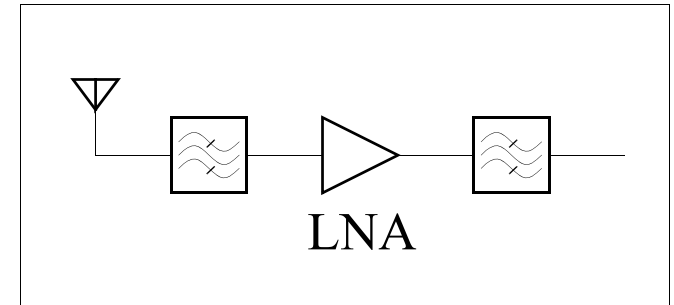


# 低噪声放大器 (LNA)

- LNA 的功能和指标
- 双极型晶体管 (BJT) 的噪声模型
- BJT LNA 的噪声系数
- MOS 晶体管的噪声模型
- CMOS 最小噪声系数和最佳噪声匹配
- 输入匹配
- 其它方面的考虑

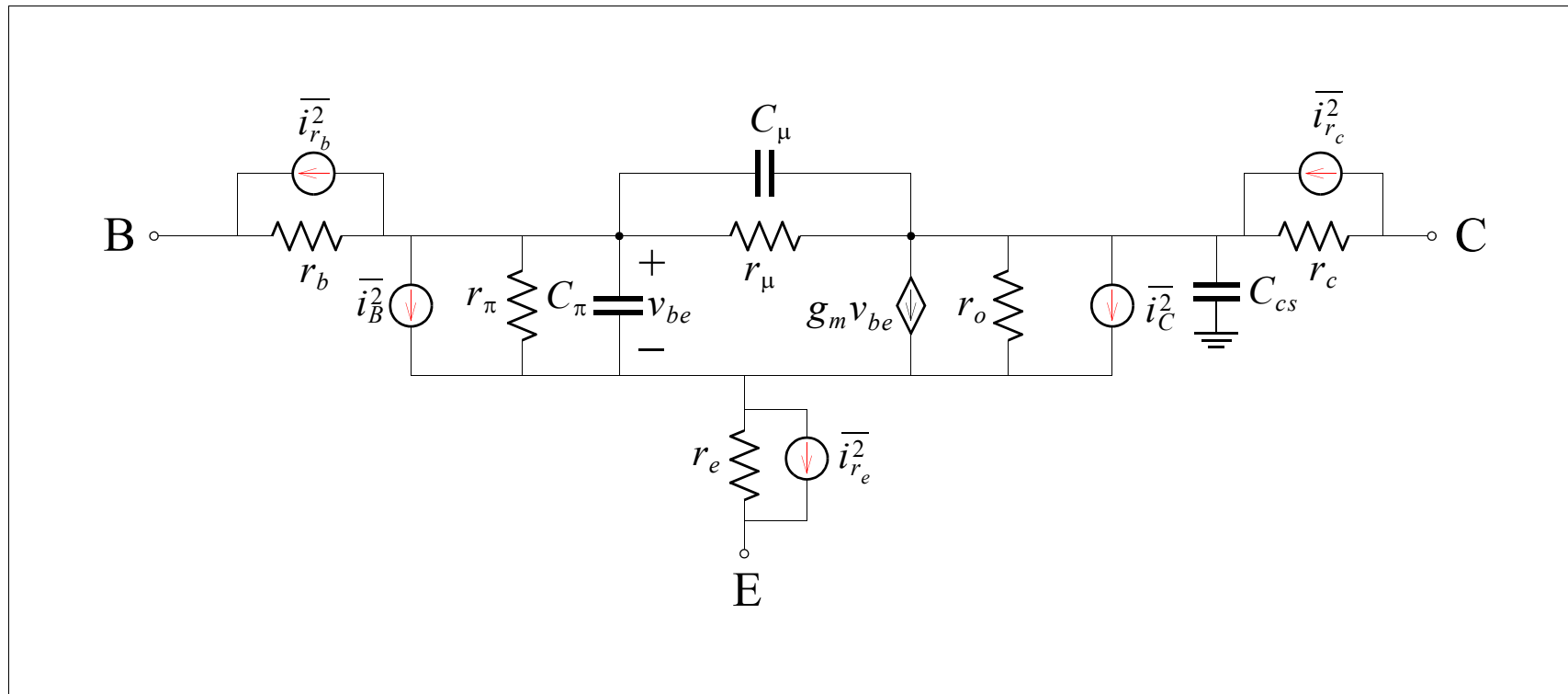
# LNA 的功能和指标

- 第一级有源电路，其噪声、非线性、匹配等性能对整个接收机至关重要
- 主要指标
  - 噪声系数  
取决于系统要求，可从 1 dB 以下到好几个 dB
  - 增益  
较大的增益有助于减小后级电路噪声的影响，但会引起线性度的恶化
  - 输入输出匹配  
决定输入输出端的射频滤波器频响
  - 线性度  
未经滤除的干扰信号可通过互调 (Intermodulation) 等方式使接收质量降低

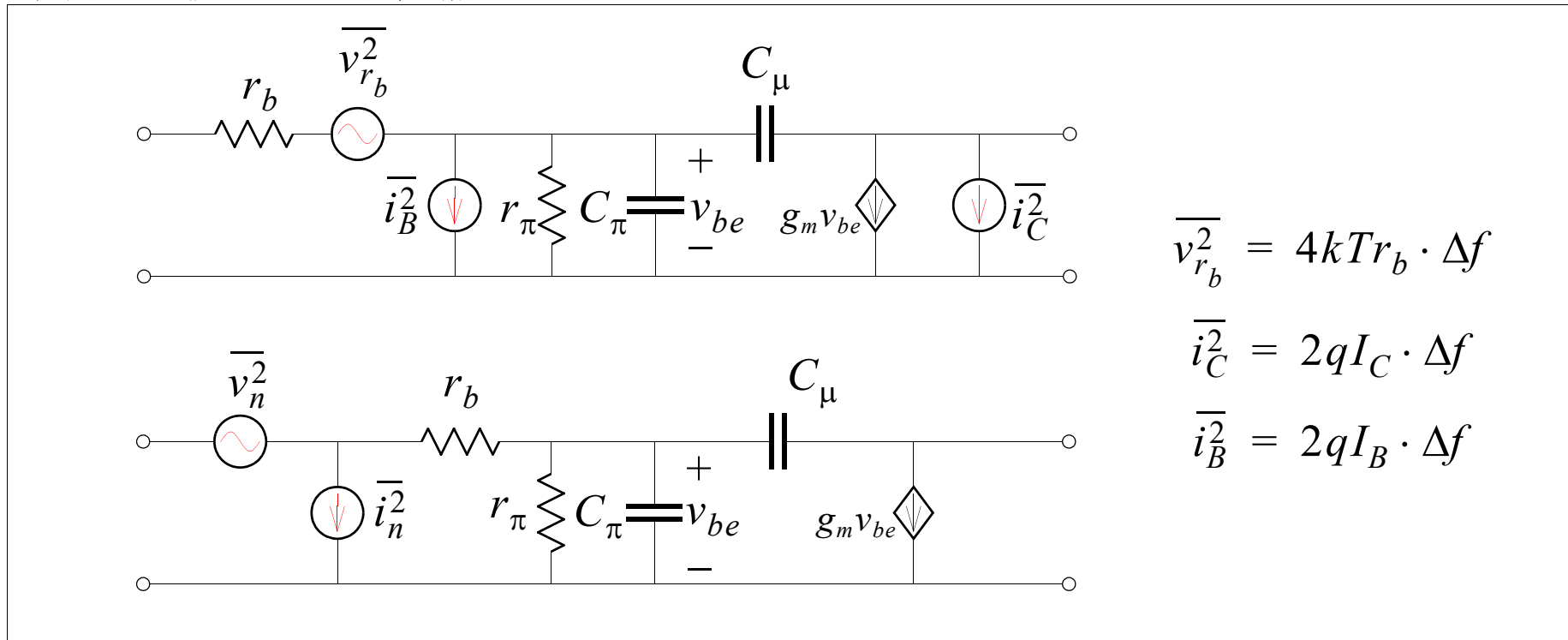


# 双极型晶体管 (BJT) 的噪声模型

- 较为完整的噪声 (小信号) 电路模型



- 简化的模型和等效输入噪声源



$$\overline{v_n^2} \approx \overline{v_{r_b}^2} + \frac{\overline{i_C^2}}{g_m^2} + \overline{i_B^2} r_b \approx \overline{v_{r_b}^2} + \frac{\overline{i_C^2}}{g_m^2}$$

$$\overline{i_n^2} = \overline{i_B^2} + \frac{\overline{i_C^2}}{|\beta(j\omega)|^2} \quad \beta(j\omega) = \frac{\beta_0}{1 + j\beta_0(\omega/\omega_T)}$$

(1)

# BJT LNA 的噪声系数

- 当信号源内阻为  $R_S$  时，电路的噪声系数

$$F = 1 + \frac{\overline{(v_n + i_n R_S)^2}}{4kTR_S \cdot \Delta f} \quad (2)$$

$$\begin{aligned} \overline{(v_n + i_n R_S)^2} &= \overline{\left\{ v_{r_b} + \frac{i_C}{g_m} + \left[ i_B + \frac{i_C}{\beta(j\omega)} \right] R_S \right\}^2} \\ &= \overline{v_{r_b}^2} + \overline{i_B^2} R_S^2 + \left| \frac{1}{g_m} + \frac{R_S}{\beta(j\omega)} \right|^2 \overline{i_C^2} \end{aligned} \quad (3)$$

为了计算方便， $v_n$  和  $i_n$  之间的相关性通常被忽略<sup>[1]</sup>，即

$$\overline{(v_n + i_n R_S)^2} = \overline{v_{r_b}^2} + \overline{i_B^2} R_S^2 + \frac{1}{g_m^2} \overline{i_C^2} + \left| \frac{R_S}{\beta(j\omega)} \right|^2 \overline{i_C^2}$$

$$\frac{\overline{(v_n + i_n R_S)^2}}{\Delta f} \approx 4kTr_b + 4kT \frac{1}{2g_m} + 2qI_C R_S^2 \left[ \frac{1}{\beta_0} + \frac{1}{|\beta(j\omega)|^2} \right] \quad (4)$$

于是

$$F = 1 + \frac{r_b}{R_S} + \frac{1}{2g_m R_S} + \frac{g_m R_S}{2} \left[ \frac{1}{\beta_0} + \frac{1}{|\beta(j\omega)|^2} \right] \quad (5)$$

所以在设计中需要尽量减小基极电阻  $r_b$ ，而跨导  $g_m$  的选择除了应减小总的噪声系数外还有增益、功耗、线性度等多方面的考虑。文献 [2] 给出了一个很好的设计实例

# MOS 晶体管的噪声模型

- 长沟道模型 [1]

- 忽略  $C_{gd}$  的影响,

$$\overline{v_n^2} = \frac{\overline{i_{nd}^2}}{g_m^2}$$

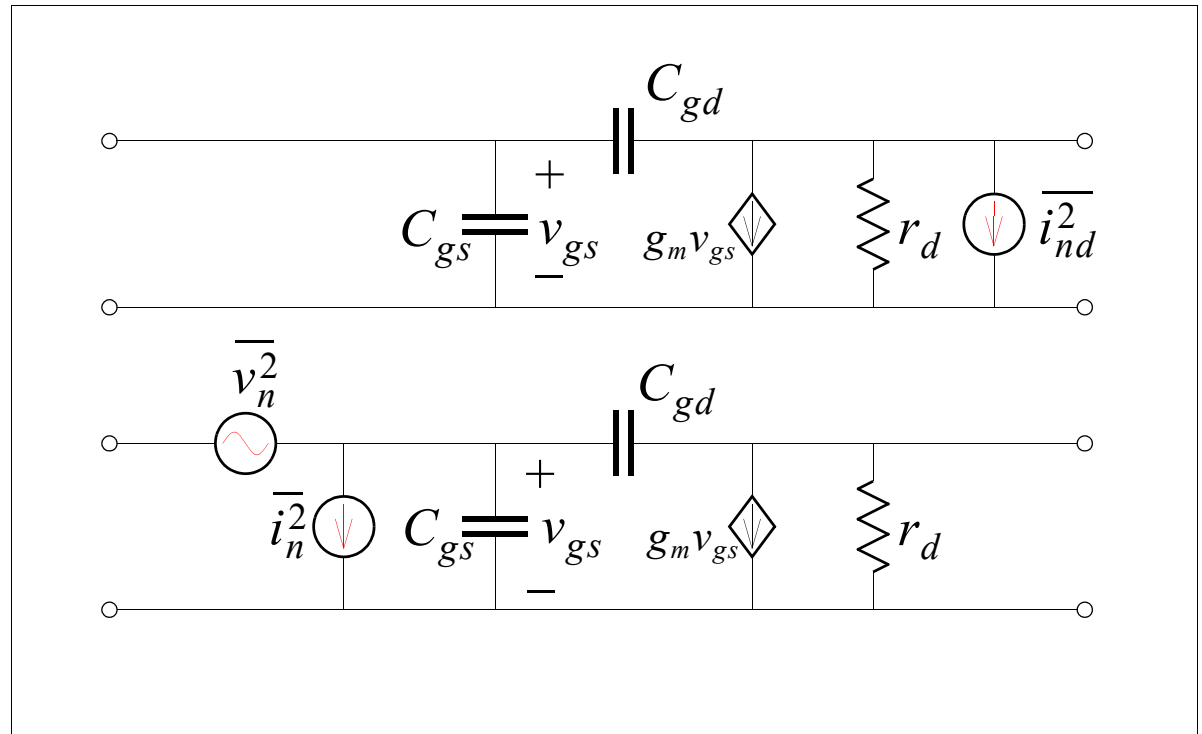
$$\overline{i_n^2} = \frac{\omega^2 C_{gs}^2}{g_m^2} \overline{i_{nd}^2}$$

其中,

- $\overline{i_{nd}^2} = 4kT \frac{2}{3} g_m \cdot \Delta f$

(饱和区, 忽略 1/f 噪声)

(6)



- 沟道热噪声更一般性的表示:

$$\overline{i_{nd}^2} = 4kT\gamma g_{d0} \cdot \Delta f \quad (7)$$

- »  $g_{d0} = \mu C_{ox} \frac{W}{L} (V_{gs} - V_{th})$  为  $V_{DS} = 0$  时的沟道电导, 在长沟道条件下  
 $g_m = g_{d0}$ , 对于短沟道器件

$$g_m = \alpha g_{d0}, \alpha < 1 \quad (8)$$

- »  $\gamma$  是一个与偏置状态有关的系数, 对于长沟道器件,

$$\frac{2}{3} \leq \gamma \leq 1 \quad (9)$$

管子工作在饱和区时取值 2/3, 线性区零偏置时取值 1。由于热电子效应, 短沟道器件的  $\gamma$  值远大于 1

- 栅极感应噪声 (**drain induced gate noise**) 和非准静态 (**NQS**) 模型

- 沟道载流子的不规则运动也会在栅极引起的感应噪声电流  $\overline{i_{ng}^2}$ :



$$\overline{i_{ng}^2} = 4kT\delta g_g \cdot \Delta f \quad (10)$$

其中 ( 饱和状态下 ),

» 长沟道器件的  $\delta \approx 4/3$ , 短沟道器件的情况不明确

$$\gg g_g = \frac{\omega^2 C_{gs}^2}{5g_{d0}}$$

— 栅噪声电流和沟道噪声电流是部分相关的, 长沟道条件下的相关系数为

$$c = \frac{\overline{i_{ng} i_{nd}^*}}{\sqrt{\overline{i_{ng}^2} \overline{i_{nd}^2}}} \approx j0.395 \quad (11)$$

故  $\overline{i_{ng}^2}$  可表示为

$$\overline{i_{ng}^2} = \overline{(i_{ngc} + i_{ngu})^2} = 4kT\Delta f\delta g_g |c|^2 + 4kT\Delta f\delta g_g (1 - |c|^2) \quad (12)$$

$i_{ngc}$  和  $i_{ngu}$  分别为与沟道热噪声相关和不相关的部分

- 当右图所示 RC 并联电路的 Q 值足够大，即

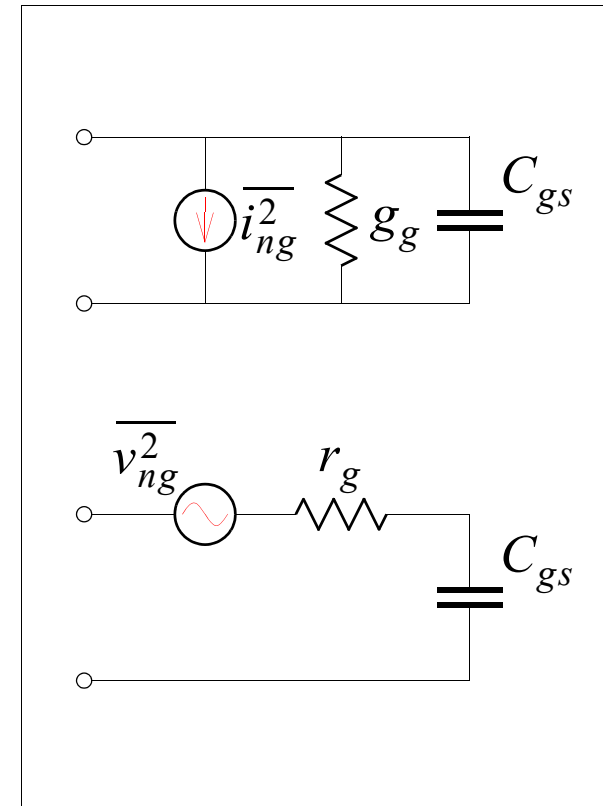
$$\frac{5g_{d0}}{\omega^2 C_{gs}^2} \cdot \omega C_{gs} = \frac{5g_{d0}}{\omega C_{gs}} \gg 1 \text{ 或}$$

$$\omega \ll \frac{5g_{d0}}{C_{gs}} \approx \frac{5\omega_T}{\alpha} \quad (13)$$

$\overline{i_g^2}$  和  $g_g$  可以等效为噪声电压源  $\overline{v_g^2}$  和串联电阻  $r_g$ :

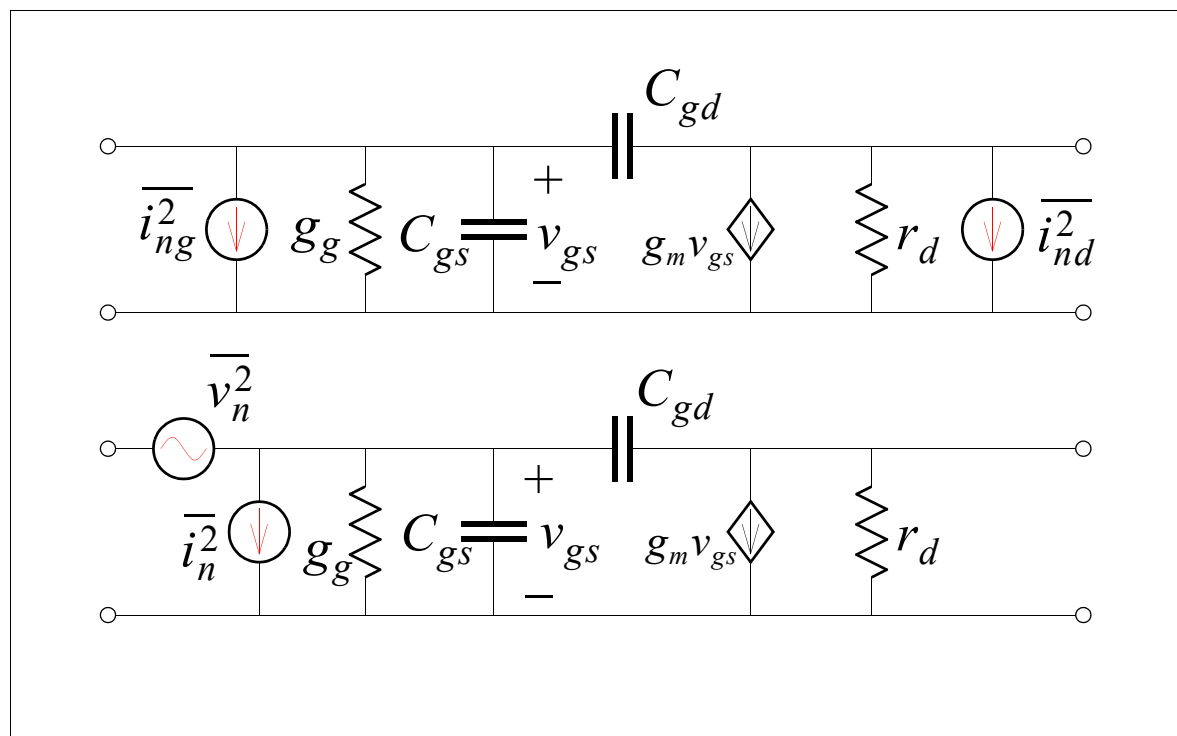
$$\overline{v_g^2} = 4kT\delta r_g \cdot \Delta f \quad (14)$$

$$r_g = \frac{1}{5g_{d0}} \quad (15)$$



- 电导  $g_g$  或电阻  $r_g$  并不是物理电阻，而是对高频时沟道电荷的反应速度跟不上栅极电压的变化而引起栅电流相对滞后这一效应的模型，所以它们本身不产生噪声，但是它们影响电路的输入阻抗

- 短沟道 MOS 管的噪声模型



$$\overline{v_n^2} = \frac{\overline{i_{nd}^2}}{g_m^2} + \overline{v_{ng}^2} \approx \frac{\overline{i_{nd}^2}}{g_m^2}$$

$$\overline{i_n^2} = \left( i_{ngc} + \frac{j\omega C_{gs}}{g_m} i_{nd} \right)^2 + 4kT\Delta f\delta g_g(1 - |c|^2)$$

(16)

# CMOS 最小噪声系数和最佳噪声匹配

- 2- 端口网络的噪声参数:

$$R_n = \frac{\overline{v_n^2}}{4kT\Delta f} = \frac{\overline{i_{nd}^2}}{g_m^2} \frac{1}{4kT\Delta f} = \frac{4kT\gamma g_{d0}\Delta f}{g_m^2 4kT\Delta f} = \frac{\gamma g_{d0}}{g_m^2} = \frac{\gamma}{\alpha g_m} \quad (17)$$

$$G_u = \frac{4kT\Delta f \delta g_g (1 - |c|^2)}{4kT\Delta f} = \delta g_g (1 - |c|^2) = \frac{\delta \omega^2 C_{gs}^2}{5g_{d0}} (1 - |c|^2) \quad (18)$$

$$Y_c = \frac{i_{ngc} + (j\omega C_{gs}/g_m) \cdot i_{nd}}{v_n} = \frac{i_{ngc} + (j\omega C_{gs}/g_m) \cdot i_{nd}}{i_{nd}/g_m} = g_m \frac{i_{ngc}}{i_{nd}} + j\omega C_{gs} \quad (19)$$

$$\frac{i_{ngc}}{i_{nd}} = \frac{i_{ngc} i_{nd}^*}{i_{nd} i_{nd}^*} = \frac{\overline{i_{ngc} i_{nd}^*}}{\overline{i_{nd} i_{nd}^*}} = \frac{\overline{i_{ngc} i_{nd}^*}}{\overline{i_{nd}^2}} = \frac{\overline{i_{ng} i_{nd}^*}}{\overline{i_{nd}^2}} = \frac{\overline{i_{ng} i_{nd}^*}}{\sqrt{\overline{i_{nd}^2}} \sqrt{\overline{i_{nd}^2}}} \sqrt{\overline{i_{ng}^2}} = \frac{\overline{i_{ng} i_{nd}^*}}{\sqrt{\overline{i_{nd}^2}} \sqrt{\overline{i_{ng}^2}}} \sqrt{\overline{i_{ng}^2}} = c \sqrt{\frac{\overline{i_{ng}^2}}{\overline{i_{nd}^2}}}$$

$$\sqrt{\frac{\overline{i_{ng}^2}}{\overline{i_{nd}^2}}} = \sqrt{\frac{4kT\delta g_g \cdot \Delta f}{4kT\gamma g_{d0} \cdot \Delta f}} = \sqrt{\frac{\delta g_g}{\gamma g_{d0}}} = \sqrt{\frac{\delta(\omega^2 C_{gs}^2)/(5g_{d0})}{\gamma g_{d0}}} = \frac{\omega C_{gs}}{g_{d0}} \sqrt{\frac{\delta}{5\gamma}}$$

$$\therefore Y_c = g_m \frac{i_{ngc}}{i_{nd}} + j\omega C_{gs} = j\omega C_{gs} + \frac{g_m c}{g_{d0}} \sqrt{\frac{\delta}{5\gamma}} \omega C_{gs} \approx j\omega C_{gs} \left( 1 + \alpha |c| \sqrt{\frac{\delta}{5\gamma}} \right) \quad (20)$$

因为  $Y_c = G_c + jB_c$ ,

$$\therefore G_c \approx 0 \quad B_c = \omega C_{gs} \left( 1 + \alpha |c| \sqrt{\frac{\delta}{5\gamma}} \right) \quad (21)$$

$$G_{opt} = \sqrt{\frac{G_u}{R_n} + G_c^2} = \alpha \omega C_{gs} \sqrt{\frac{\delta}{5\gamma} (1 - |c|^2)} \quad (22)$$

$$B_{opt} = -B_c = -\omega C_{gs} \left( 1 + \alpha |c| \sqrt{\frac{\delta}{5\gamma}} \right)$$

$$F_{min} = 1 + 2R_n(G_{opt} + G_c) \approx 1 + \frac{2}{\sqrt{5}} \frac{\omega}{\omega_T} \sqrt{\gamma \delta (1 - |c|^2)} \quad (23)$$

- 给定功耗条件下的噪声优化

- 在信号源导纳为  $Y_s = G_s + jB_s$  时，噪声系数为

$$F = F_{min} + \frac{R_n}{G_s} [(G_s - G_{opt})^2 + (B_s - B_{opt})^2] \quad (24)$$

假设  $B_s = B_{opt}$ ,

$$F = F_{min} + \frac{R_n}{G_s} (G_s - G_{opt})^2 \quad (25)$$

为简练起见，定义

$$\gg Q_{opt} = \frac{G_{opt}}{\omega C_{gs}} = \alpha \sqrt{\frac{\delta}{5\gamma} (1 - |c|^2)}$$

$$\gg Q_s = \frac{1}{\omega C_{gs} R_s}$$

于是有

$$F = F_{min} + \frac{\gamma}{\alpha} \frac{1}{g_m} \frac{(Q_s \omega C_{gs} - Q_{opt} \omega C_{gs})^2}{Q_s \omega C_{gs}} = F_{min} + \frac{\gamma}{\alpha} \cdot \frac{1}{g_m R_s} \cdot \left[ 1 - \frac{Q_{opt}}{Q_s} \right]^2 \quad (26)$$

为了在噪声系数的表达式中引入功耗 ( 电流 ), 我们来看一下漏电流

$$I_D = \frac{\mu C_{ox} W (V_{gs} - V_{th})^2 (L E_{sat})}{2 L (V_{gs} - V_{th}) + L E_{sat}} \quad (27)$$

$E_{sat} = \frac{2v_{sat}}{\mu}$ , 定义  $\rho = \frac{V_{gs} - V_{th}}{L E_{sat}}$ , 公式 (27) 可写成

$$I_D = W L C_{ox} v_{sat} E_{sat} \frac{\rho^2}{1 + \rho} \approx \frac{3}{2} C_{gs} v_{sat} E_{sat} \frac{\rho^2}{1 + \rho} \quad (28)$$

直流功耗  $P_D = V_{DD} I_D = V_{DD} \frac{3}{2} C_{gs} v_{sat} E_{sat} \frac{\rho^2}{1 + \rho}$ , 令  $P_0 = \frac{3}{2} \frac{V_{DD} v_{sat} E_{sat}}{\omega R_s}$ ,

$$Q_s = \frac{1}{\omega C_{gs} R_s} = \frac{1}{\omega R_s} \cdot \frac{3}{2} V_{DD} v_{sat} E_{sat} \frac{\rho^2}{1 + \rho} = \frac{P_0}{P_D} \frac{\rho^2}{1 + \rho} \quad (29)$$

假设  $\rho \ll 1$  (低功率的情况下成立), 在给定 PD 的条件下,

$$\rho \approx \frac{P_D}{P_0} \sqrt{\frac{\delta}{5\gamma} (1 - |c|^2) (1 + \sqrt{7/4})} \quad (30)$$

给出最小噪声系数, 此时

$$Q_s = |c| \sqrt{\frac{5\gamma}{\delta}} \left[ 1 + \sqrt{1 + \frac{3}{|c|^2} \left( 1 + \frac{\delta}{5\gamma} \right)} \right] \approx 4 \quad (31)$$

$$W = \frac{3}{2} \frac{1}{\omega L C_{ox} R_s Q_s} \approx \frac{1}{3 \omega L C_{ox} R_s} \quad (32)$$

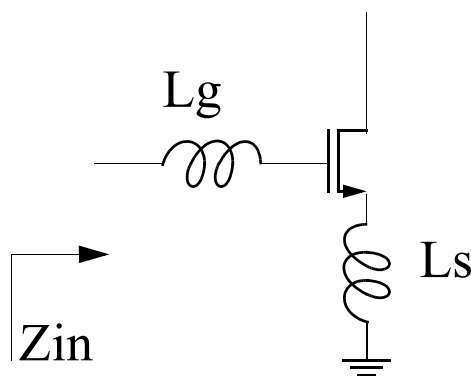
对于  $50\Omega$  信号源, 栅宽频率积约为  $750\mu\text{m-GHz}$

$$F = 1 + 2.4 \frac{\gamma}{\alpha} \frac{\omega}{\omega_T} \quad (33)$$



# 输入匹配

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$$Z_{in} = s(L_g + L_s) + \frac{1}{sC_{gs}} + \frac{g_m}{C_{gs}}L_s = s(L_g + L_s) + \frac{1}{sC_{gs}} + \omega_T L_s \quad (34)$$

## 其它方面的考虑

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- 电感的影响
- 共栅放大级的噪声
- 多晶硅栅电阻

- 单端连接的多指结构  $R_g = \frac{1}{3n^2} \frac{R_{sq}W}{L}$

- 双端连接的多指结构  $R_g = \frac{1}{12n^2} \frac{R_{sq}W}{L}$

## 参考文献

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