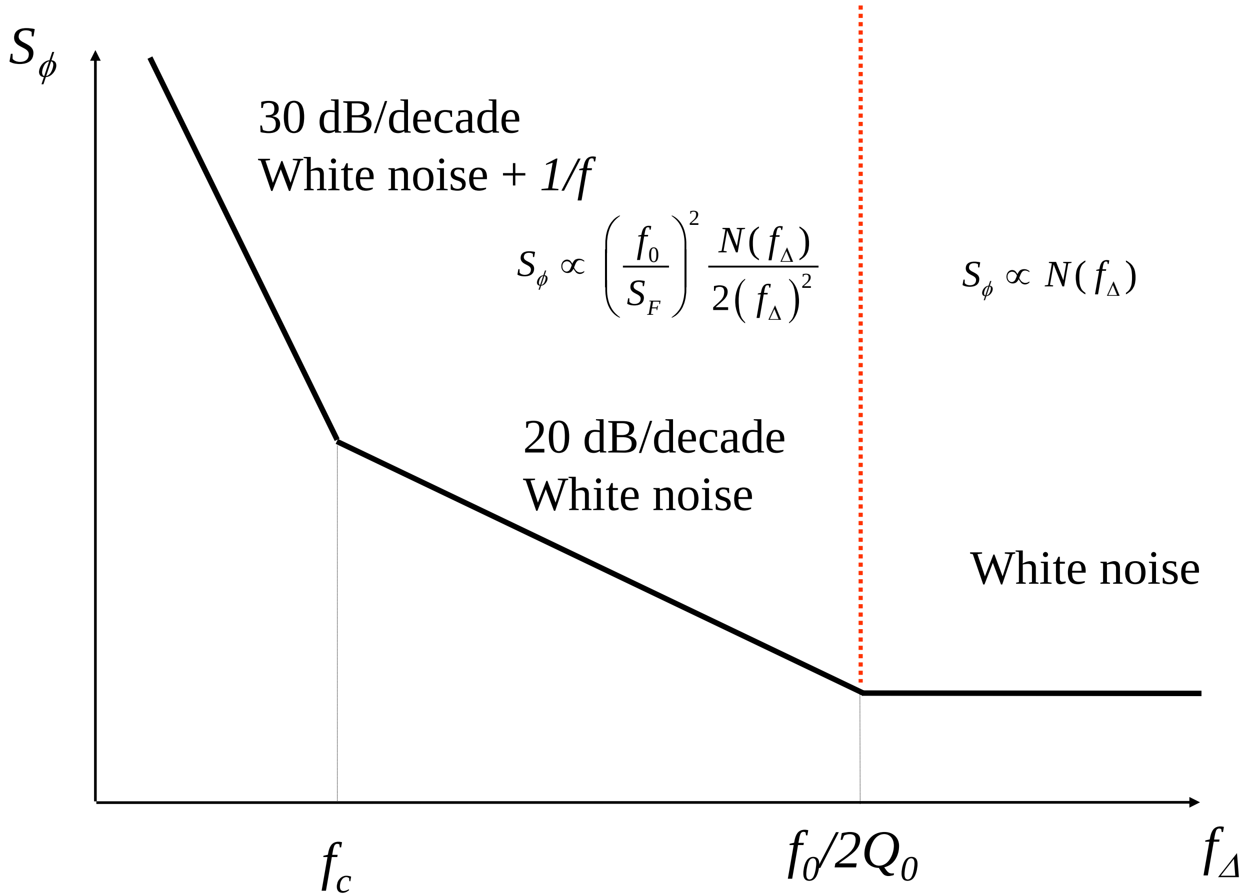
$S_\phi(\Delta f)$ distant from f_0

The Leeson's model holds true for the noise components inside the band of Gloop. This band (*B*) is the frequency interval within of which the oscillation condition are about satisfied. *B* is mainly determined by the selectivity of the feedback network (β). We can relate the value of *B* to the quality factor Q_0 of the feedback network through the well know relationship:

$$B = \frac{f_0}{Q_0}$$

Outside the band *B* the noise is simply added to the signal and the spectrum results proportional to the noise spectrum (white, density *N*).

Typical phase noise spectrum



Spectrum of oscillation voltage

- The spectrum of $V_u(t)$ around f_0 is proportional to $S_\phi(f_\Delta)$
- The spectrum of $V_u(t)$ is symmetric if only phase noise is present
- The *"Carrier to noise ratio" (CNR)* is defined as:

$$CNR(f_\Delta) = \frac{P_0}{S_{V_0}\left(f_0 + f_\Delta\right)} = \frac{P_0}{S_\phi\left(f_\Delta\right)}$$

- CNR is the main figure of merit of an oscillator concerning the phase noise; it is typically specified (in dB) for small deviations with respect f_0 (from few Hz to several MHz). Typical values in microwave amplifiers span from 80 dBc to over 120 dBc (for f_Δ= 100 KHz).