On the Phase Noise and Noise Factor in Circuits and Systems - New Thoughts on an Old Subject

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Outline

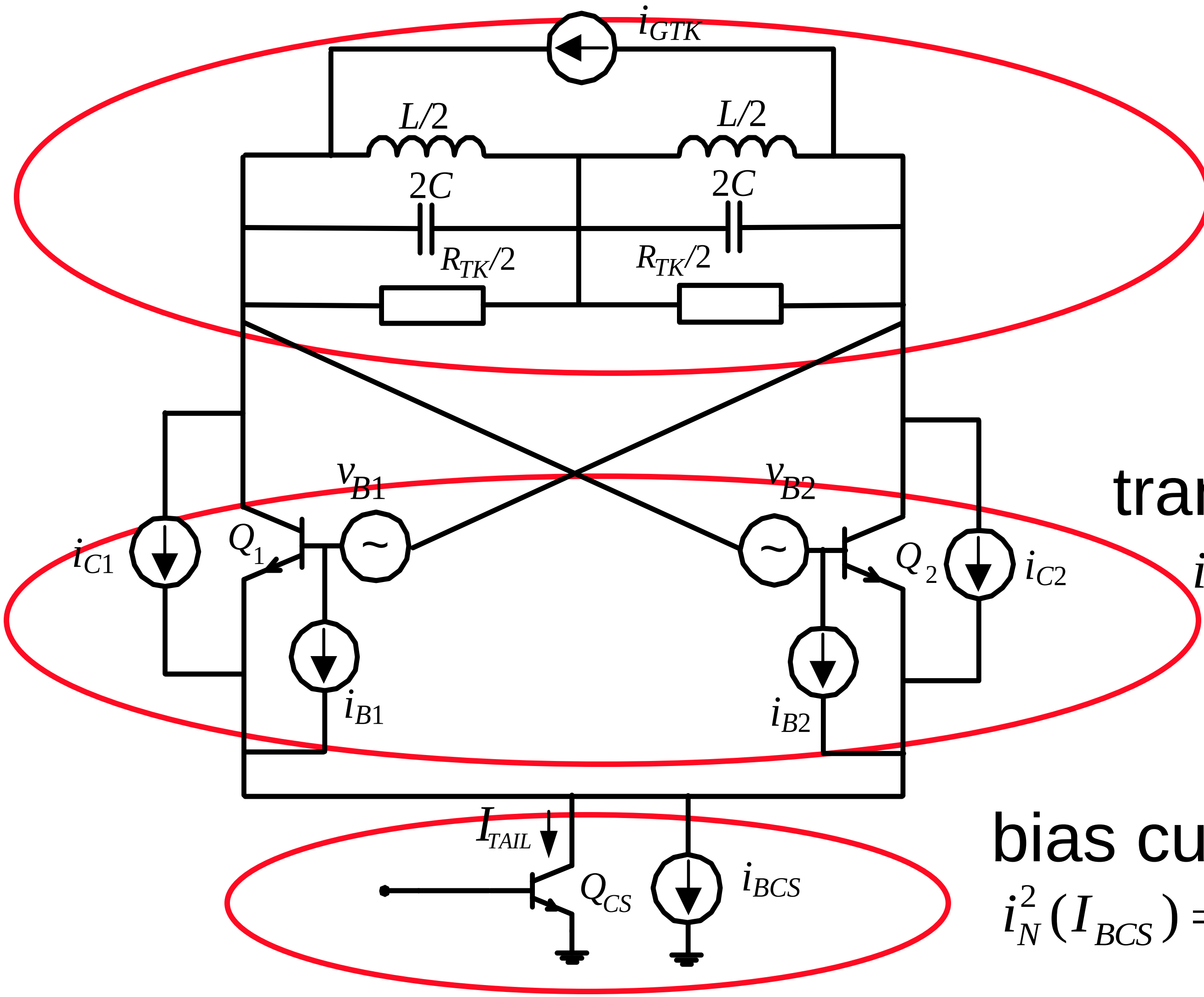
- **Spectral Analysis of Noise in LC-Oscillators**
  - LC-tank, g_m-cell, bias current source noise
  - (Phase-) Noise factor
- **Bipolar vs. CMOS LC-Oscillators**
- **LC-Oscillators Noise Reduction Methods**
- **Mixer Noise Factor from VCO Noise Factor**
- **Oscillator Phase Noise in Receiver's SNR**
- **LNA and Mixer Noise Factors in a Receiver**
- **BBFilter Noise Transfer vs. LO/Mix Duty**

Phase Noise Model of Bipolar and CMOS LC-Oscillators

Outline

- Oscillation Condition
- LC-Tank Noise Folding
- g_m-Cell Noise Folding
- Bias-Current Source Noise Folding
- Phase-Noise Model of Bipolar LC-Oscillators
- Phase-Noise Model of CMOS LC-Oscillators
- Bipolar vs. CMOS LC-Oscillators

LC-Oscillator Noise Sources



LC-tank noise

$$i_N^2(G_{TK}) = 2KTG_{TK}$$

transconductor noise

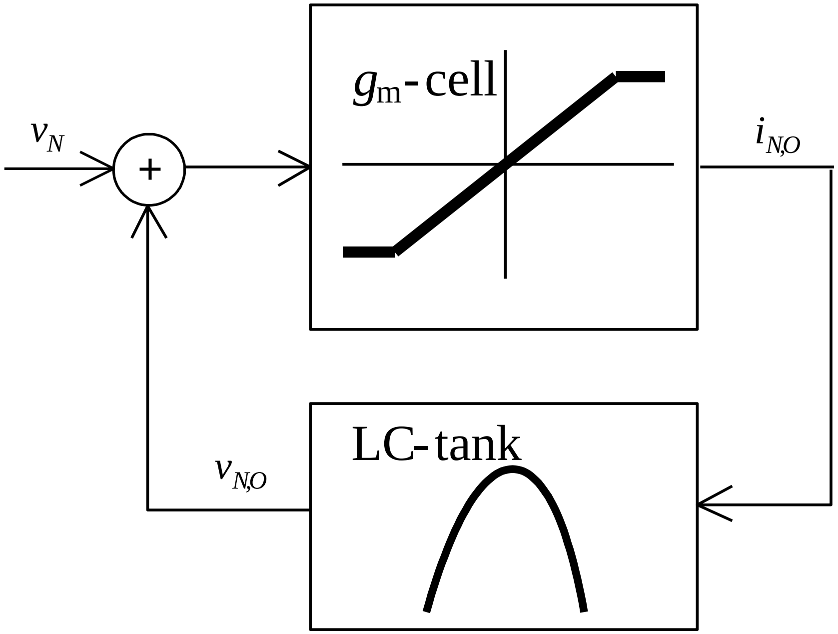
$$i_N^2(I_C) = qI_C = 2KTg_m/2$$

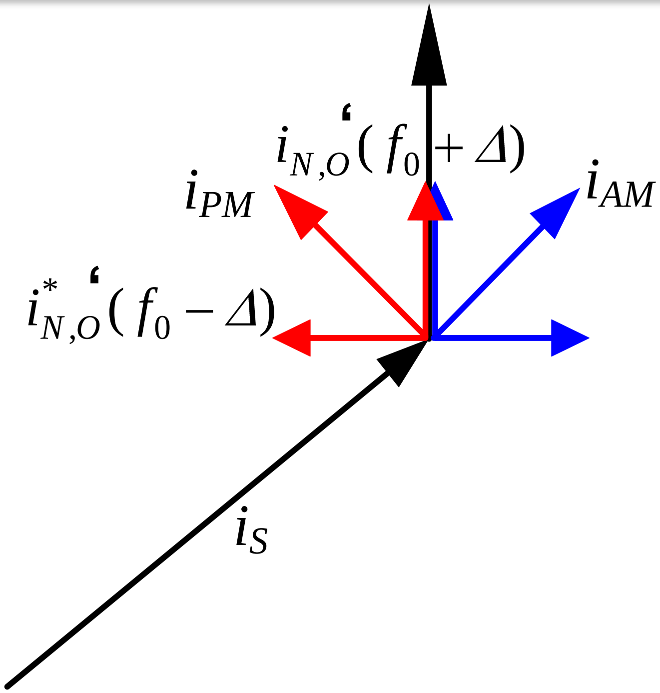
$$v_N^2(r_B) = 2KTr_B$$

bias current source noise

$$i_N^2(I_{BCS}) = KTg_{m,CS}(1+2r_{B,CS}g_{m,CS})$$

Oscillator and Phase-Noise Model





- phase-modulating noise component (double-sided)

$$i_{PM}(f_0+\Delta)=\frac{1}{2}\left[i_{N,O}(f_0+\Delta)+i^*_{N,O}(f_0-\Delta)\right]$$

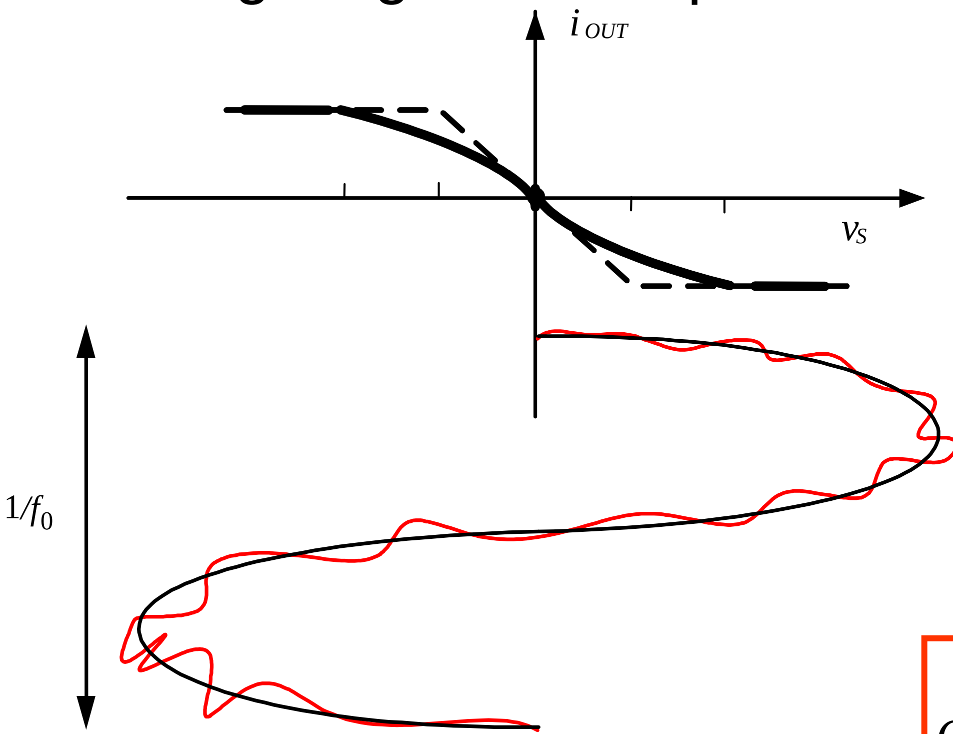
$$i_{PM}(-f_0-\Delta)=\frac{1}{2}\left[i_{N,O}(-f_0-\Delta)+i^*_{N,O}(-f_0+\Delta)\right]$$

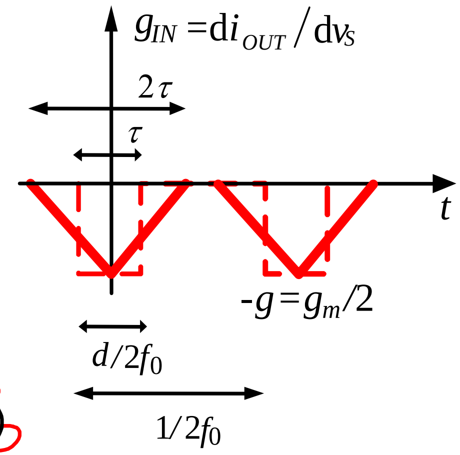
- phase-related noise power (single-sided)

$$v^2_{PM,TOT}=\frac{1}{2}\left[i_{PM}(f_0+\Delta)+i_{PM}(-f_0-\Delta)\right]^2\left|Z(f_0+\Delta)\right|^2=\frac{i^2_{PM,TOT}}{4\pi C_{TOT}\Delta^2}$$

g_m-Cell Transfer Function

- small-signal gain in the presence of a large signal



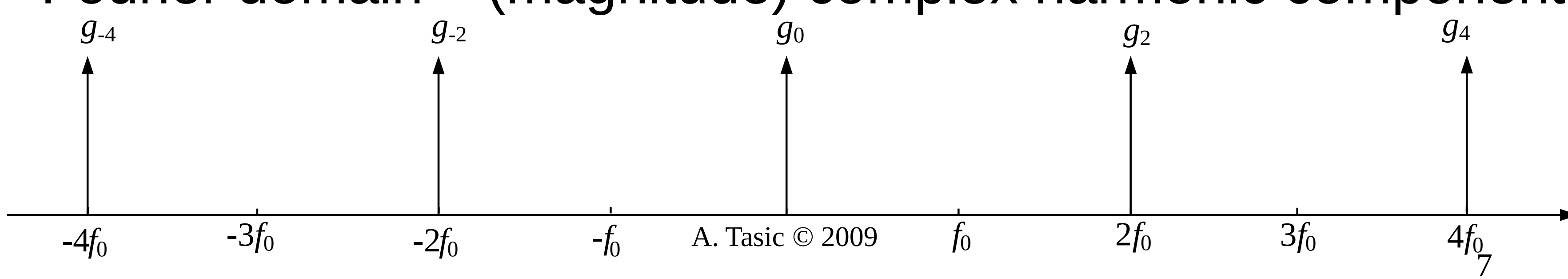


$$g_{2i} = \left| \frac{2}{T_0} \int_{-T_0/4}^{T_0/4} g(t) e^{-j2i\omega_0 t} dt \right|$$

$$g_{2i} = gd \left| \frac{\sin(i\pi d)}{i\pi d} \right|^2$$

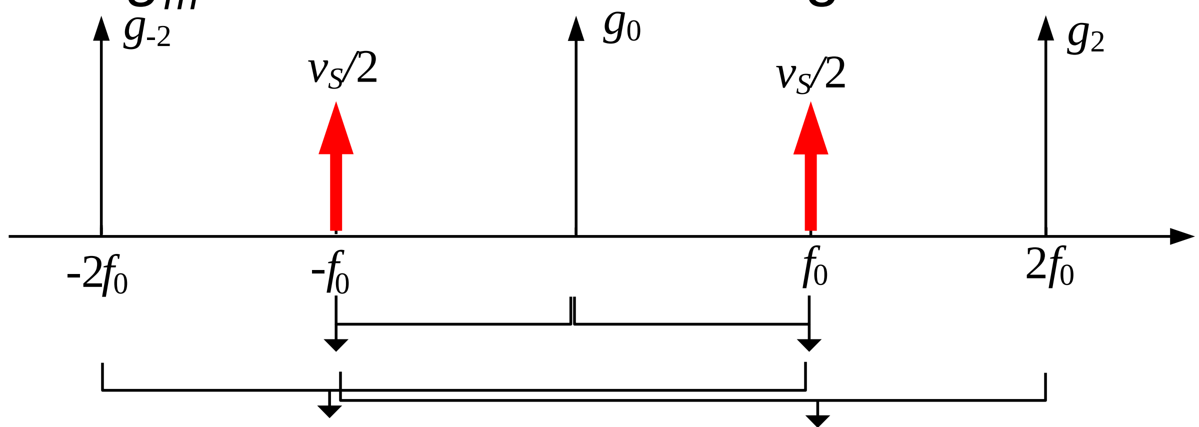
$$d = \frac{1}{2k}$$

- Fourier domain – (magnitude) complex harmonic components

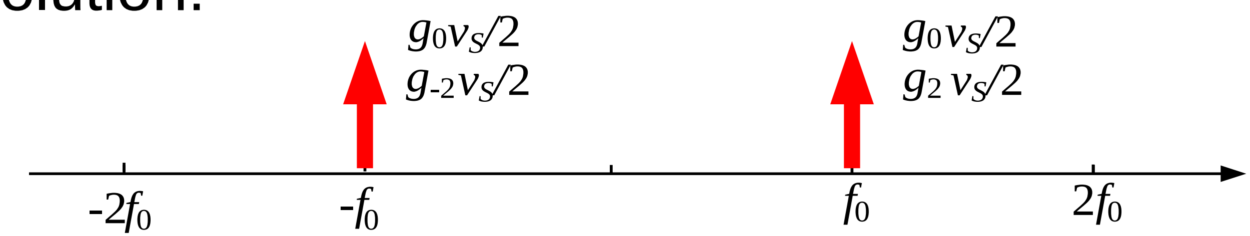


Oscillation Condition

- harmonics: g_m-cell and oscillation signal



- convolution:



- oscillation signal:

$$v_S = \left(\frac{v_S(-f_0)}{2} g_0 + \frac{v_S(+f_0)}{2} g_0 + \frac{v_S(-f_0)}{2} g_2 + \frac{v_S(+f_0)}{2} g_{-2} \right) R_{TK} = (g_0 + g_2) v_S R_{TK}$$

- oscillation condition:

$$g_0 + g_2 = G_{TK}$$

small-signal loop gain:

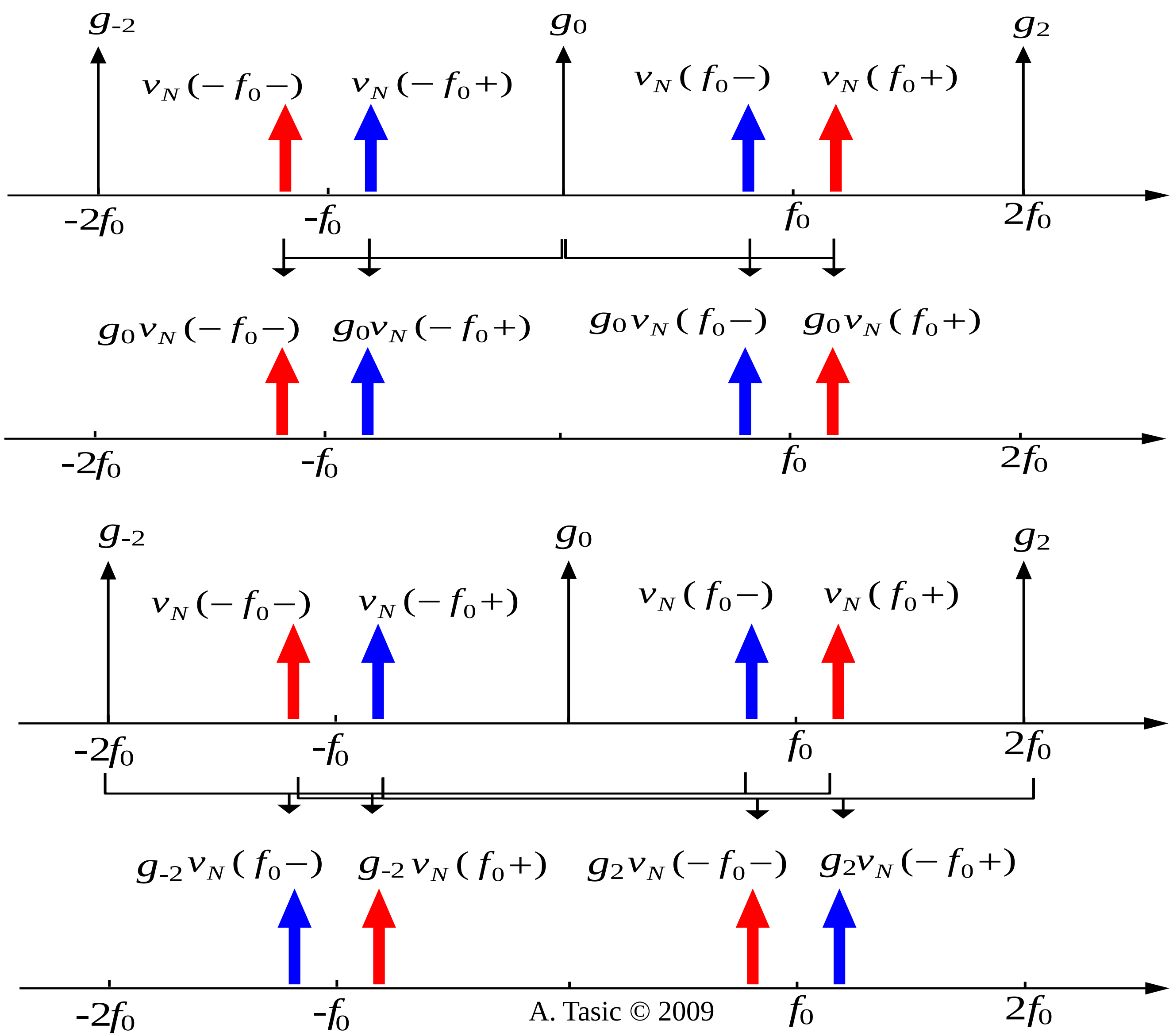
$k = R_{TK} g_m / 2$

duty cycle:

$d = 1/(2k)$

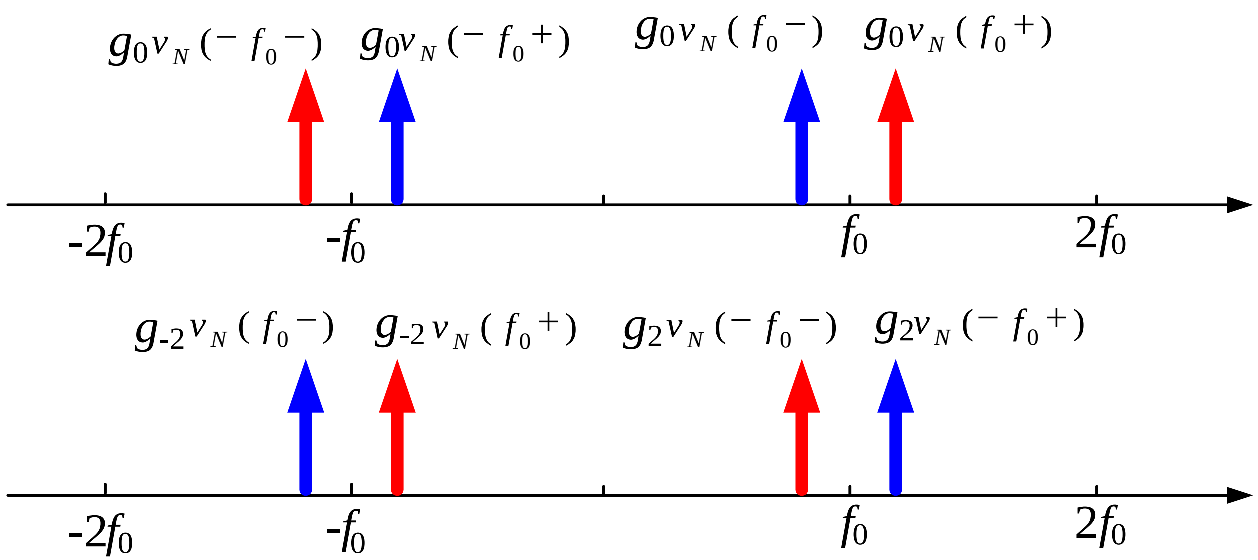
LC-Tank Noise Folding

- convolution: g_0 and g_2 harmonics and LC-tank noise



LC-Tank Noise Folding

- LC-tank noise contribution:



$$i_{N,O}(f_0-\Delta)=g_0 v_N(f_0-\Delta)+g_2 v_N(-f_0-\Delta)$$

$$i_{N,O}(-f_0+\Delta)=g_0 v_N(-f_0+\Delta)+g_{-2} v_N(f_0+\Delta)$$

$$i_{N,O}(f_0+\Delta)=g_0 v_N(f_0+\Delta)+g_2 v_N(-f_0+\Delta)$$

$$i_{N,O}(-f_0-\Delta)=g_0 v_N(-f_0-\Delta)+g_{-2} v_N(f_0-\Delta)$$

LC-Tank Noise Contribution

- phase-modulating noise component:

$$i_{PM} = \frac{1}{2}\left[i_{N,O}(f_0 + \Delta) + i_{N,O}(-f_0 + \Delta) + i_{N,O}(-f_0 - \Delta) + i_{N,O}(f_0 - \Delta) \right]$$

$$i_{PM} = (g_0 + g_2) v_N(f_0 + \Delta) + (g_0 + g_2) v_N(f_0 - \Delta)$$

- phase-related noise power (k>>1, $g=g_0=g_2$):

$$i^2_{PM}(R_{TK}) = (g_0 + g_2)^2 v^2_N(R_{TK})$$

- LC-tank noise transfer function:

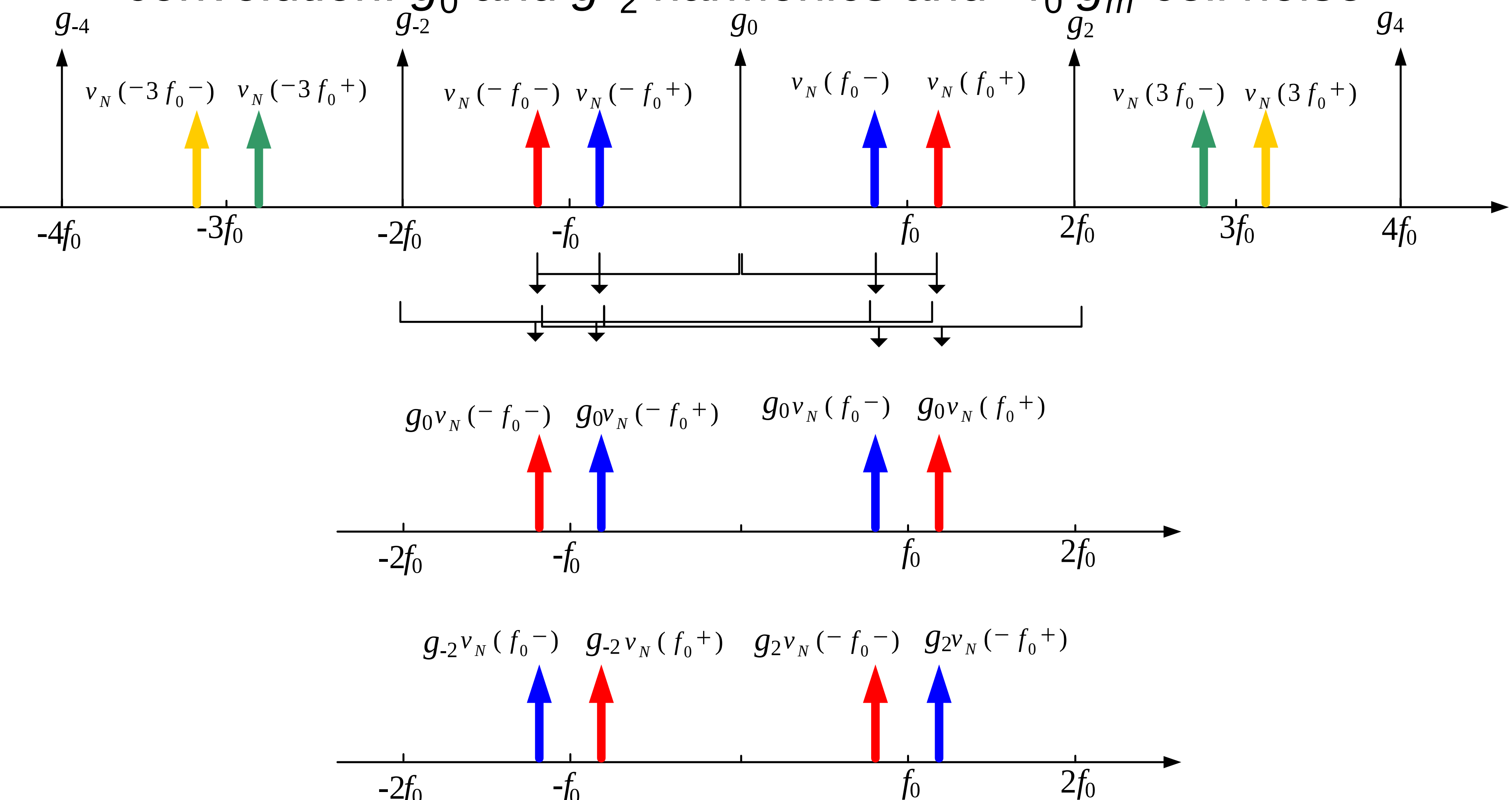
$$g^2(R_{TK}) = (g_0 + g_2)^2 = G^2_{TK}$$

- LC-tank noise factor:

$$F(R_{TK}) = \frac{2 i^2_{PM}(R_{TK})}{4KTG_{TK}} = \frac{2(g_0 + g_2)^2 v^2_N(R_{TK})}{4KTG_{TK}} = \frac{2 G^2_{TK} v^2_N(R_{TK})}{4KTG_{TK}} = \frac{4KTG_{TK}}{4KTG_{TK}} = 1$$

g_m-Cell Noise Folding

- convolution: g_0 and $g\ _2$ harmonics and f_0 g_m-cell noise



- g_m-cell noise around odd multiples of the oscillation frequency is folded to the LC-tank noise around the oscillation frequency

g_m-Cell Noise Contribution

- phase-modulating noise component:

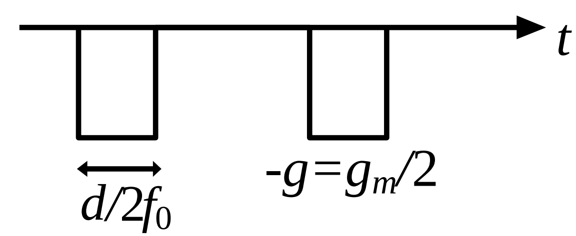
$$i_{PM} = (g_0 + g_2)v_N(f_0 + \Delta) + (g_0 + g_2)v_N(f_0 - \Delta) +$$
$$+(g_2 + g_4)v_N(3f_0 + \Delta) + (g_2 + g_4)v_N(3f_0 - \Delta) + \ldots$$
$$+(g_{2i-2} + g_{2i})v_N((2i-1)f_0 + \Delta) + (g_{2i-2} + g_{2i})v_N((2i-1)f_0 - \Delta)$$

- phase-related noise power (k>>1, g=g_0=g_2=…):

$$i^2_{PM}(g_{m-IN}) = \left[(g_0 + g_2)^2 + (g_2 + g_4)^2 + \ldots + (g_{2i-2} + g_{2i})^2\right] v^2_N(g_{m-IN})$$

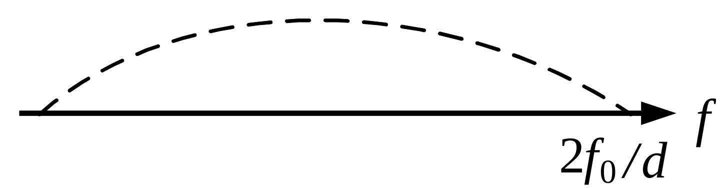
- number of g_{2i} harmonic components:

$$\frac{2f_0}{d}\frac{1}{2f_0} = \frac{1}{d}$$



- number of (g_{2i-2}+g_{2i}) folding pairs:

$$\boxed{\frac{1}{2d} = \frac{2k}{2} = k}$$



g_m-Cell Noise Contributions

- phase-related noise power:

$$i^2_{PM}(g_{m-IN}) = \frac{1}{2d}(g_{2i-2} + g_{2i})^2 v^2_N(g_{m-IN}) = \frac{2g^2_{2i}}{d} v^2_N(g_{m-IN}) = 2dg^2 v^2_N(g_{m-IN})$$

- g_m-cell noise transfer function:

$$g^2(g_{m-IN}) = 2dg^2 = 2d(\frac{g_m}{2})^2 = 2\frac{1}{2k}(kG_{TK})^2 = kG^2_{TK}$$

- g_m-cell noise factors:

$$F(2r_B) = \frac{2i^2_{PM}(2r_B)}{4KTG_{TK}} = \frac{2kG^2_{TK}4KTr_B}{4KTG_{TK}} = 2kr_B G_{TK} = kc$$

$$F(2I_C) = \frac{2i^2_{PM}(2I_C)}{4KTG_{TK}} = \frac{2kG^2_{TK}2KT/g_m}{4KTG_{TK}} = kG_{TK}/g_m = \frac{1}{2}$$

r_B Noise Contribution – Be Precise

- phase-related noise power (k>>1):

$$i_{PM}^2(r_B) = \left[2g_0^2 + 4g_2^2 + 4g_4^2 + \ldots + 4g_{2i-2}^2 \right] v_N^2(r_B)$$

- Paseval's Theorem:

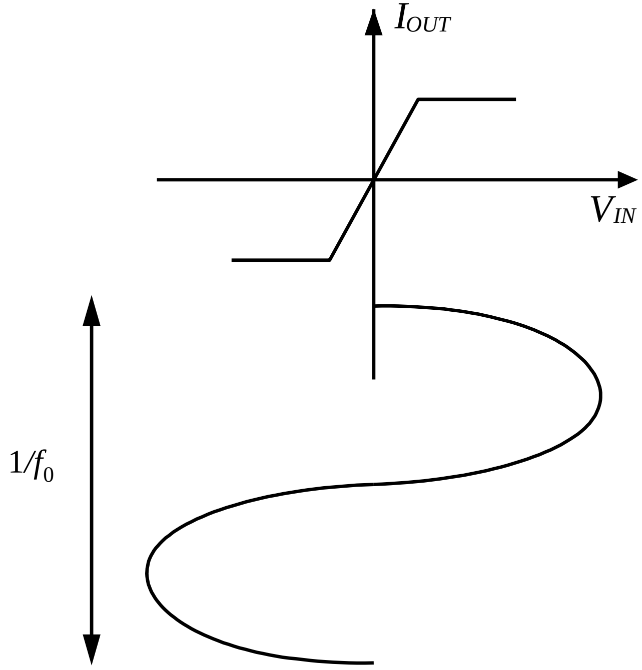
$$g^2(r_B) = 2\left(g_0^2 + 2\sum_{i=1}^{\infty} \left| g_{2i} \right|^2 \right) = \frac{2}{T_2} \int_{-T_2/2}^{T_2/2} g_{\nabla}^2(t)dt = \frac{4}{T_2} \int_0^{\tau} g^2(1-\frac{t}{\tau})^2 dt = \frac{4}{3} g^2 d$$

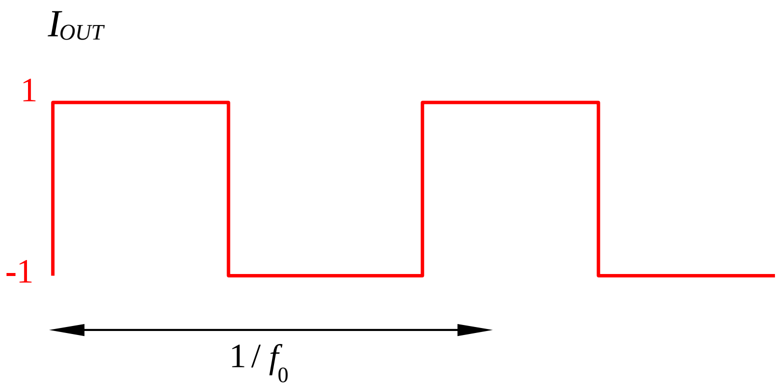
- r_B noise factor:

$$F(2r_B) = 2\frac{2i_{PM}^2(r_B)}{4KTG_{TK}} = \frac{2}{3}kc$$

Bias Current-Source Noise Transfer Function

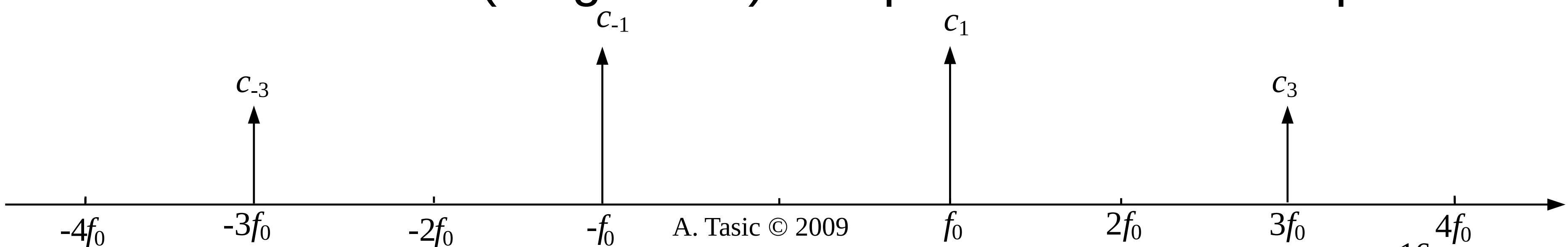
- g_m-cell large-signal *V*-to-*I* transfer function





$$c_{2i+1} = \left| \frac{\sin((2i+1)\pi/2)}{(2i+1)\pi/2} \right|$$

- Fourier domain – (magnitude) complex harmonic components



BCS Noise Contribution

BCS noise around even multiples of the oscillation frequency is folded to the LC-tank noise around the oscillation frequency

- phase-related noise power:

$$i_{PM}^2(I_{BCS}) = \frac{i_{PM,DIFF}^2(I_{BCS})}{4} = \frac{1}{4} i_N^2(I_{BCS})$$

- BCS noise transfer function:

$$g^2(I_{BCS}) = \frac{1}{4}$$

- BCS noise factor:

$$F(I_{BCS}) = \frac{2i_{PM}^2(I_{BCS})}{4KTG_{TK}} = \frac{KTg_m(1+2r_B g_m)}{4KTG_{TK}} = \frac{KT2kG_{TK}(1+2kc)}{4KTG_{TK}} =$$

$$= \frac{1}{2}k(1+2kc) = k(\frac{1}{2}+kc) \cong k \quad F(2I_C) + F(2r_B)$$

Phase-Noise Model of Bipolar Switching LC-Oscillators

- Noise factor:

$$F = F(R_{TK}) + F(2I_C) + F(2r_B) + F(I_{BCS})$$

$$F = 1 + \frac{1}{2} + \frac{2}{3}kc + k(\frac{1}{2} + kc) = 1 + \frac{1}{2}(1+k) + kc(\frac{2}{3} + k)$$

- Phase noise:

$$\mathcal{L} = \frac{\mathcal{L}(R_{TK}) + \mathcal{L}(2I_C) + \mathcal{L}(2r_B) + \mathcal{L}(I_{BCS})}{(4\pi C_{TOT}\Delta)^2} = \frac{4KTG_{TK}F}{v_s^2(4\pi C_{TOT}\Delta)^2} \qquad v_s = \frac{8}{\pi}kV_T$$

$$\mathcal{L} = \frac{4KTG_{TK}}{(4\pi C_{TOT}\Delta)^2}(\frac{\pi}{8V_T})^2 \frac{1 + \frac{1}{2}(1+k) + kc(\frac{2}{3} + k)}{k^2}$$

Phase Noise Model of Bipolar Switching LC-Oscillators

$$F = 1 + \frac{1}{2} + \frac{2}{3}kc + k(\frac{1}{2} + kc)$$

- **Constant phase-noise contributions**
  - LC-tank noise contribution ~ 1
  - g_m-cell current shot noise contribution ~ ½
- **Small-signal loop-gain related contributions**
  - g_m-cell base-resistance noise contribution ~ 0.66ck
  - phase-noise contribution of the bias current source is k-times larger then the noise contribution of the g_m-cell ~ k(½+ck)!

Low/High-Performance VCO Designs

- high ss loop-gain, high quality LC-tank, BCS noise eliminated:

  e.g., k>>1(=10), c<<1(~0.01)

$$\mathcal{L} \sim \frac{1+\frac{1}{2}+\frac{2}{3}kc}{k^2} = \frac{7.8}{5}\frac{1}{10}\frac{1}{10} \sim \frac{1}{k^2}$$

- high ss loop-gain, high quality LC-tank, BCS noise present:

  e.g., k>>1(=10), c<<1(~0.01)

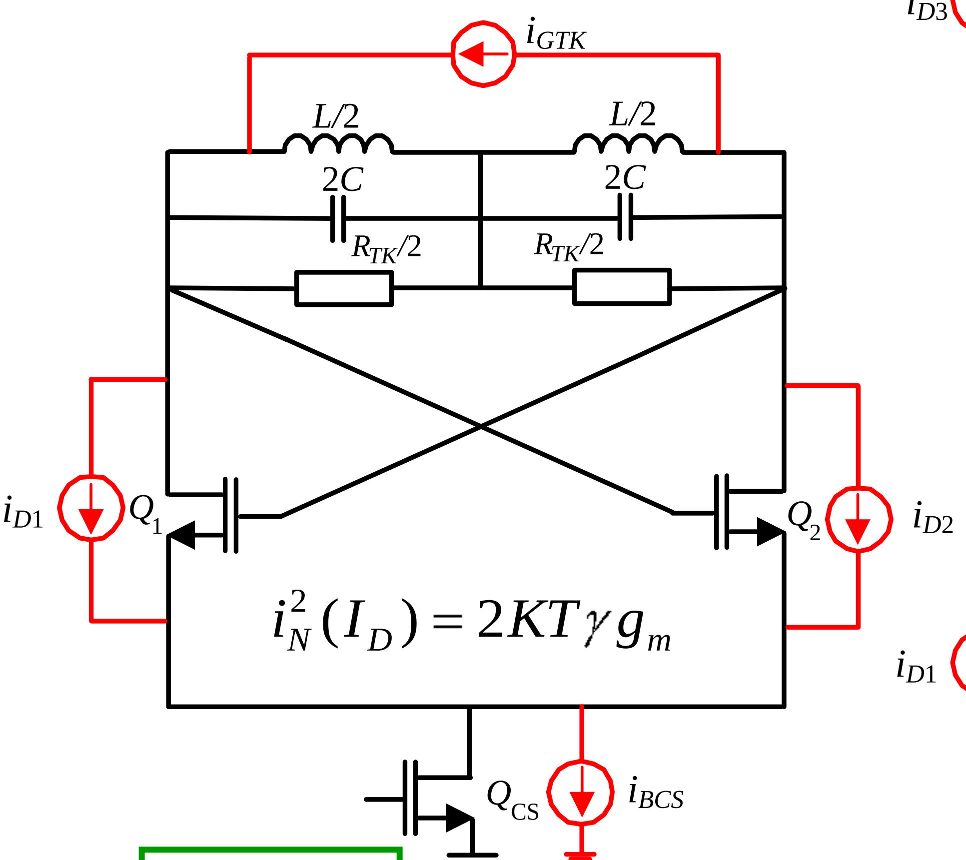
$$\mathcal{L} \sim \frac{k(\frac{1}{2}+kc)}{k^2} = \frac{\frac{1}{2}+kc}{k} = \frac{3}{5}\frac{1}{10} \sim \frac{1}{k}$$

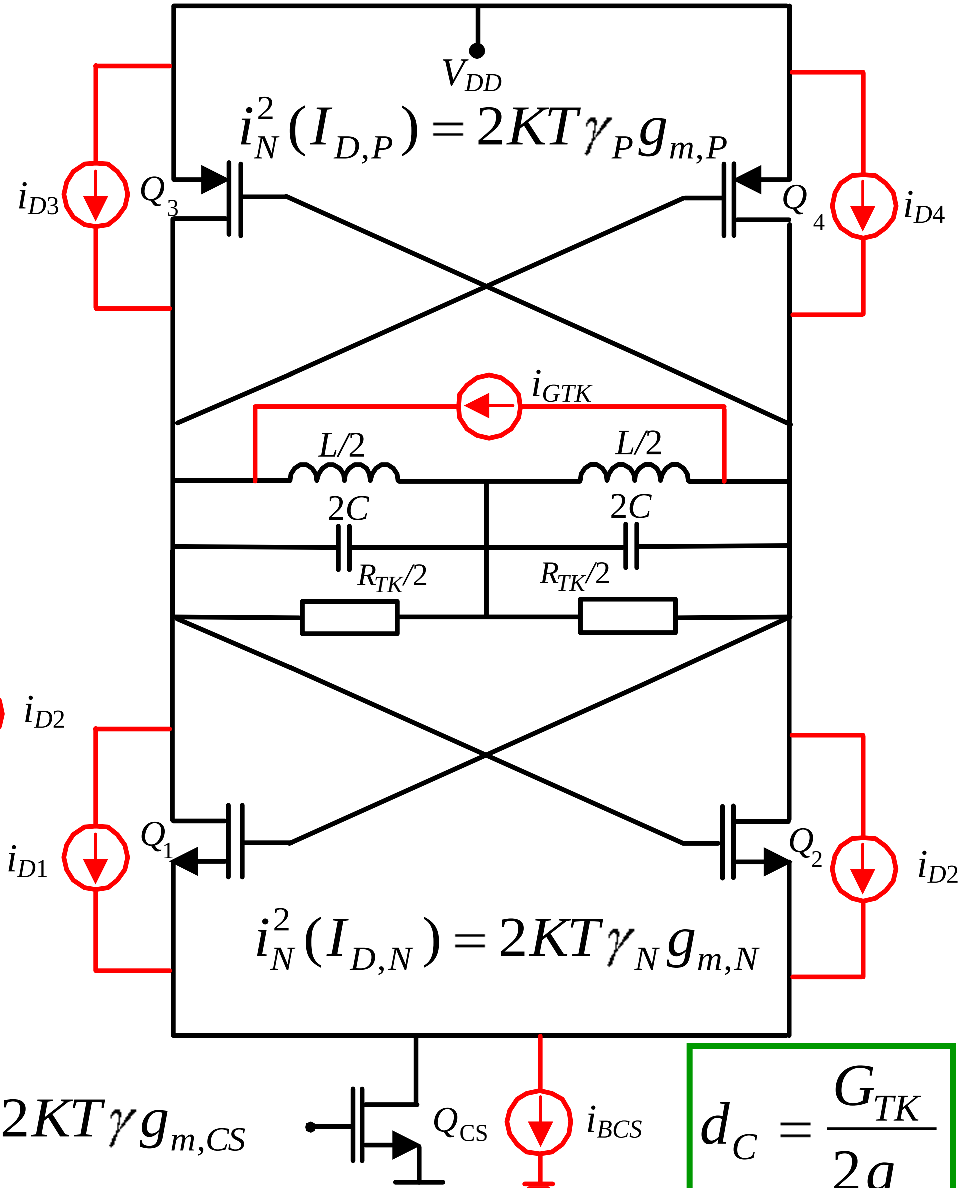
- low ss loop-gain, low quality LC-tank, BCS noise present:

  e.g., k~1(=2), c~1(~0.5)

$$\mathcal{L} \sim \frac{\frac{7}{6}+(1+k)\frac{3}{2}}{k^2} = \frac{5}{4} \sim 1$$

Single/Double-Switch CMOS LC-VCOs





$$d_N = \frac{G_{TK}}{g_m}$$

$$i_N^2(I_{BCS}) = 2KT\gamma g_{m,CS}$$

$$d_C = \frac{G_{TK}}{2g_m}$$

Phase Noise Model of CMOS LC-Oscillators

- Noise factor ($\gamma_N=\gamma_P$, $g_{m,N}=g_{m,P}$):

$$F_{SS} = F(R_{TK}) + F(2I_D) + F(I_{BCS})$$
$$F_{SS} = 1 + \gamma + \gamma g_{m,CS}/(4G_{TK})$$

$$F_{DS} = F(R_{TK}) + F(4I_D) + F(I_{BCS})$$
$$F_{DS} = 1 + \gamma + \gamma g_{m,CS}/G_{TK}$$

- Phase noise:

$$\mathcal{L} = \frac{\mathcal{L}(R_{TK}) + \mathcal{L}(2I_D) + \mathcal{L}(I_{BCS})}{(4\pi C_{TOT}\Delta)^2} = \frac{4KTG_{TK}F}{v_s^2(4\pi C_{TOT}\Delta)^2}$$

$$\mathcal{L}_{SS} = \frac{4KTG_{TK}}{(4\pi C\Delta)^2}\frac{1+\gamma+\gamma g_{m,CS}/(4G_{TK})}{(\frac{2}{\pi}I_{TAIL}R_{TK})^2}$$

$$\mathcal{L}_{DS} = \frac{4KTG_{TK}}{(4\pi C\Delta)^2}\frac{1+\gamma+\gamma g_{m,CS}/G_{TK}}{(\frac{4}{\pi}I_{TAIL}R_{TK})^2}$$

Phase Noise Model of CMOS LC-Oscillators

$$F = 1 + \gamma + \gamma g_{m,CS} / G_{TK}$$

- **Constant phase-noise contributions**
  - LC-tank noise contribution ~ 1
  - g_m-cell drain-current thermal noise contribution ~ γ
- **Small-signal loop-gain related contributions (?)**
  - bias current source noise contribution ~ $\gamma g_{m,CS}/G_{TK}$ $(k\gamma)$

CMOS vs. Bipolar LC-Oscillators

- noise factors (for removed BCS noise):

$$F_{BIP} = 1 + \frac{1}{2} + \frac{2}{3} kc$$

$$F_{CMOS} = 1 + \gamma$$

- bipolar VCO better for the same power consumption ($v_{s,BIP} = v_{s,CMOS}$)

$$\frac{3}{2} + \frac{2}{3} kc < \frac{5}{3} \quad => \quad kr_B < \frac{R_{TK}}{8}$$

- e.g., k=10, R_{TK}=800Ω

$$r_B < \frac{800}{80} = 10\ \Omega$$

- e.g., k=10, R_{TK}=80Ω

$$r_B < \frac{80}{80} = 1\ \Omega$$

CMOS vs. Bipolar LC-Oscillators

- power consumption figure of merit:

$$FOM = 10\log\left(\mathcal{L}(\Delta)\left(\frac{\Delta}{\omega_0}\right)^2 V_{CC} I_{CC}\right)$$

- V_{CC}=1.8V, $v_{s,BIP}$=0.4V, $v_{s,SS\text{-}CMOS}$=1.2V, ($3I_{CC,BIP}=I_{CC,SS\text{-}CMOS}$)

$$FOM_{BIP} = FOM_{SS-CMOS} + 4.8dB$$

- V_{CC}=1.8V, $v_{s,BIP}$=0.4V, $v_{s,DS\text{-}CMOS}$=1.2V, ($1.5I_{CC,BIP}=I_{CC,DS\text{-}CMOS}$)

$$FOM_{BIP} = FOM_{DS-CMOS} + 7.8dB$$

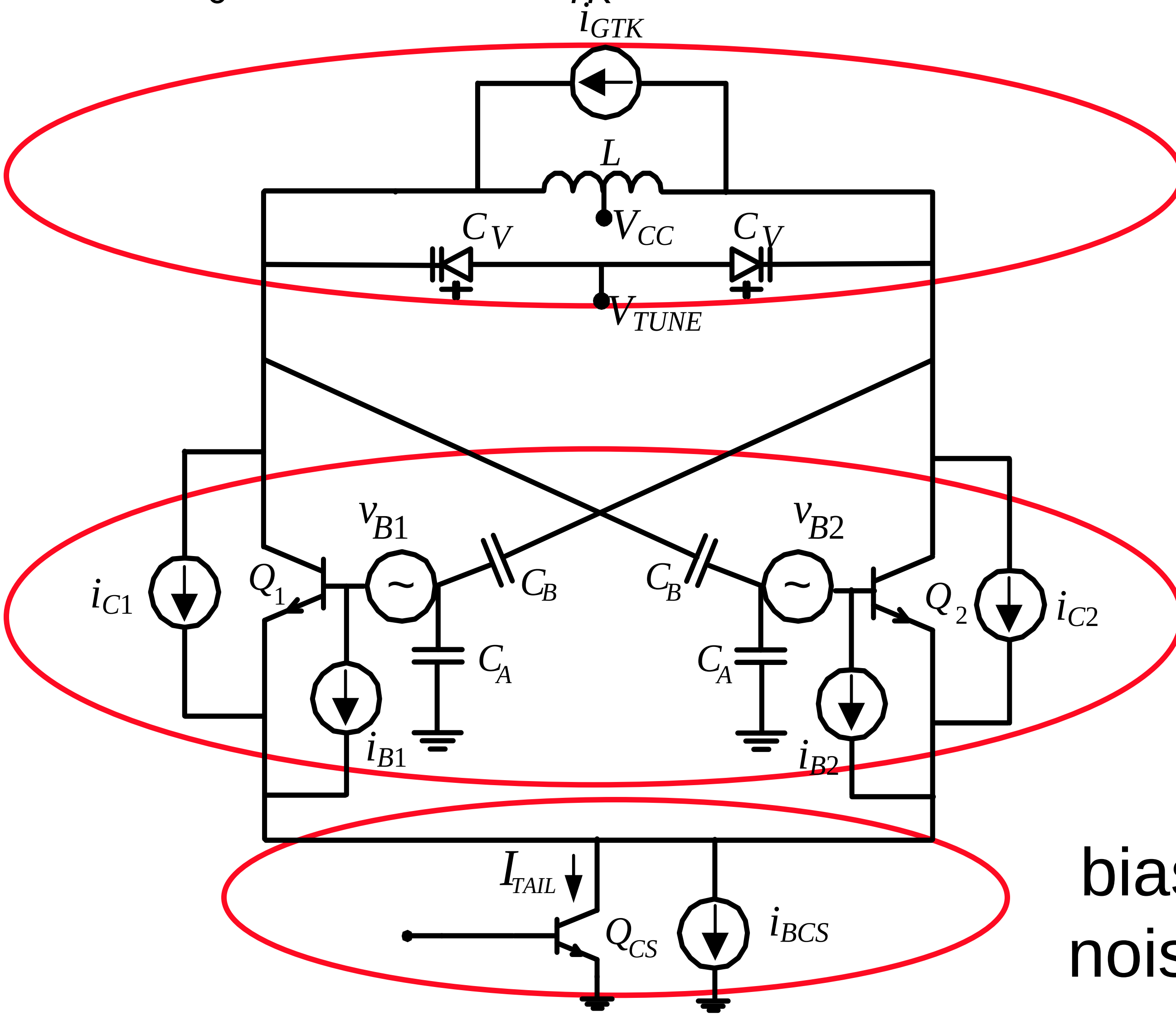
Phase-Noise Model Conclusions

- Parametric Phase-Noise Model
  - electrical circuit parameters (ss loop gain)
  - worst-case phase noise (bandwidth unlimited)
- Bipolar vs. CMOS LC-Oscillators
  - bipolar ss loop-gain related contributions
  - $v_{S,\mathrm{BIP}} \sim k$ ($\ll V_{CC}$), $v_{S,CMOS} \sim V_{CC}$
  - bipolar capacitive tapping for larger $v_{S,\mathrm{BIP}}$, but also larger *k*-related noise contributions and power consumption

Verification of the Phase-Noise Model

VCO Noise Contributions

- f_0~5.74GHz, R_{TK}~340Ω, n~1.65, c~0.25, V_{CC}=2.2V



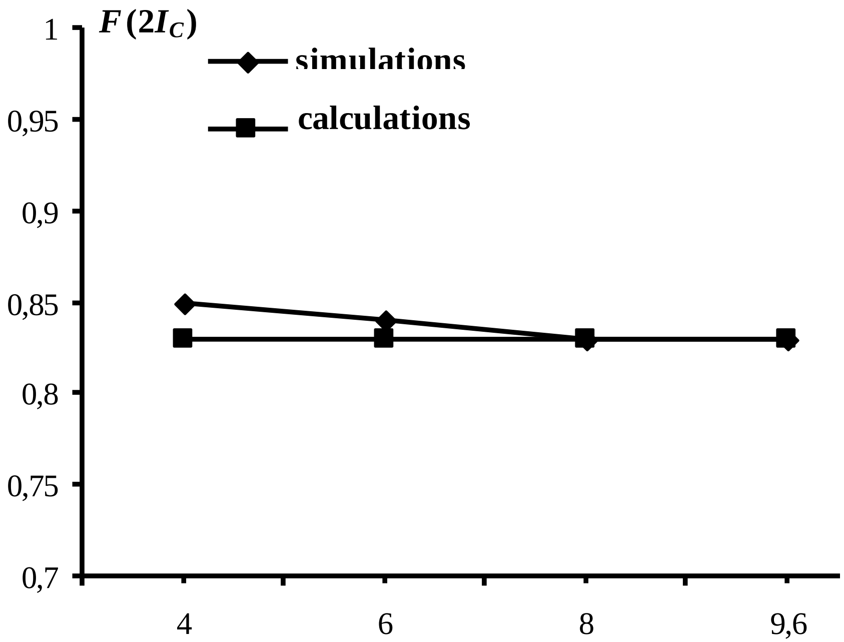
LC-tank noise ~ 1

transconductor noise ~ $n(0.5+0.66c\bullet k)$

bias current-source noise ~ $n(0.5+c\bullet k)\bullet k$

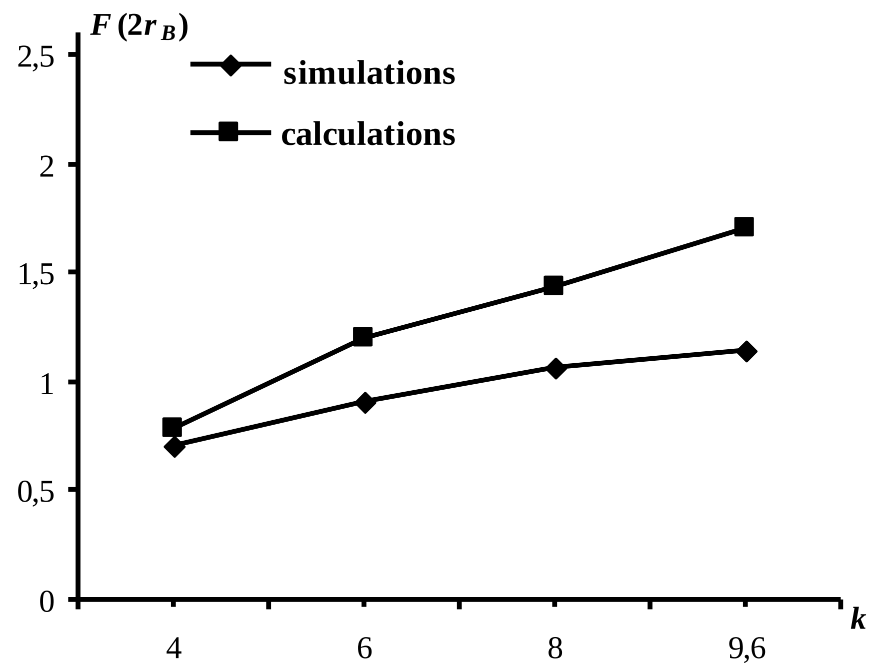
g_m-Cell Noise Contributions

- $k = 0.5 g_m R_{TK} < 0.5 g_{m,actual} R_{TK} = 0.5 g_m R_{TK} / (1 + g_m r_E) = k_{actual}$

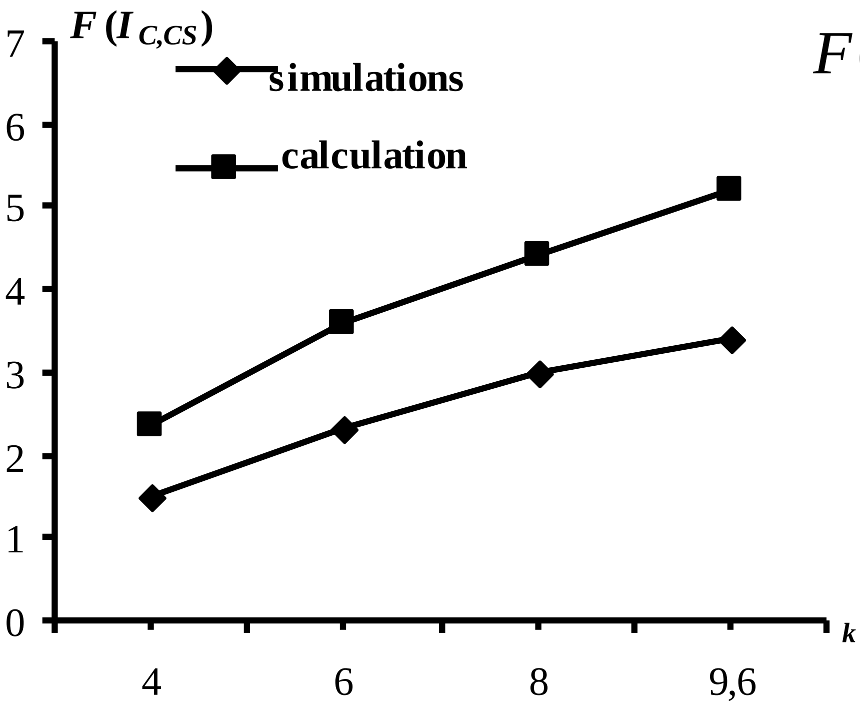


$$F(I_C) = \frac{n}{2} \cong 0.87$$

$$F(2r_B) = \frac{2}{3} nkc = \frac{2}{3} 1.65 \cdot 0.25 \cdot k \cong 0.27 \cdot k$$

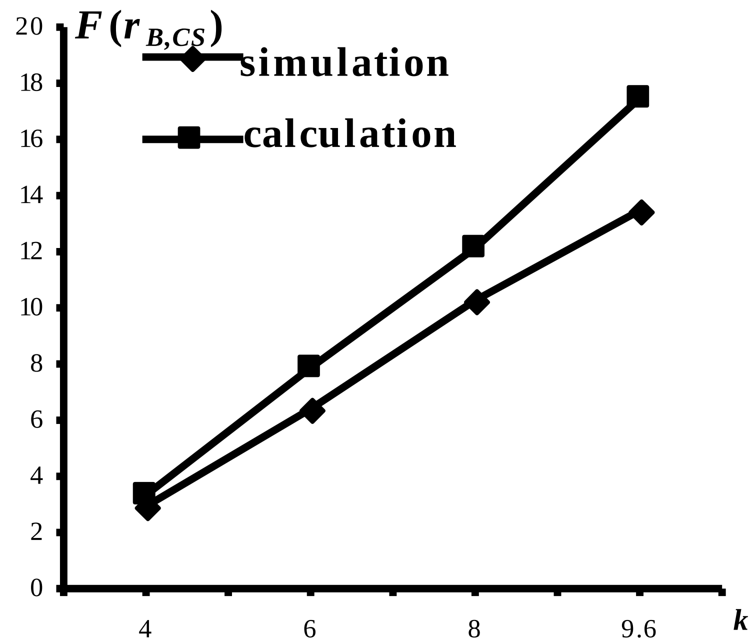


Bias Noise Contributions



$$F(I_{C,CS}) = \frac{1}{2}nk = 0.82k$$

$$F(r_{B,CS}) = knkc = 1.65 \cdot 0.25 \cdot k^2 \cong 0.41 \cdot k^2$$

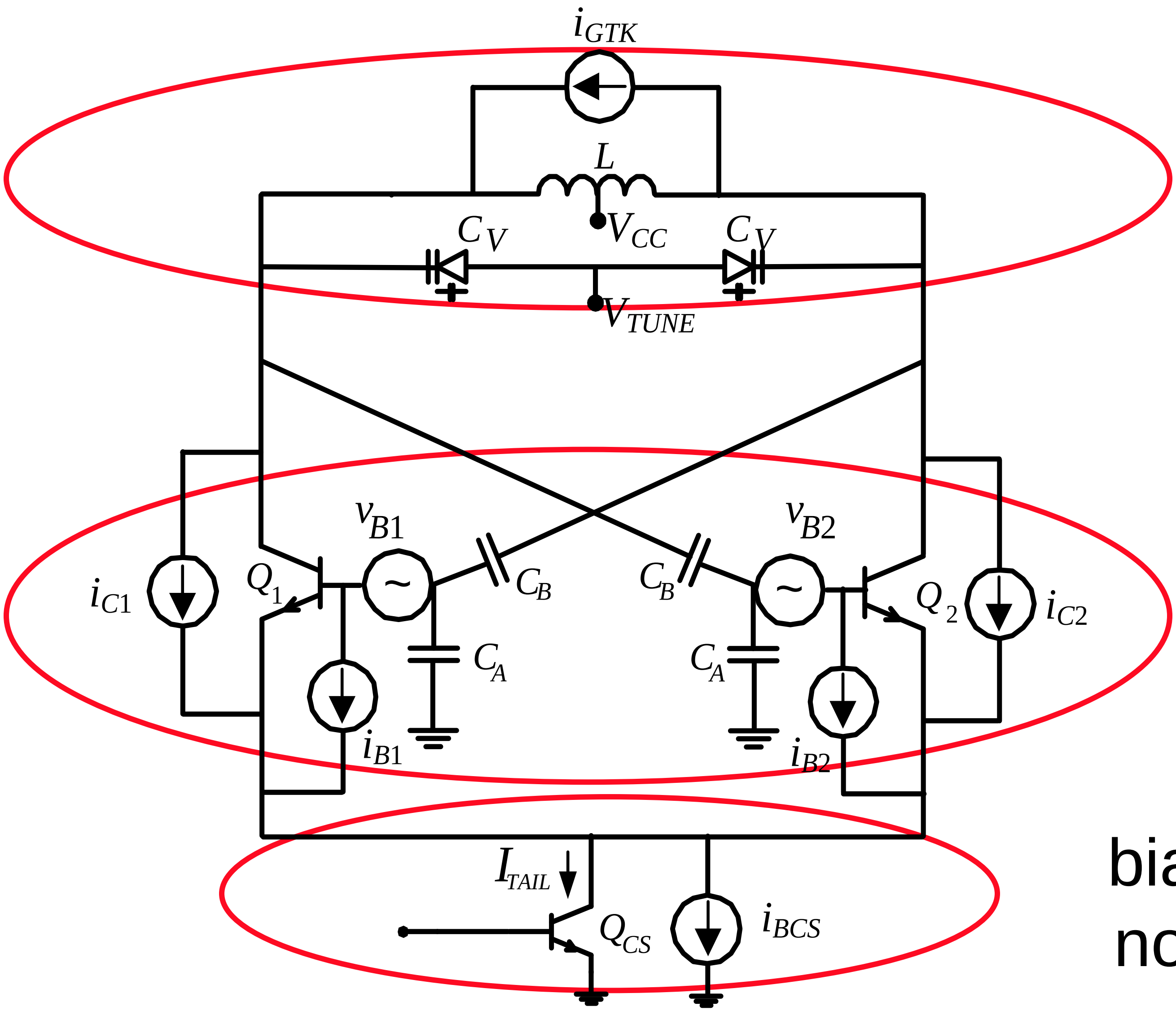


Suppression of Bias Current-Source Noise in LC-Oscillators

Outline

- Contribution of Bias Current-Source Noise to Phase Noise of LC-Oscillators
- Techniques for Reduction of Bias Current-Source Noise
- Noise Analysis of Degenerated Bias Current Source
- Bias Noise Suppression - Design Example

VCO Noise Contributions



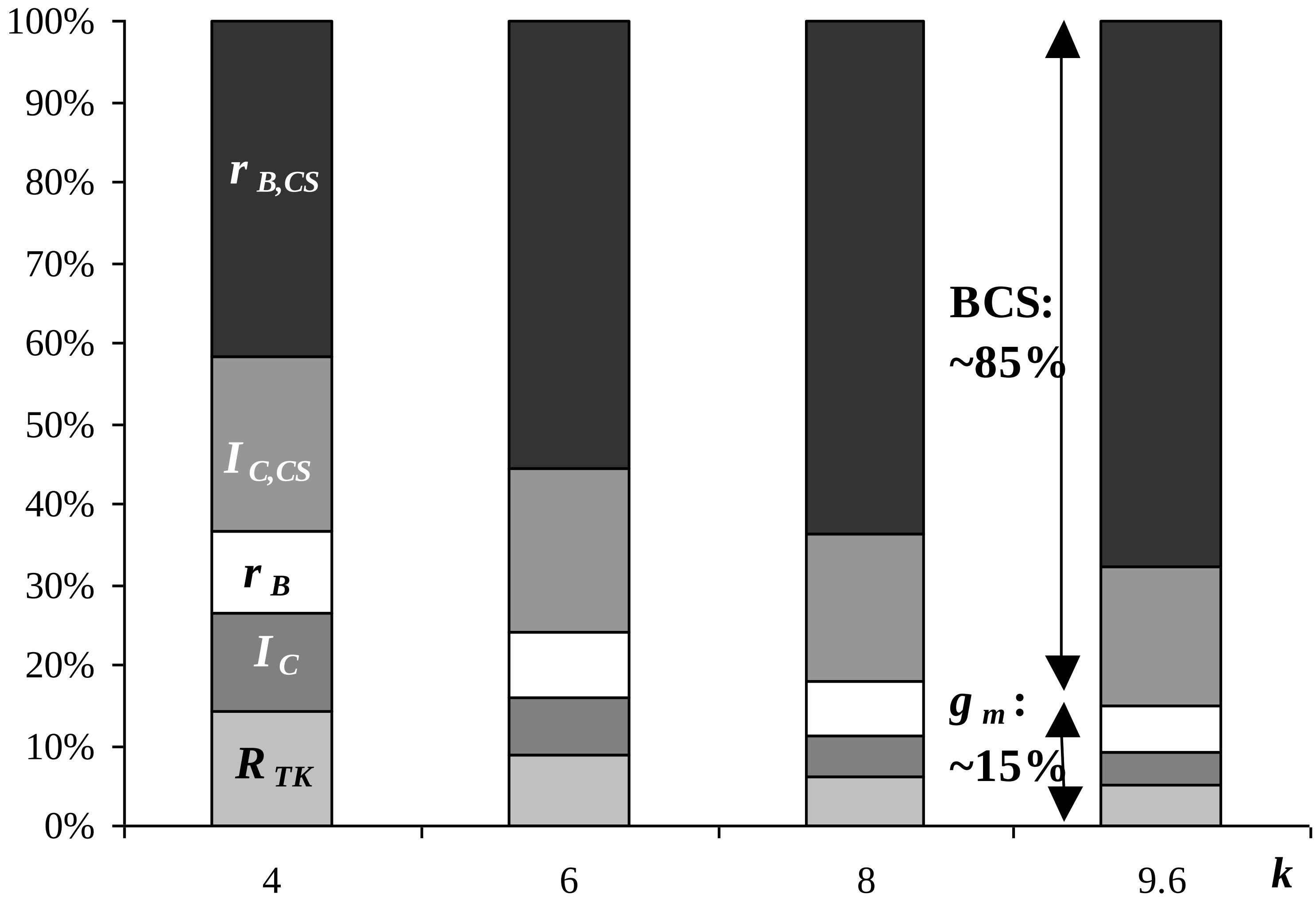
LC-tank
noise ~ 1

transconductor
noise ~ 0.5+*c*•*k*

bias current-source
noise ~ (0.5+*c*•*k*)•*k*

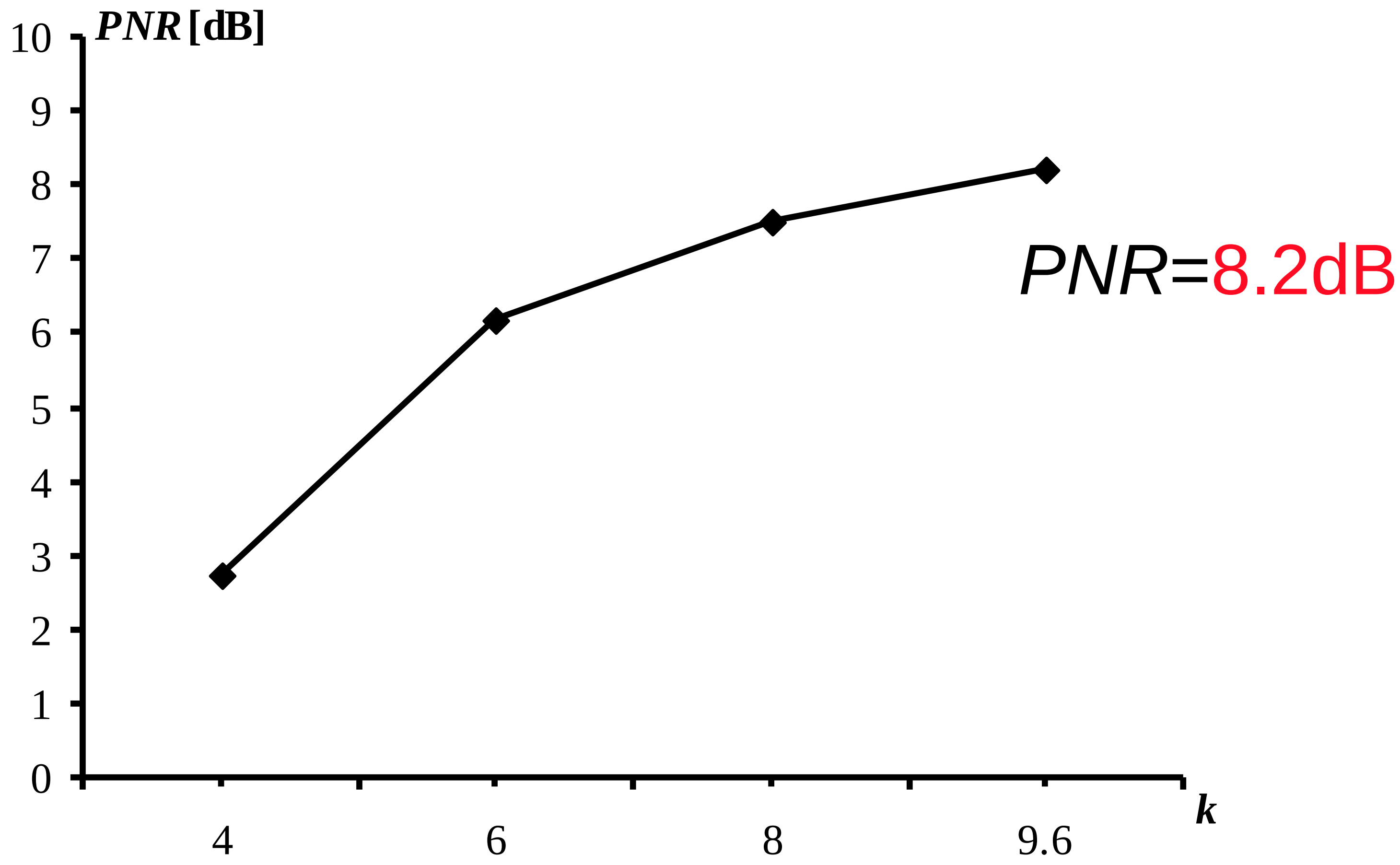
VCO Noise Contributions

- f_0~5.74GHz, R_{TK}~340Ω, n~1.65, c~0.25, V_{CC}=2.2V



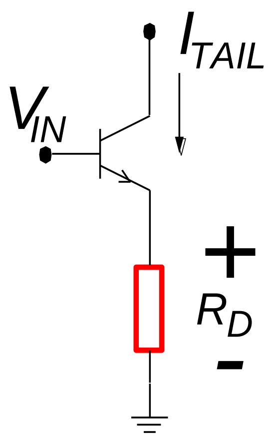
Phase-Noise Ratio

$$PNR = \frac{\mathcal{L}(R_{TK}) + \mathcal{L}(2I_C) + \mathcal{L}(2r_B) + \mathcal{L}(I_{BCS})}{\mathcal{L}(R_{TK}) + \mathcal{L}(2I_C) + \mathcal{L}(2r_B)} = 1 + \frac{k(\frac{n}{2} + nkc)}{1 + \frac{n}{2} + \frac{2}{3}nkc}$$



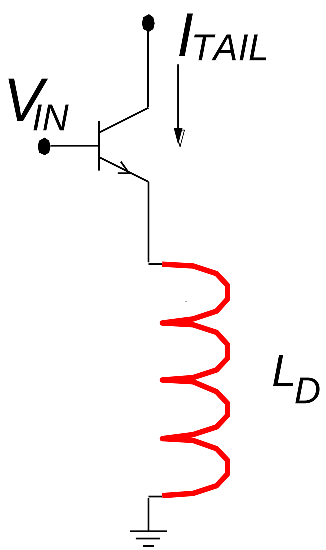
Bias Noise Reduction Techniques

resistive degeneration



☹ high supply required

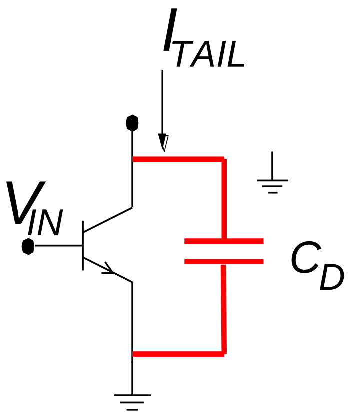
inductive degeneration



☹ large area if integrated

☹ noise injection if discrete

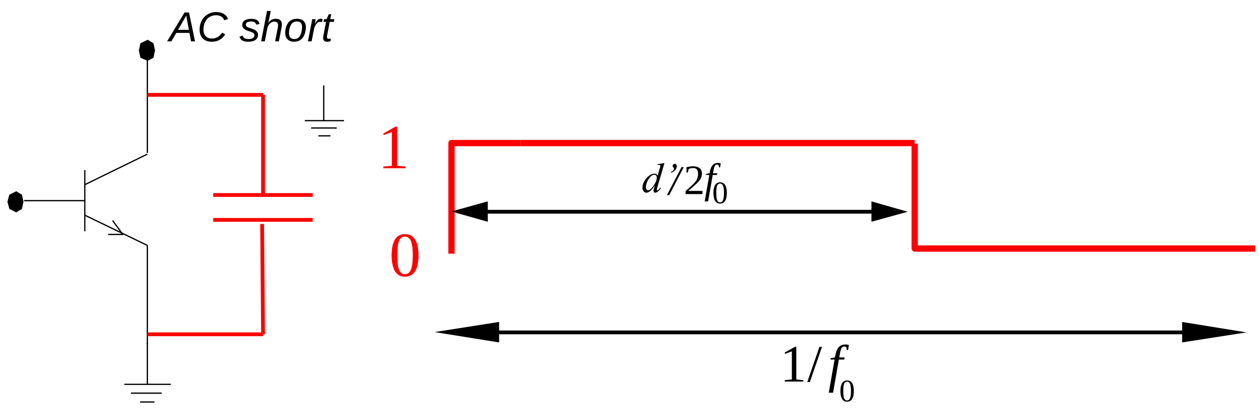
filtering?



☹ transconductor noise always ON

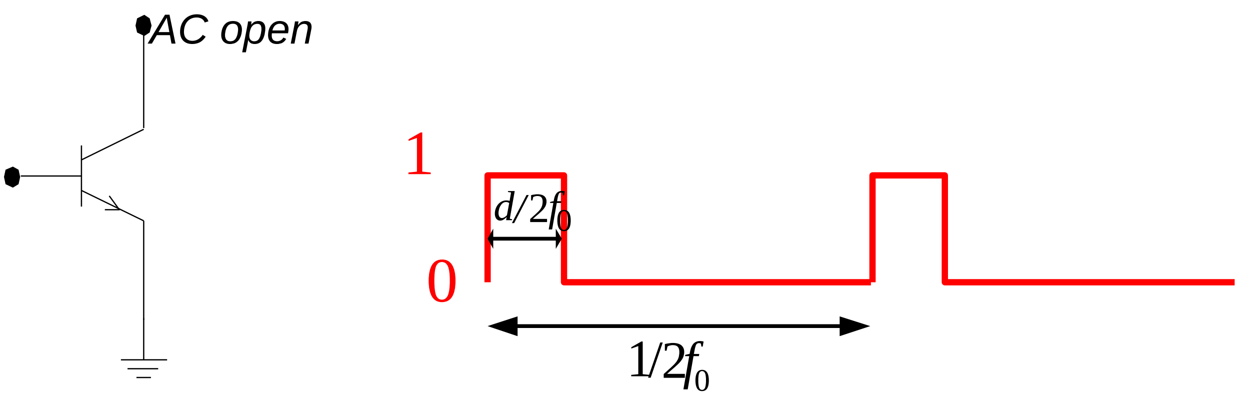
☹ reduced output impedance

Capacitive Filtering



$$d' = \frac{1}{2}(1+d)$$

$$F'(2I_C) \sim k\frac{n}{2}$$

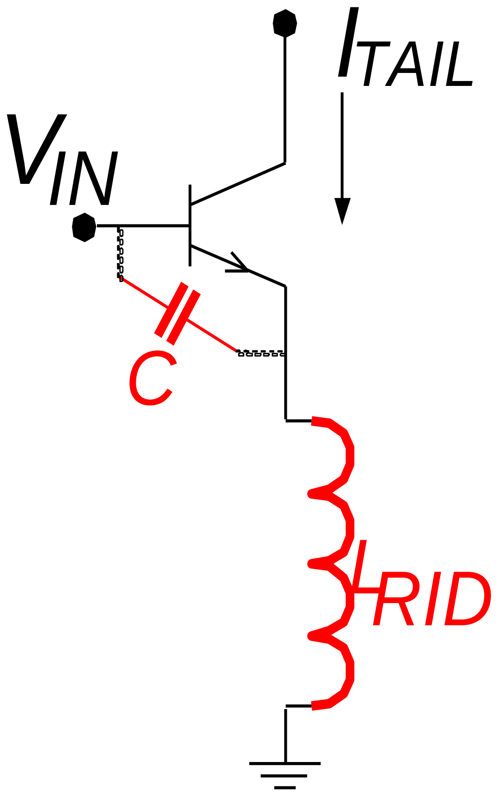


$$d = \frac{1}{2k}$$

$$F(2I_C) \sim \frac{n}{2}$$

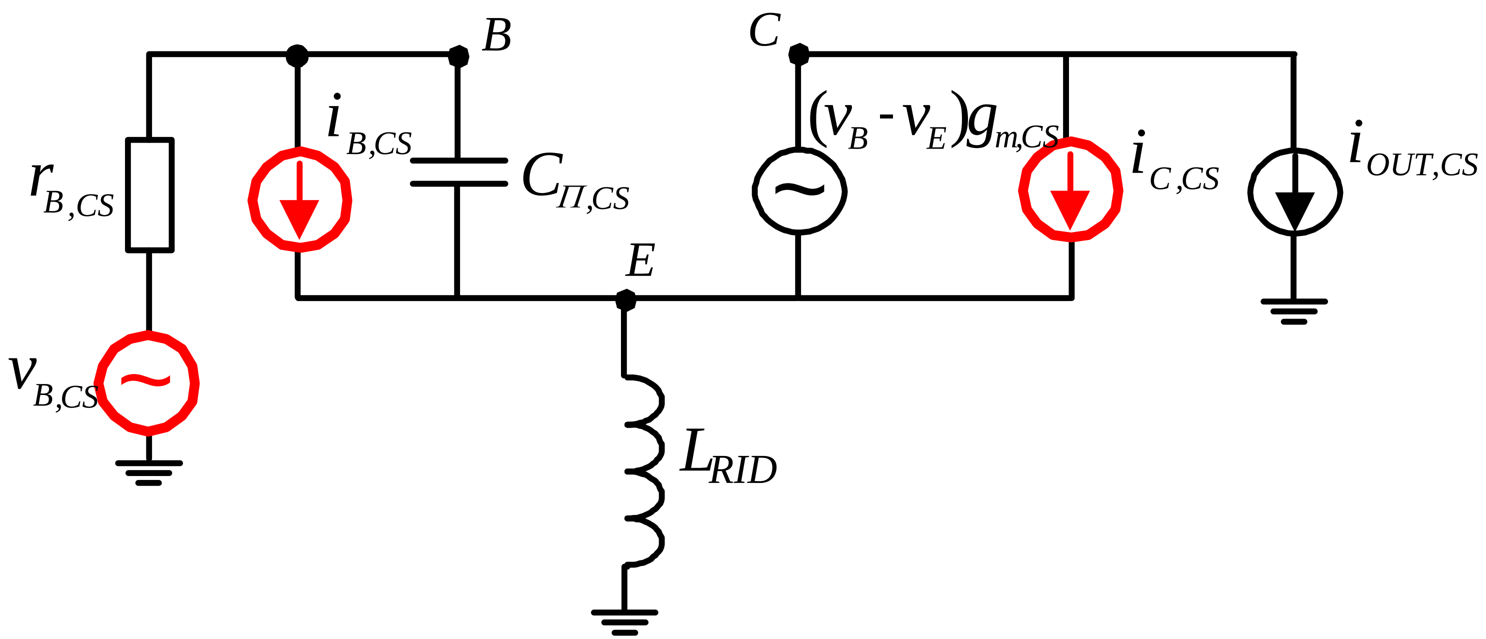
- for k=10, d=5%, d'=52.5%, and $F' > F$

Bias Current Source with Resonant-Inductive Degeneration



- L_{RID} matched to C_{Π} at $2f_0$
- $r_{B,CS}$ noise contribution reduced
  - transconductance gain small at resonance
  - series resonance
- $I_{B,CS}$ noise contribution small
  - common-base like configuration (gain of 1)
- $I_{C,CS}$ noise contribution removed
  - parallel resonance
  - emitter open at resonance ($I_{C,CS}$ floats)

Circuit Diagram for Noise Transfer Functions



- $i_{C,CS}$ to i_{OUT}: $v_{B,CS}$ short, $i_{B,CS}$ open
- $i_{B,CS}$ to i_{OUT}: $v_{B,CS}$ short, $i_{C,CS}$ open
- $v_{B,\ CS}$ to i_{OUT}: $i_{C,CS}$ open, $i_{B,CS}$ open

Bias Current-Source Noise Contributions

$$\frac{i_{OUT}}{v_N(r_{B,CS})}(f) = -\frac{1}{\omega_T L_{RID} + j\omega L_{RID} + \frac{1}{j\omega C_\Pi}}\frac{\omega_{T,CS}}{\omega} = -g_m\left(\frac{f}{f_{T,CS}}\right)$$

series resonance

$$\frac{i_{OUT}}{i_N(I_{B,CS})}(f) = \frac{g_{m,CS}}{g_{m,CS} + \frac{C_\Pi r_{B,CS}}{L_{RID}} + j\omega C_\Pi + \frac{1}{j\omega L_{RID}}} = \frac{1}{1 + r_B g_m\left(\frac{f}{f_T}\right)^2} \cong 1$$

parallel resonance

$$\frac{i_{OUT}}{i_N(I_{C,CS})}(f) = 1 - \frac{g_{m,CS}}{g_{m,CS} + \frac{C_\Pi r_{B,CS}}{L_{RID}} + j\omega C_\Pi + \frac{1}{j\omega L_{RID}}} = 1 - \frac{1}{1 + r_B g_m\left(\frac{f}{f_{T,CS}}\right)^2} \cong 0$$

parallel resonance

BCS w/ RID vs. BCS w/o RID

- BCS noise with degeneration

$$\overline{i^2_{CS,RID}} = 4kT\frac{g_{m,CS}}{2}\left[0 + \left(\frac{f_{T,CS}}{2f_0}\right)^2\frac{1}{\beta} + 2r_{B,CS}\,g_{m,CS}\right]\left(\frac{2f_0}{f_{T,CS}}\right)^2$$

- BCS noise without degeneration

$$\overline{i^2_{CS}} = 4kT\frac{g_{m,CS}}{2}\left[1 + 0\cdot\left(\frac{f_{T,CS}}{2f_0}\right)^2\frac{1}{\beta} + 2r_{B,CS}\,g_{m,CS}\right]$$

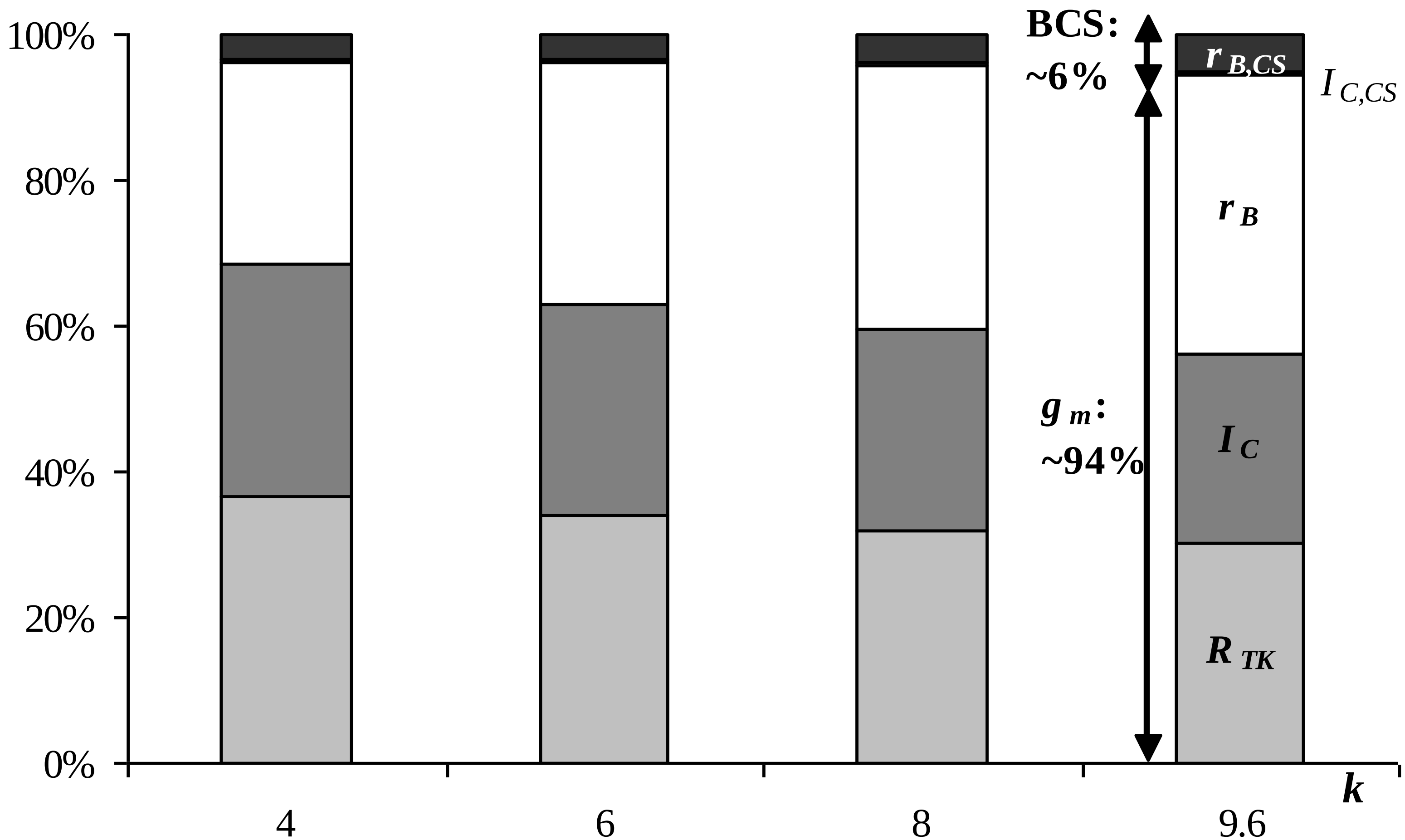
- more than a factor $(f_{T,CS}/2f_0)^2$ noise reduction after RID

$$\overline{i^2_{CS,RID}} < \overline{i^2_{CS}}\left(\frac{2f_0}{f_{T,CS}}\right)^2$$

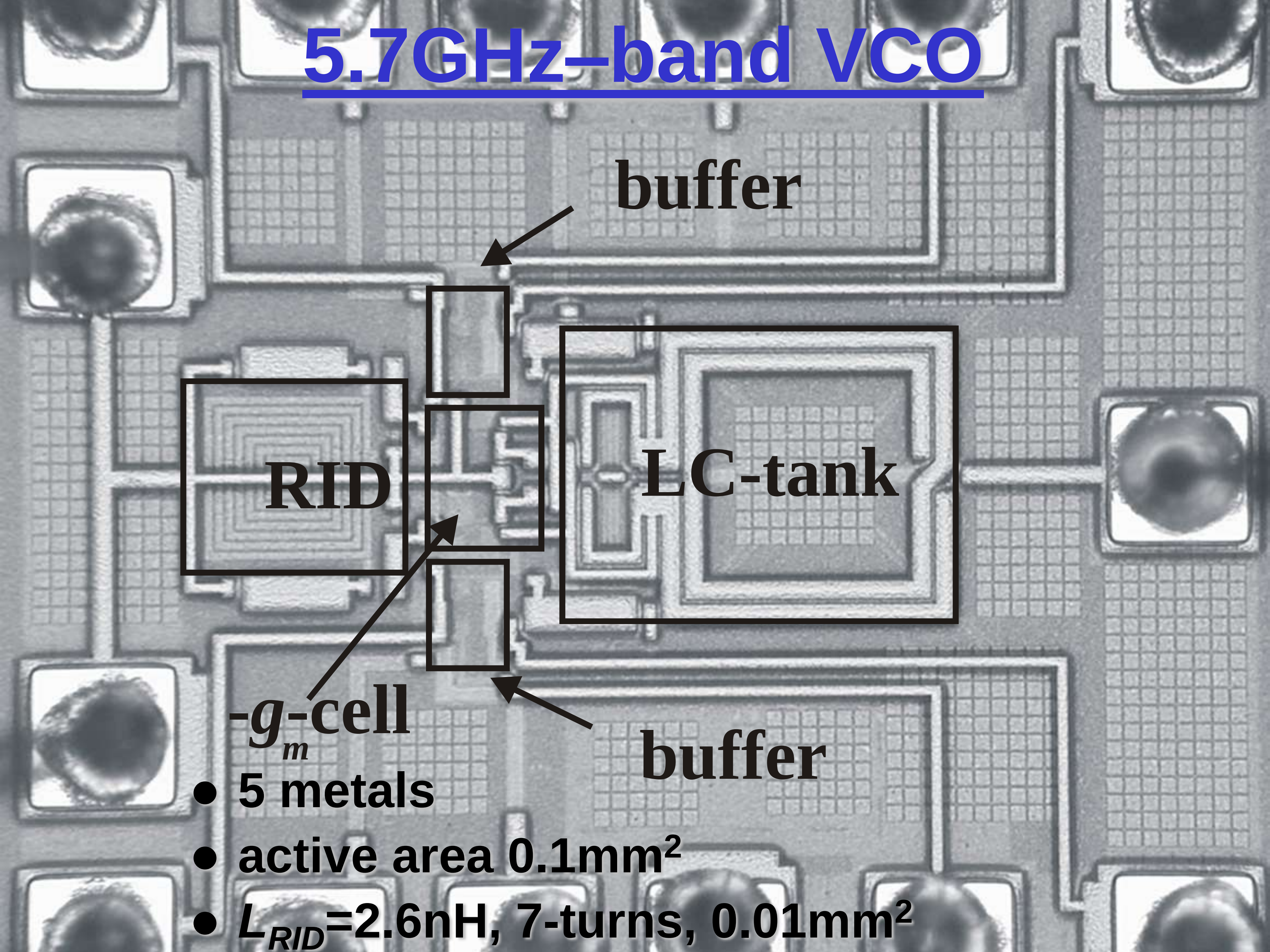
- for $(f_{T,CS}/2f_0)=5$, a factor of 25 reduction

VCO Noise Contributions after RID applied to BCS

- f_0~5.74GHz, L_{RID}~1.3nH, R_{TK}~340Ω, n~1.65, c~0.25, V_{CC}=2.2V

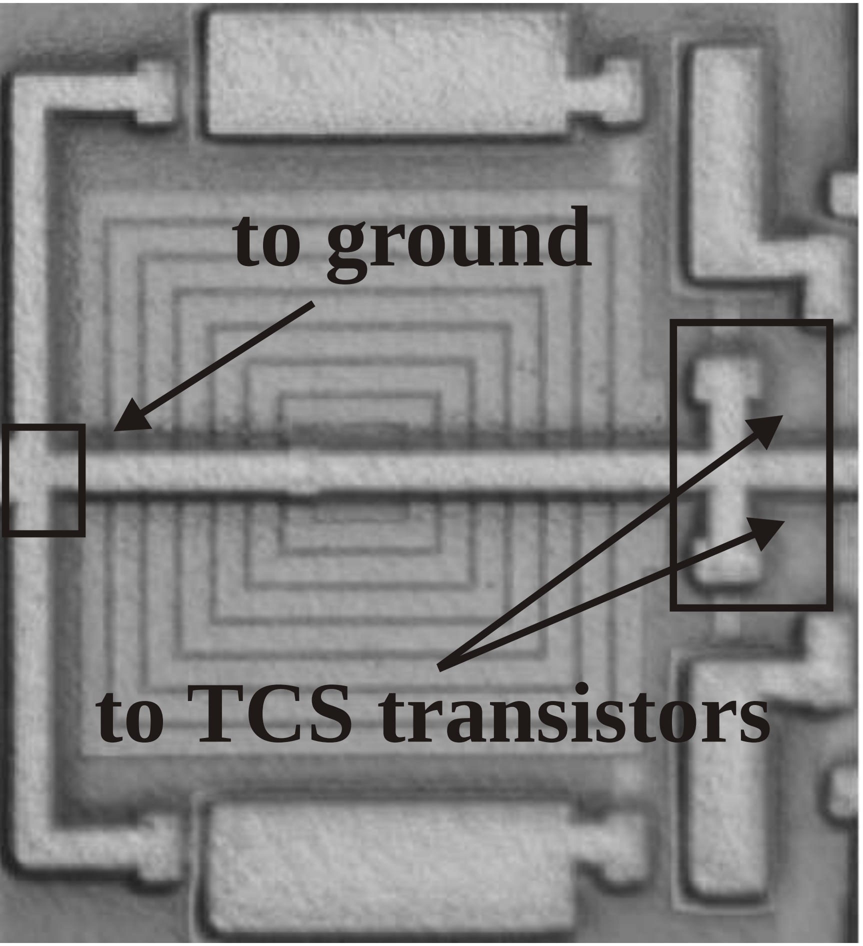


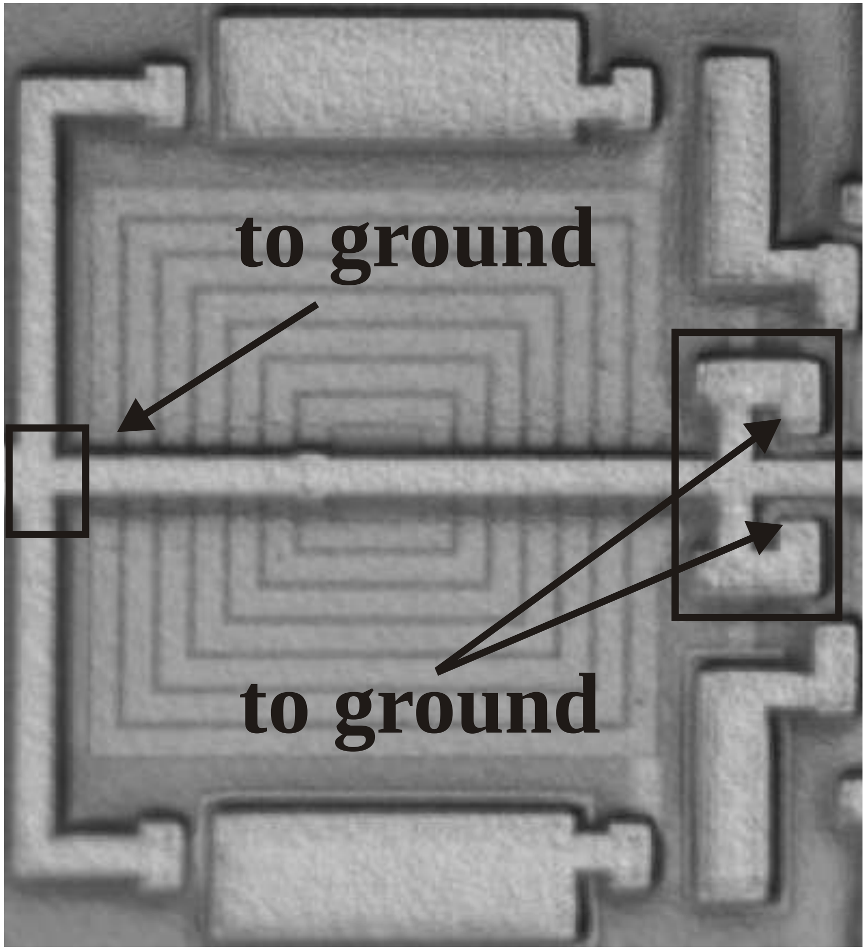
5.7GHz–band VCO



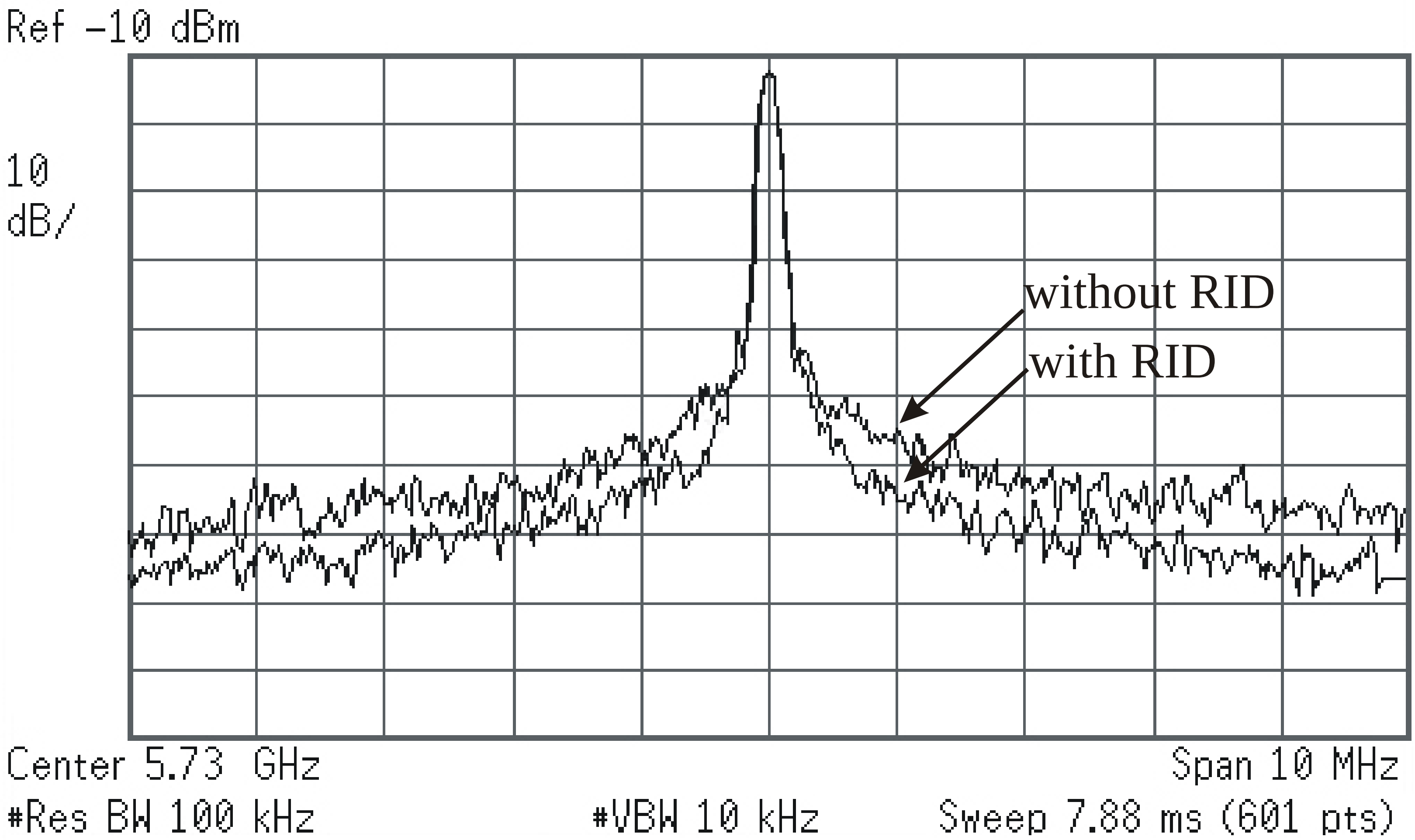
- 5 metals
- active area 0.1mm^2
- L_{RID}=2.6nH, 7-turns, 0.01mm^2

VCO w/ RID vs. VCO w/o RID





Phase Noise (w/ RID vs. w/o RID)



- 6dB phase-noise improvement with RID
- -112dBc/Hz @1MHz from 5.7GHz @ 4.8mA&2.2V

RID Conclusions

- BCS noise >> g_m-cell and *LC*-tank noise
- Resonant inductive degeneration

☺ good suppression of high frequency BCS noise

☺ low voltage operation

☺ small chip area (vs. discrete solutions)

☹ BCS DC noise upconversion

☹ large area (vs. resistive degeneration)

☹ poorer noise suppression at high supplies (vs. resistive degeneration)

Oscillator Conclusions

- Spectral Analysis of Noise in LC-Oscillators
- Phase-Noise Model
  - LC-tank, g_m-cell, bias current source contributions
- Bipolar vs. CMOS LC-Oscillators
- Oscillator Noise Reduction Methods
  - Resonant-Inductive Degeneration

Future Worries

- Low-(Supply and Swing)-Voltage Operation
  - Linear and Quasi-Linear Phase-Noise Model
  - Low-Performance Oscillators
  - Noise-Reduction Methods

Conclusions

Conclusions

- **Spectral Analysis of Noise in LC-Oscillators**
  - LC-tank, g_m-cell, bias current source noise contributions
- **Bipolar and CMOS VCO Noise Factors**
- **LC-Oscillators Noise Reduction Methods**
- **Mixer Noise Factor from VCO Noise Factor**
- **Oscillator Phase Noise in Receiver's SNR**
- **Mixer Noise Factor in a Receiver**
- **LNA Noise Factor in a Receiver**
- **BBFilter Noise Transfer vs. LO/Mix Duty**