Why RF?
&
What is different at RF?

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Electronic Research Laboratory (ELCA)

(RF/wireless Education Track, EE4C10specialization lecture)

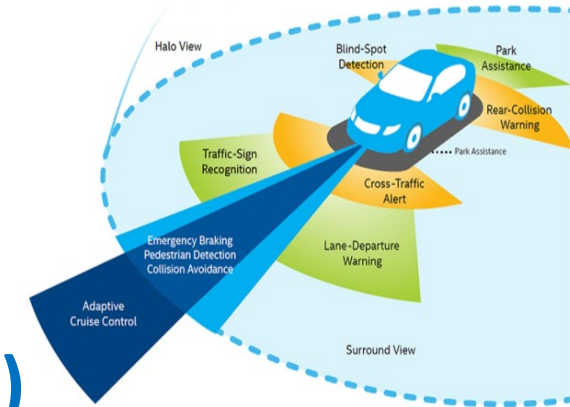
Outline “RF specialization EE4C10”

- Applications of RF
- What is different at RF?
  - Wavelength is shrinking
  - Characteristic impedances & Matched conditions
- Active devices at high frequencies
  - g_m, f_T, f_{max}
  - FET/BJT (black box) descriptions and simplifications
  - Noise behavior, The noise figure F
- Defining transfer functions
- Example LNA using both **Analog** as well **RF** techniques
- Conclusions Analog & RF techniques
- Brief discussion **Homework** “RF specialization EE4C10”
- There is so much more to tell…., so if time still permits…
  - Distortion in circuits
  - Matching

RF = Application Driven

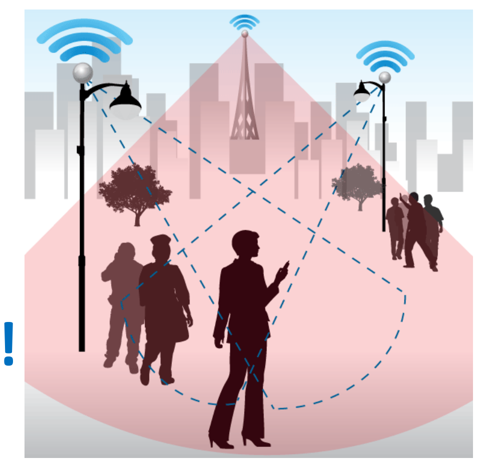
Sensing: (Resolution $\propto$ Bandwidth)

- Radar (e.g. 77GHz band)
  → e.g. car radar/ autonomous driving
- Tissue / Skin cancer detection
- Safety



Communication (Data rate $\propto$ Bandwidth)

- Line drivers (SerDes)
- Wireless
  - » Wideband: Wifi, 3G, 4G, 4.5G, → **5G**
  - » IOT: smart environment, monitoring, medical devices etc.



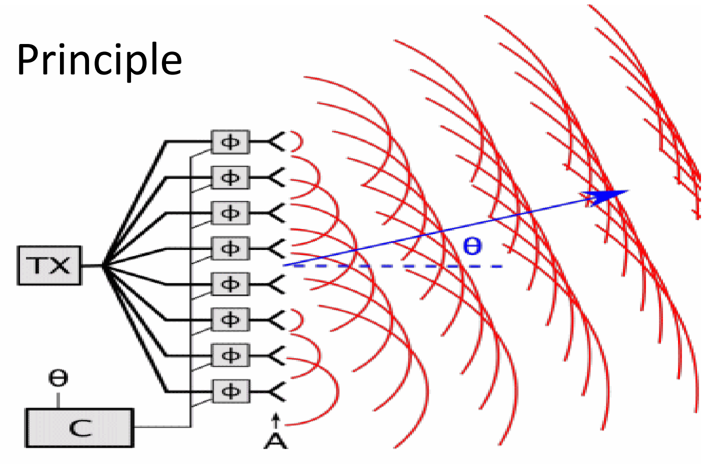
More Bandwidth available at (higher) RF frequencies!

Needed: RF/mm-wave Transmitters & Receivers

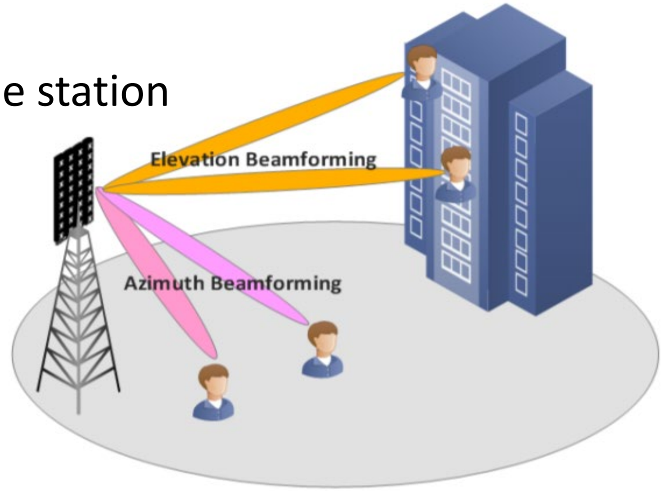
Challenges: Linearity, S/N, **Energy consumption, Costs!**

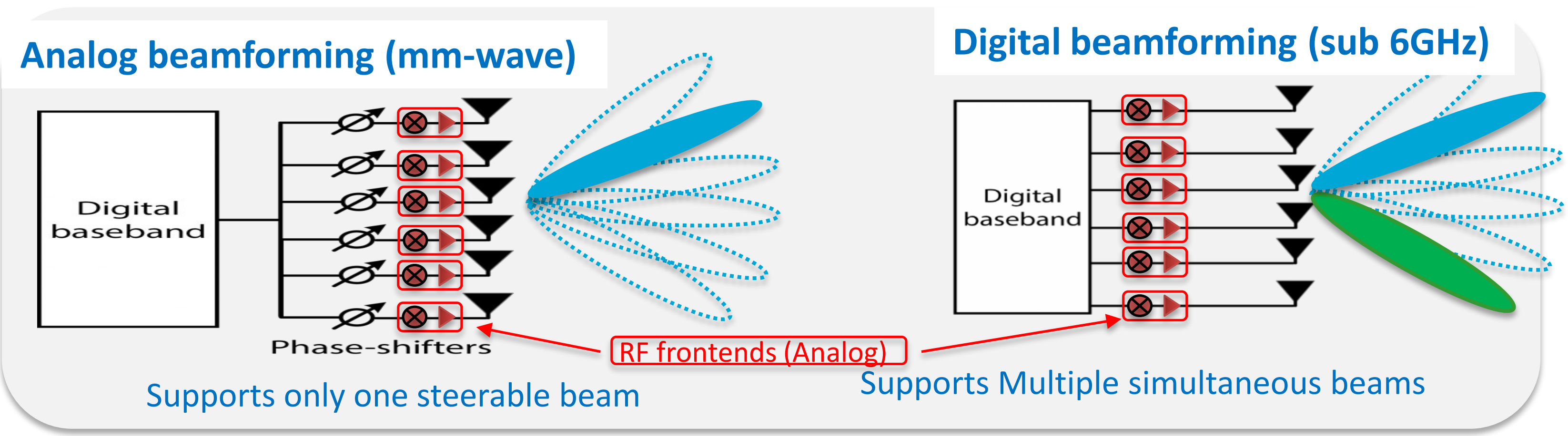
Basics: 5G Beamforming & mMIMO

Principle



Base station

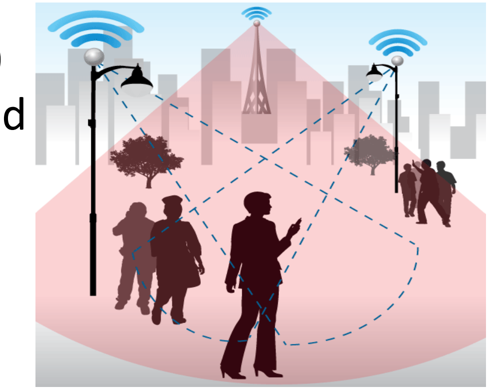


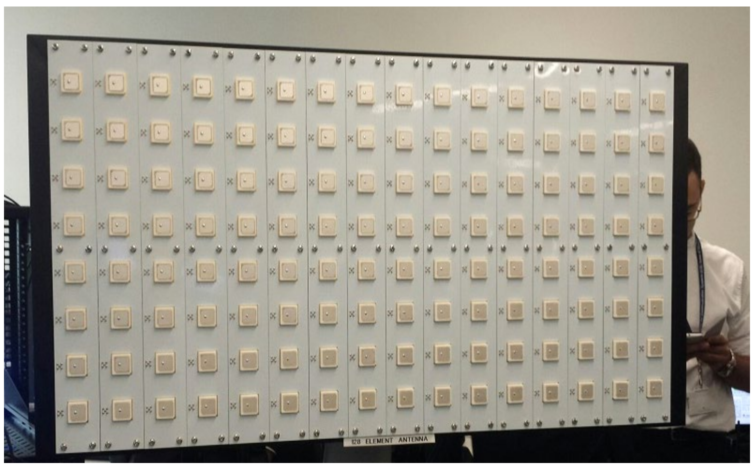


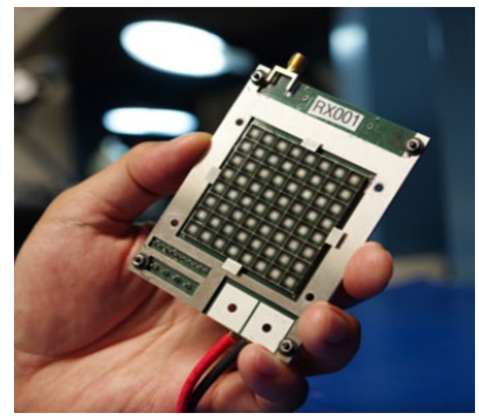
5G Beam Forming Base Stations

Sub-6GHz band
mMIMO

mm-wave (28 GHz)
Base station frontend







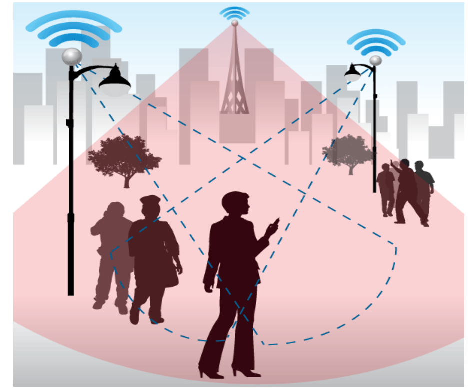
Question (1) What is the energy efficiency of these transmitting systems?
(select the correct statement)

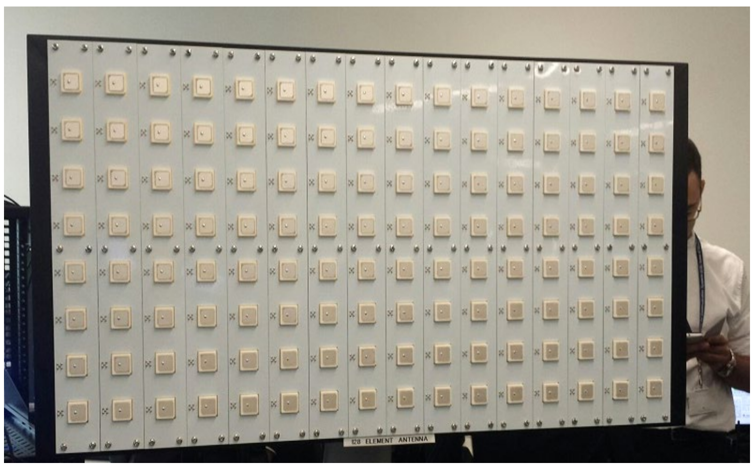
a) Sub-6GHz, better than 30%, mm-wave better than 20%
b) Sub-6GHz, better than 20%, mm-wave better than 10%
c) Sub-6GHz, better than 10%, mm-wave better than 5%
d) Sub-6GHz, better than 5%, mm-wave better than 2.5%

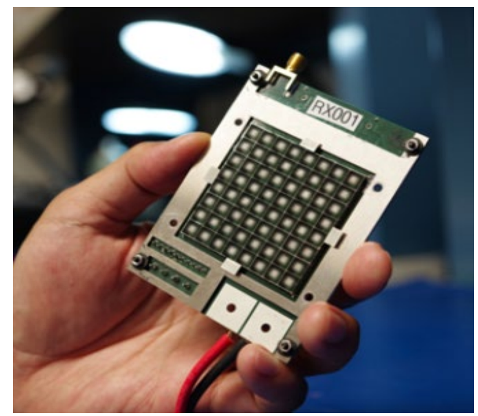
5G Beam Forming Base Stations

Sub-6GHz band
~10% efficiency

mm-wave (28 GHz)
~3% efficiency







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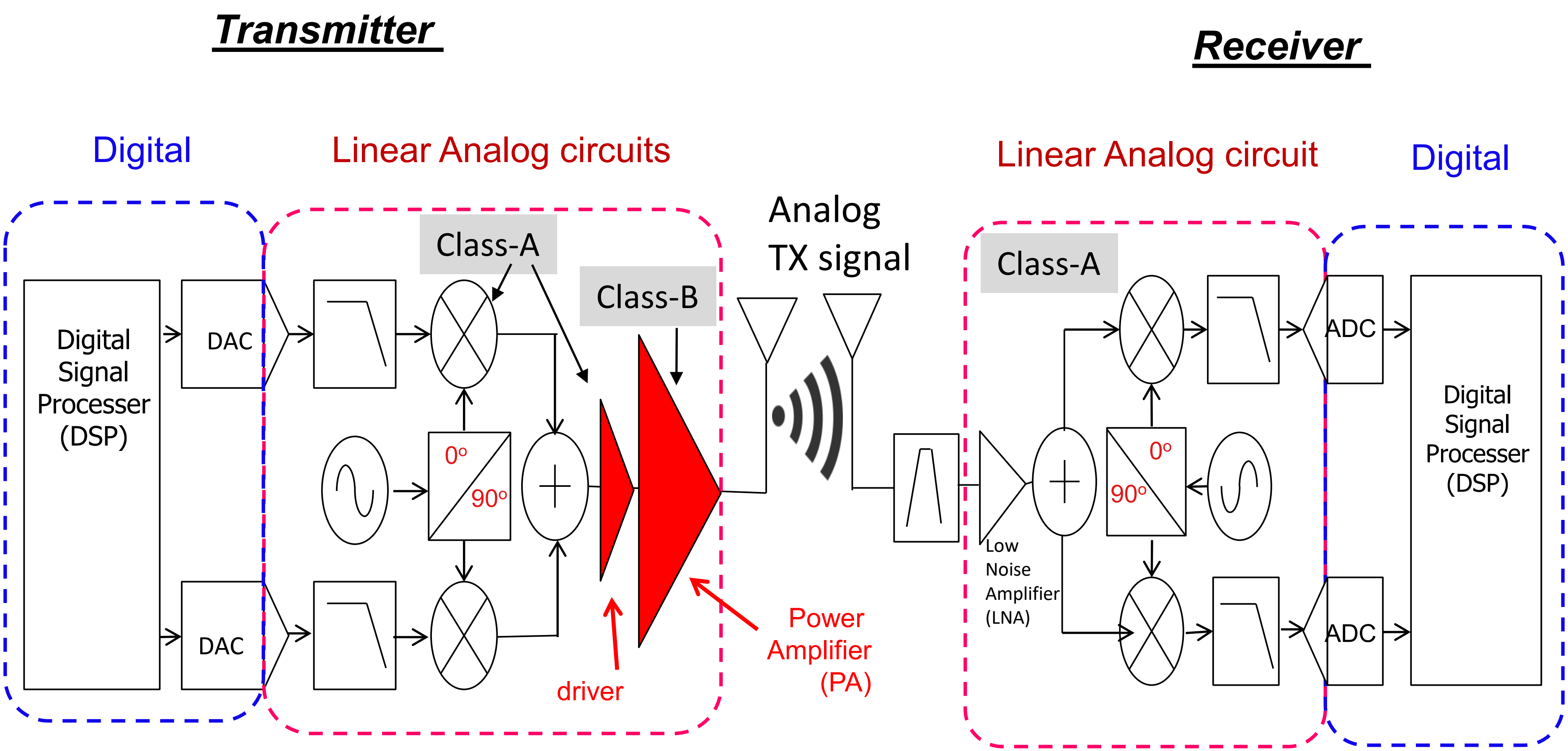
RF, Transmitters & Receivers

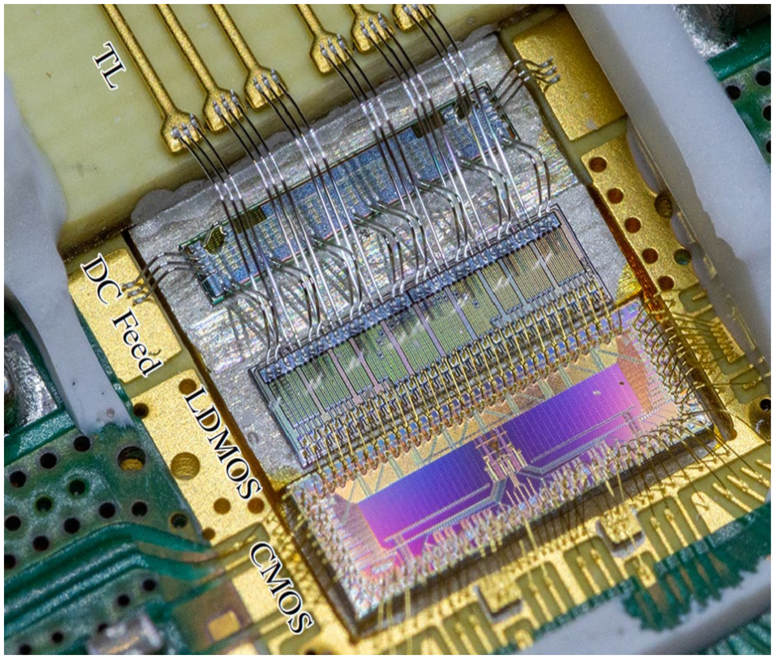


→ *Conventional "linear" Analog transceivers consume a lot of power!*

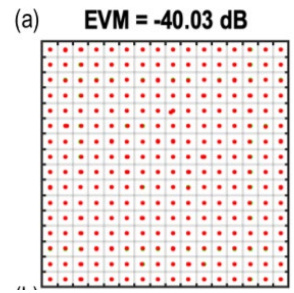
→ *But we can only broadcast and receive analog signals!!*

Some Recent ELCA Research Examples

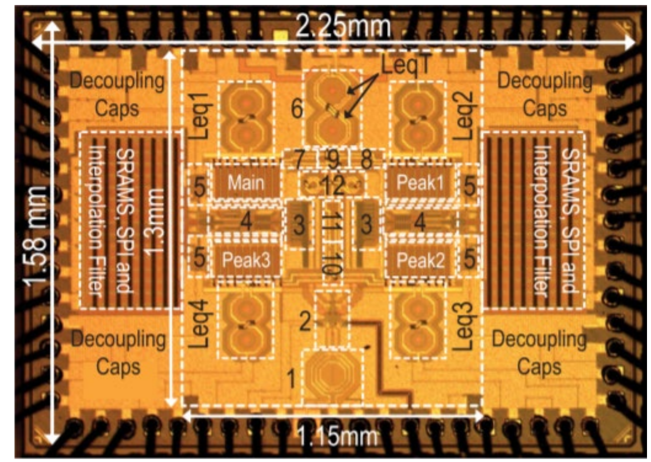
Digital intensive transmitter sub-6GHz



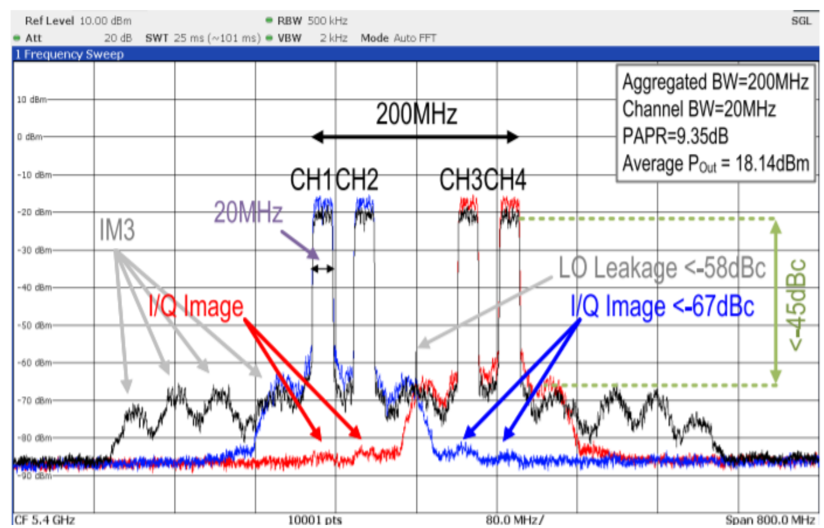
Constellation diagram



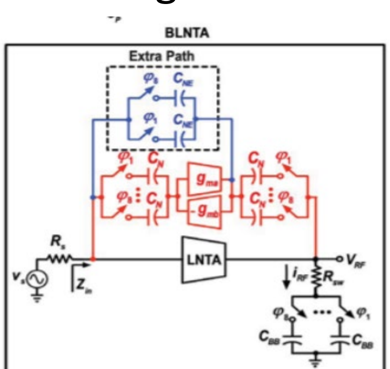
Four-way Integrated Doherty TX

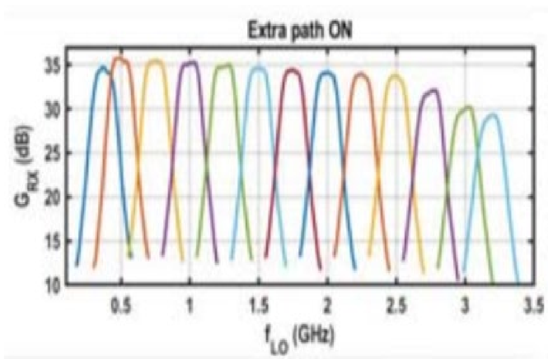


Spectral purity test



Reconfigurable blocker tolerant receiver (LNA)





- In this lecture we will restrict us to the more basic Examples of RF/mmwave design

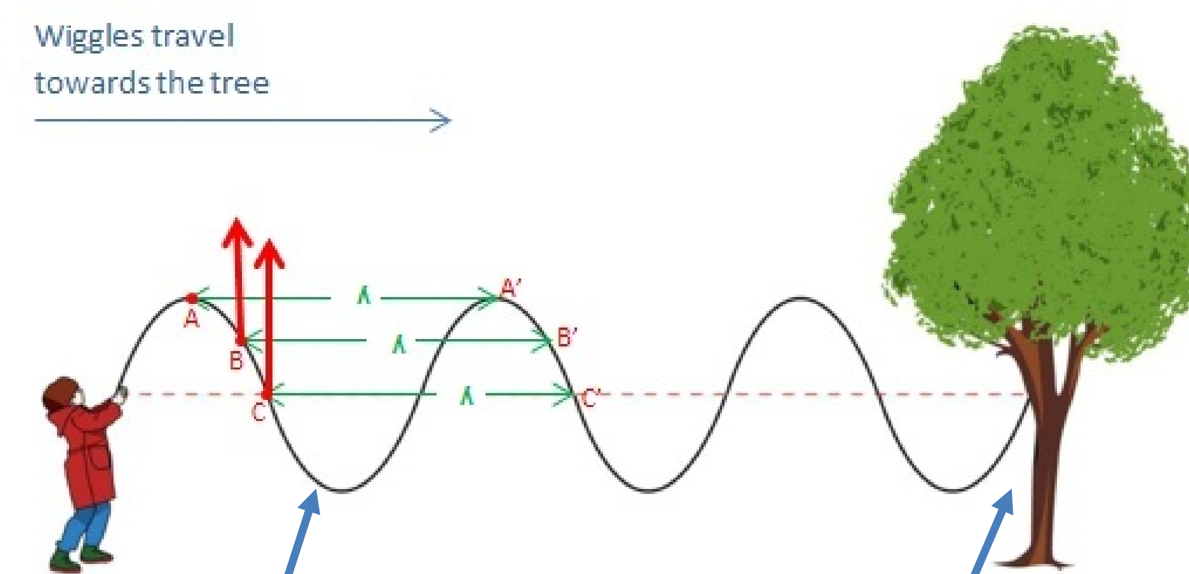
What is different at RF?

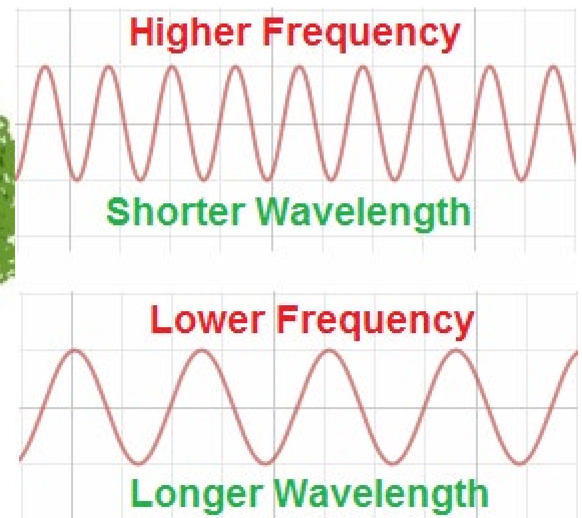
More extensive information on s-parameters, transmission lines, use of Smith chart and impedance matching is available in EE4C05 (See slides by Dr. Marco Spirito)

In this contribution to EE4C10, we gives some practical issues in RF design and give a first glip of what are the difference between analog and RF design

@RF: The wavelength is shrinking!

Let’s pop up the frequency!



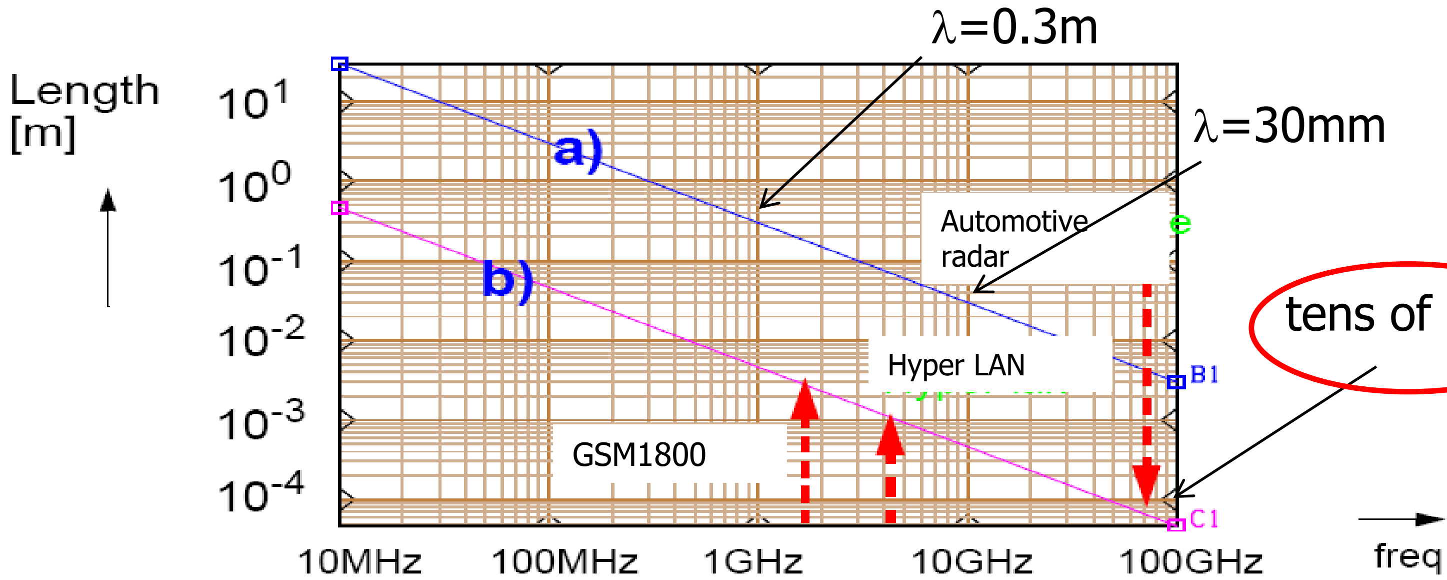


Here reflection of the wave will occur

Rope with given mass per unit length and applied tension

@RF: The wavelength is shrinking!

@RF circuit **connections are** no longer ideal nodes, nor "capacitive loaded nodes" in fact they are → **"transmission lines"**) .



Distances that you can no longer ignore!

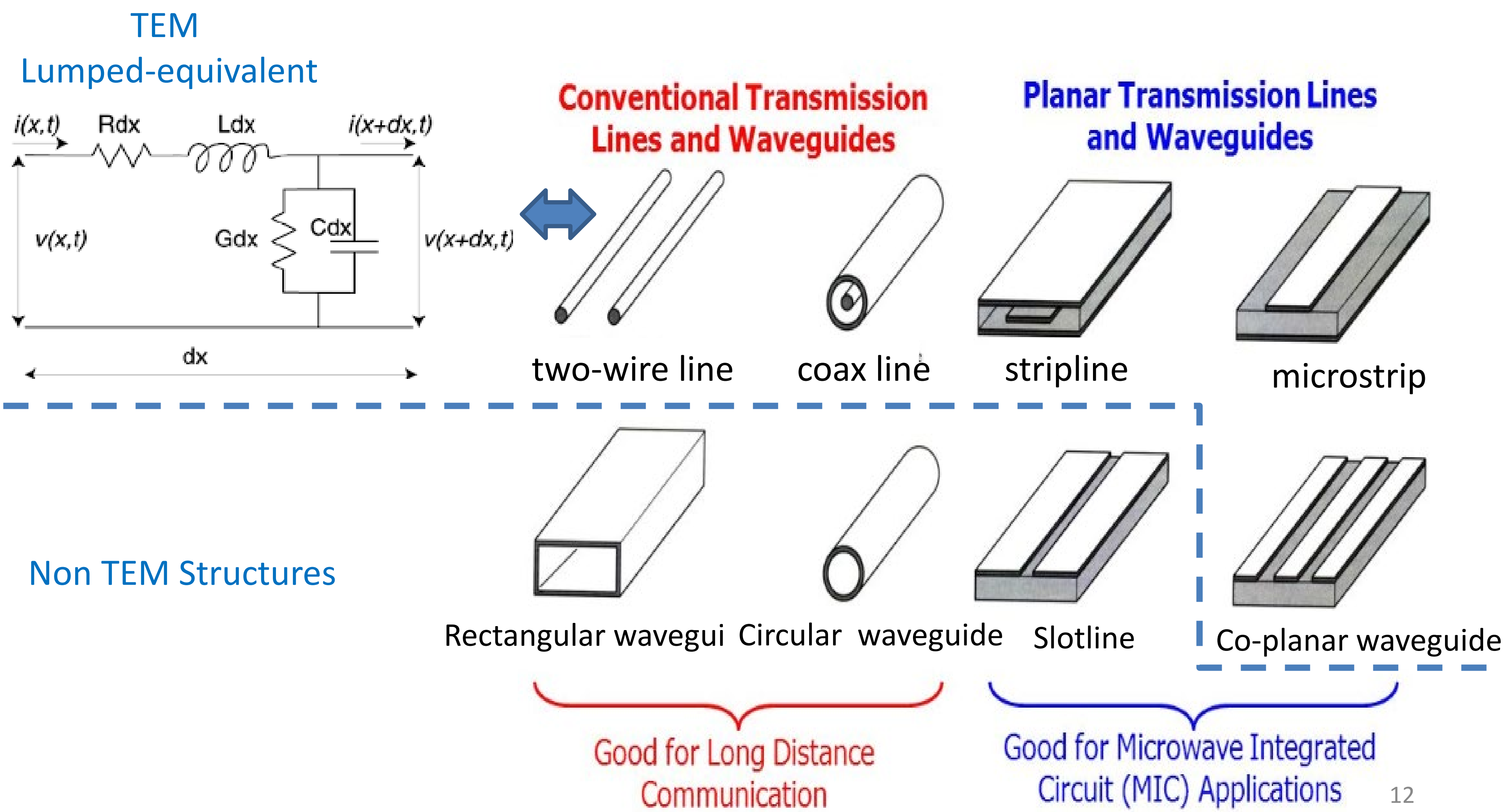
a) Wavelength as function of frequency in air

b) Significant connection length on substrates & ICs: $\left(\dfrac{\lambda_{air}}{10 \cdot \sqrt{\varepsilon_{r\ \mathrm{eff}}}}\right)$ ← *Rule of thumb*

At higher frequencies transmission lines can be used in designs due to their feasible dimensions!

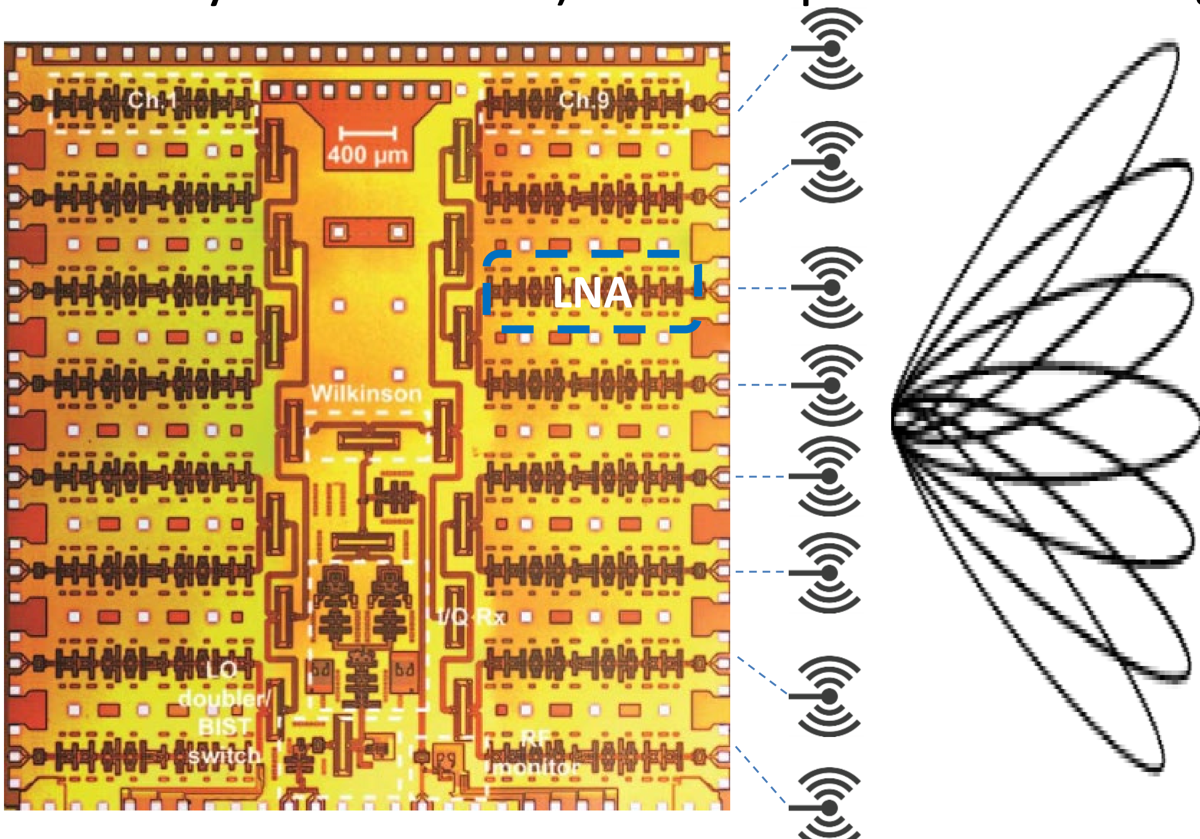
@RF: The wavelength is shrinking!

→Connections become “transmission lines”

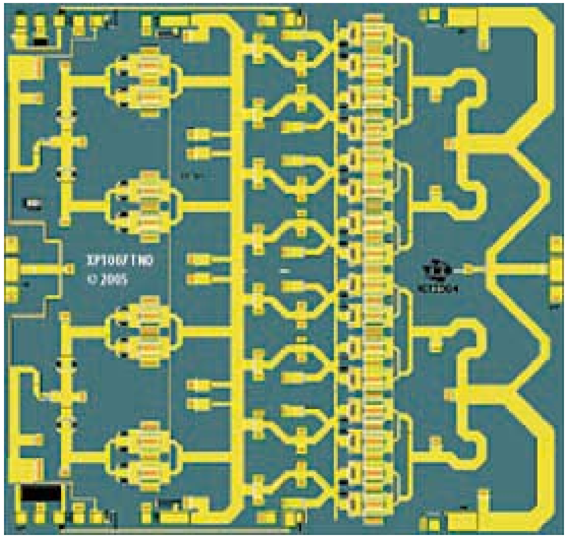


@RF: “The impact of a connection”

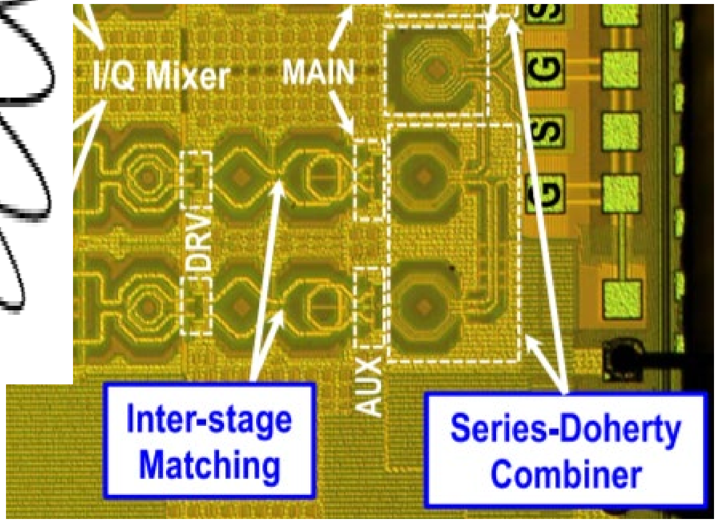
All connections matter! (they are no longer infinitely small nodes) and are part of the design



"A 77-81 GHz 16-Element Phased-Array Receiver with +/-50° Beam Scanning (SiGe, 5.5 X 5.8 mm^2) **(UCSD)**

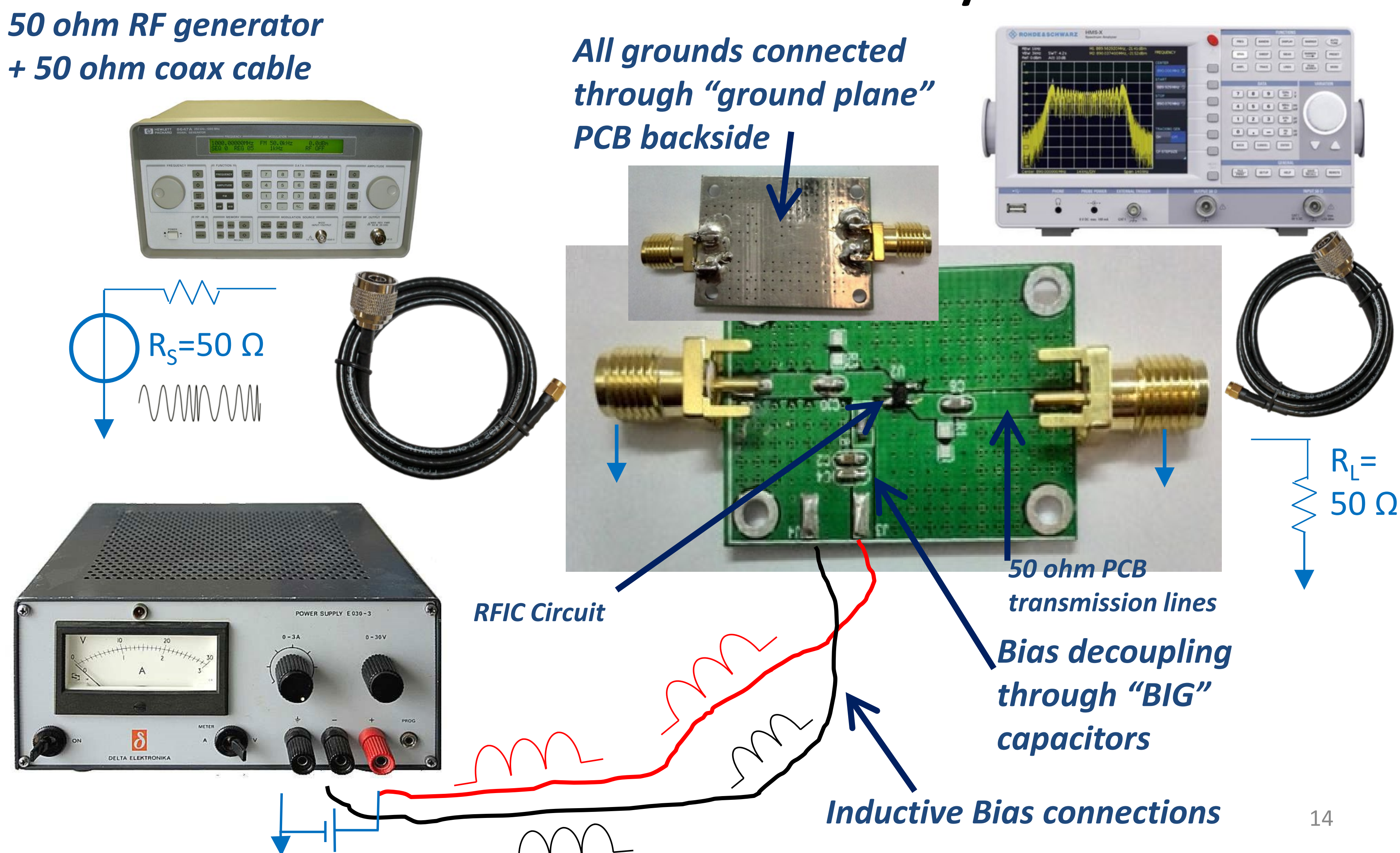


8.7 To 10.7 GHz GaAs MMIC



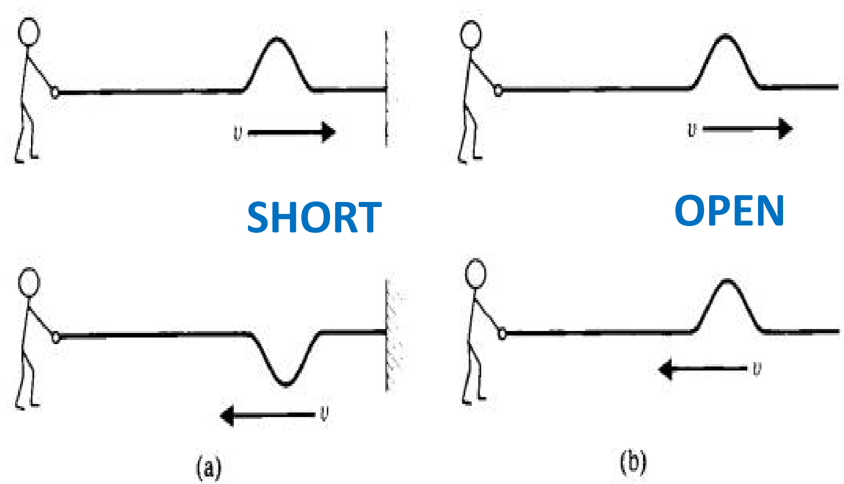
Integrated mm-wave TX **(TU Delft)**

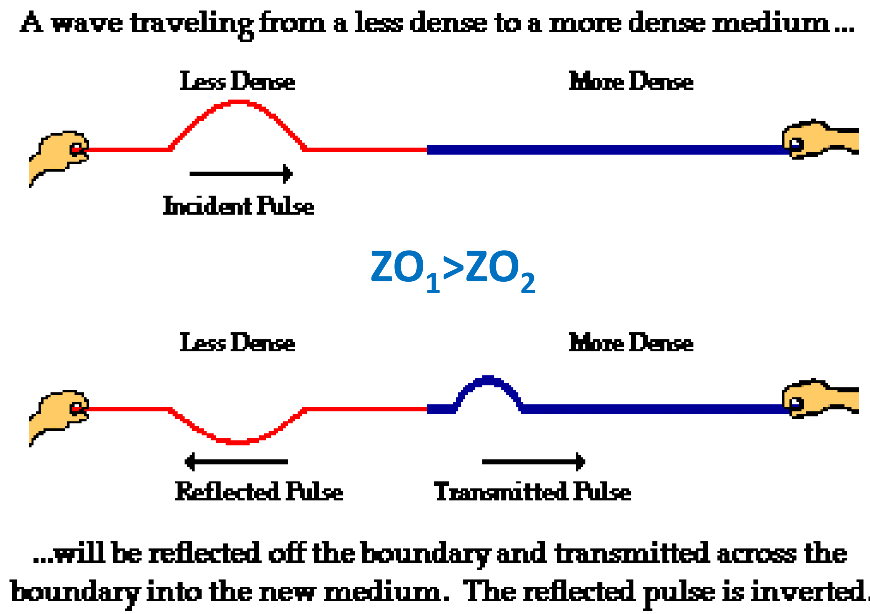
@RF: Ideal current and Voltage sources do not exist anymore!



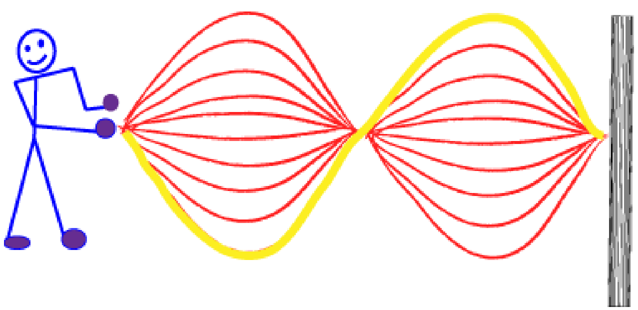
@RF: Why using a characteristic "system" impedance?

- Reflections of waves occur when going to another "impedance" level





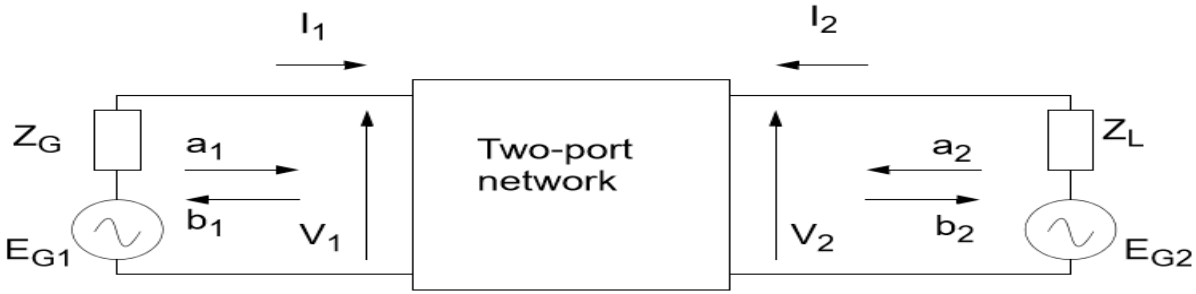
$ZO_1 > ZO_2$



Reflection results in standing waves → signal transfer becomes depended on distance/location

(Maximum power transfer only happens under (conjugate) **matched conditions**!)

Black-box Descriptions (Refresh)



- Admittance notation

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

→ Links port-voltages to port-currents

- Chain or ABCD notation

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}$$

→ Links output-port voltage and current to input-port

- Chain matrix of a loss-less transmission line

$$\begin{bmatrix} u_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A_{TL} & B_{TL} \\ C_{TL} & D_{TL} \end{bmatrix} \begin{bmatrix} u_2 \\ i_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & jZ_o \sin\theta \\ \frac{j}{Z_o}\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_2 \\ i_2 \end{bmatrix}$$

In which:

- *θ= electrical length*
- *Z_o =characteristic impedance*

@RF: Signal transfer described by ratio’s of normalized “power” waves

a_n = incident normalized wave
b_n = emanating normalized wave

“local” voltage & current:

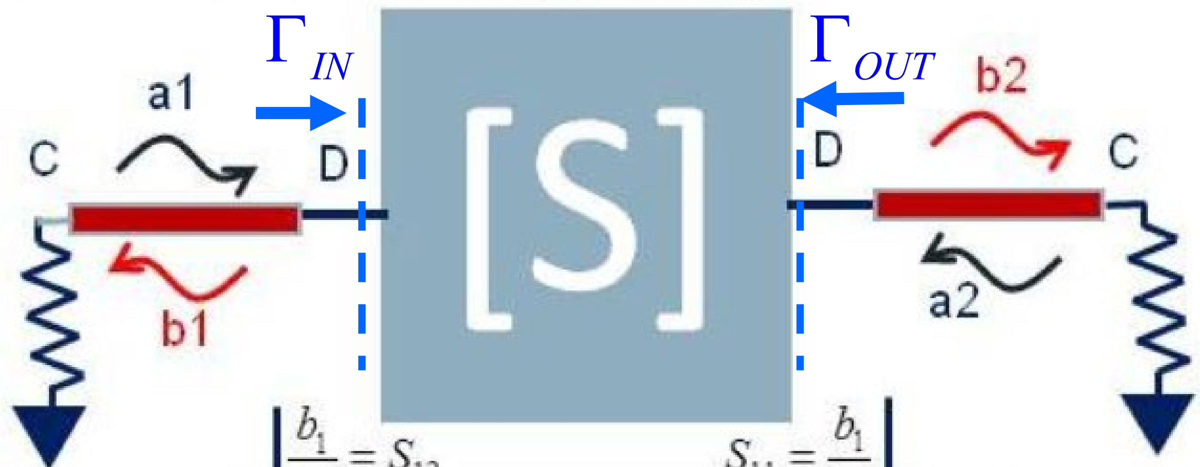
$$V_n = \sqrt{Z_0}.(a_n + b_n)$$
$$I_n = \frac{1}{\sqrt{Z_0}}.(a_n + b_n)$$

Related s-parameter definition:

$$b_1 = S_{11} \cdot a_1 + s_{12} \cdot a_2$$
$$b_2 = S_{21} \cdot a_1 + s_{22} \cdot a_2$$

$$a = \frac{V^+}{\sqrt{Zc}} \quad b = \frac{V^-}{\sqrt{Zc}}$$

$$b = \Gamma \cdot a$$



$$a_1 = 0 \left| \frac{b_1}{a_2} = S_{12} \right.$$

$$S_{11} = \frac{b_1}{a_1} \right|_{a_2 = 0}$$

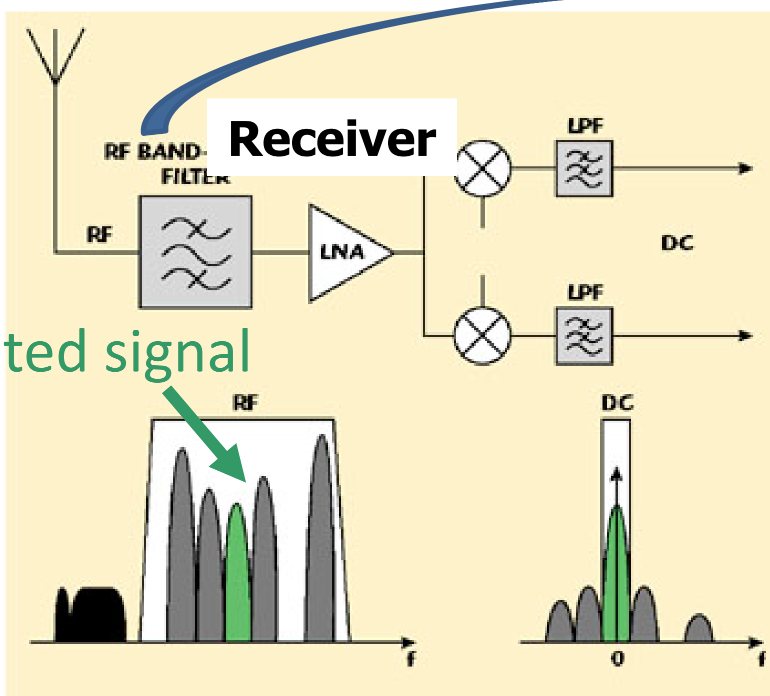
$$a_1 = 0 \left| \frac{b_2}{a_2} = S_{22} \right.$$

$$S_{21} = \frac{b_2}{a_1} \right|_{a_2 = 0}$$

@RF: Use of matched conditions!

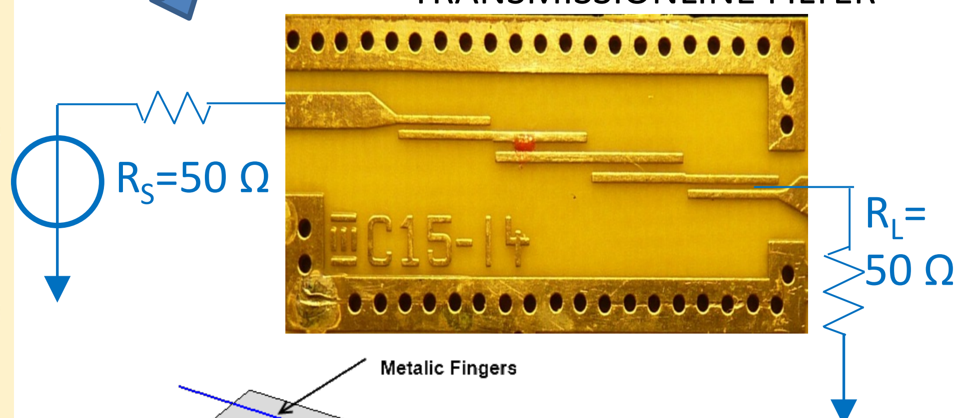
- Matched conditions are needed to; transfer power, make connections predictable and allow filters, antennas, circulators and hybrids to operate correctly

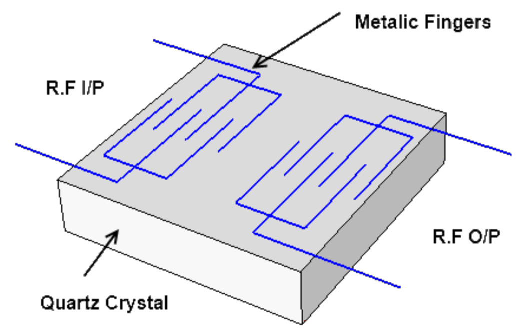
So circuit blocks need to provide correct impedances (e.g. to the filters)



Example channel selection in a direct conversion receiver

TRANSMISSIONLINE FILTER

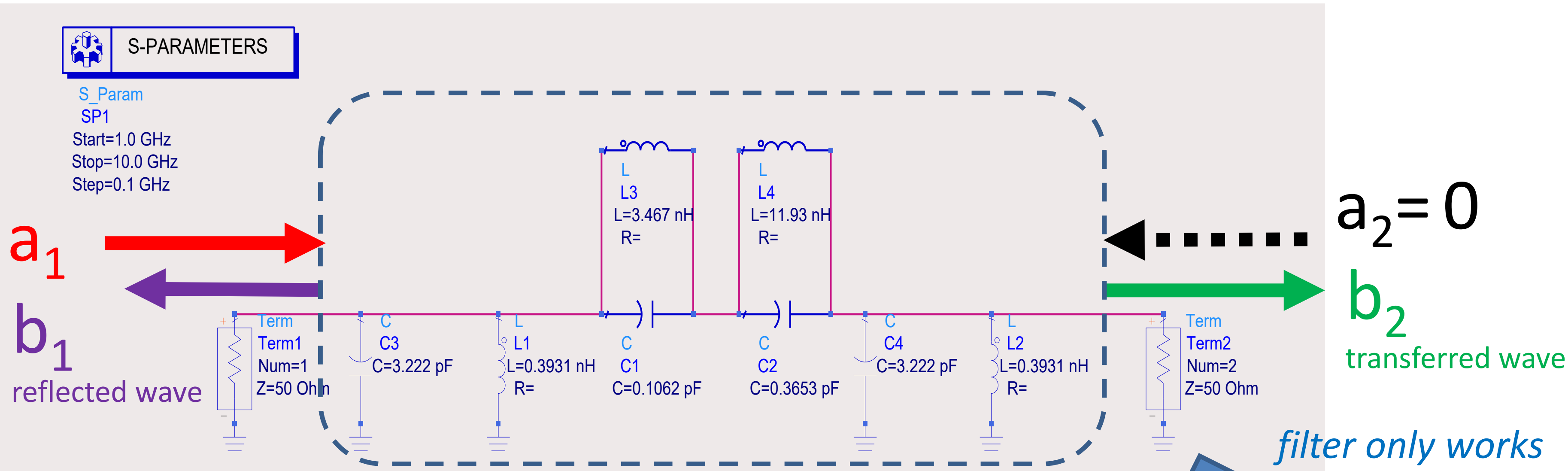




SAW FILTER

GAIN and FREQUENCY SELECTIVITY IS NEEDED in wireless!!!

@RF: Matched Conditions, Band-pass Filter



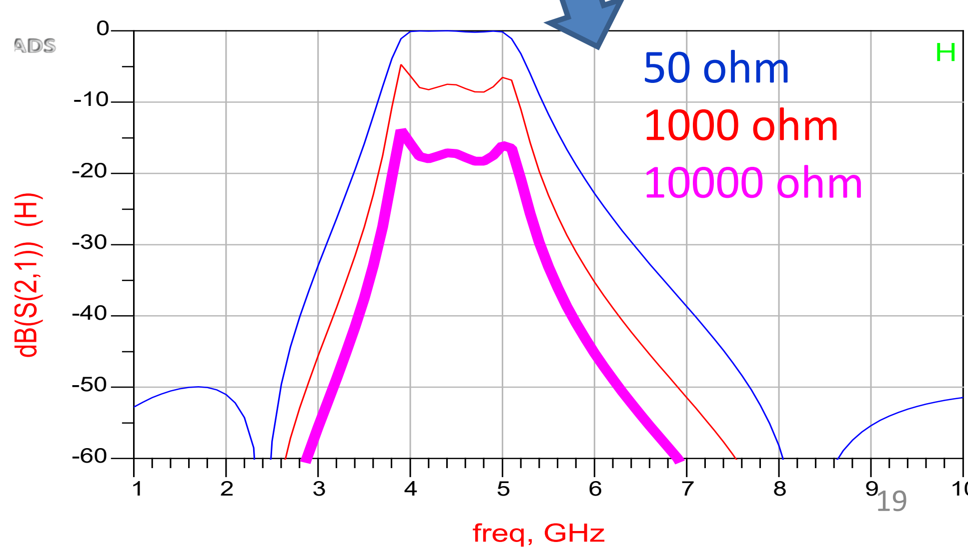
filter only works well with 50 ohm terminations

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0}$$

ratio of transferred normalized "power" waves

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0}$$

ratio of reflected normalized "power" waves



@RF: Matching questions (1),

Question (2) Why do we used impedance matched conditions in RF?
(select the correct statements)

1. To maximize power transfer
2. To avoid reflections
3. To lower the noise
4. To save chip area
5. Current mode design does not work at RF
6. To lower the impact of non-linear distortion
7. To Improve efficiency

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4. To save chip area
5. Current mode design does not work at RF
6. To lower the impact of non-linear distortion
7. To Improve efficiency

True!

Not true!

True!

@RF: Matching questions (2),

Question (3) Why do we use in RF 50 ohm as matching condition?
(select the correct statements)

1. 50 ohm allows us to transfer the highest RF power through a coax cable
2. Antennas simply offer this impedance at their connector due to the free space impedance
3. A characteristic impedance of 50ohm gives us the lowest loss for a coax cable
4. It is was simply set to 50 ohm by a standardization committee

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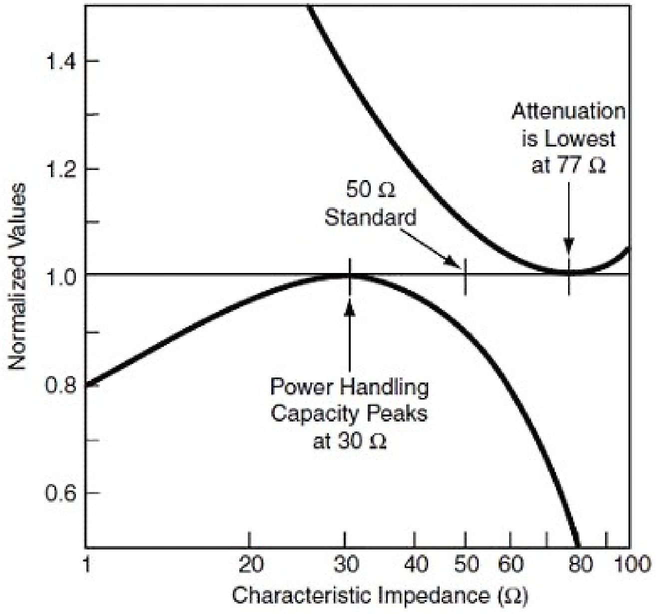
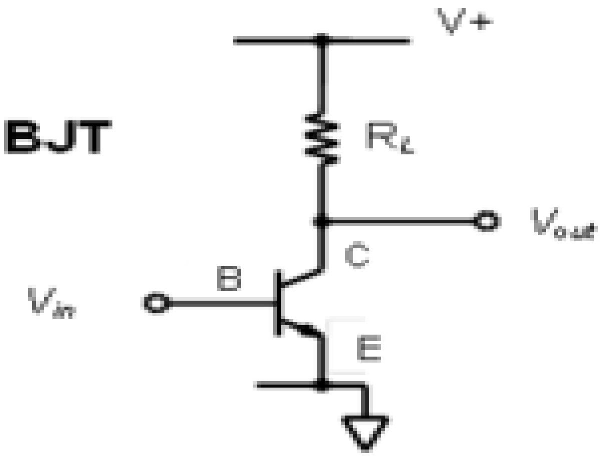
(Taken from Marco Spirito's slides)

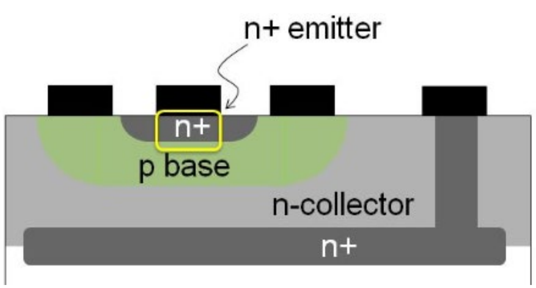


RF Components

- Active Devices
  - FETs, BJT
- Passive Components
  - Resistors
  - Inductors
  - Capacitors
  - Transmission lines

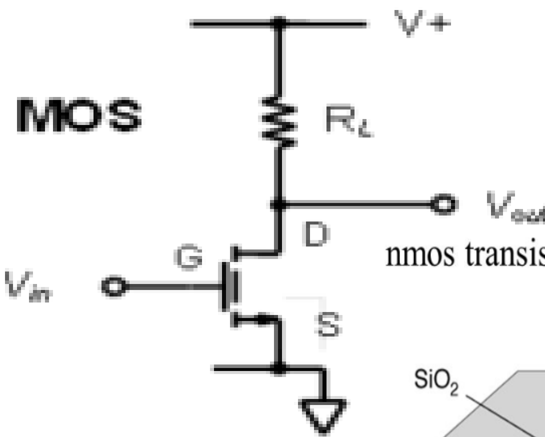
@RF: Providing Gain or Power takes Energy!



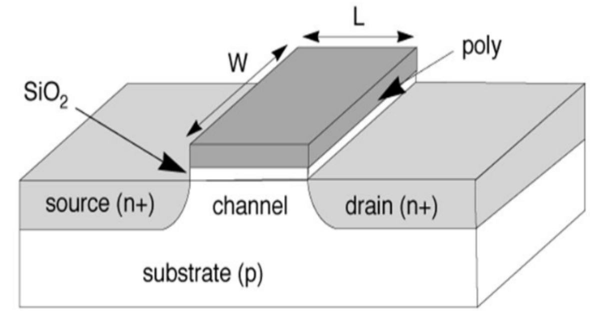


$$I_c = I_s\left(e^{\frac{V_{be}}{V_T}} - 1\right)$$

$$gm = \frac{\partial I_c}{\partial V_{be}} \approx \frac{I_c}{V_T} \approx 40.I_c$$



nmos transistor:



$$I_D = \mu_n C_{ox}.\frac{W}{2.L}(V_{gs} - V_T)^2 \Rightarrow g_m = \mu_n C_{ox}\frac{W}{L}(V_{gs} - V_t)$$

Long channel device: $gm = \dfrac{\partial I_d}{\partial V_{gs}} \approx \sqrt{2\mu_n C_{ox}\dfrac{W}{L}.I_D}$

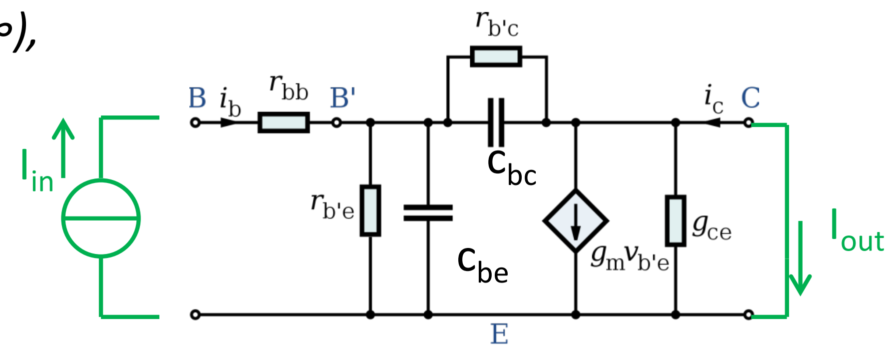
Short channel device:

$$gm = \frac{\partial I_d}{\partial V_{gs}} \approx \frac{\partial\left(\mu_n C_{ox}\frac{W}{2}(V_{gs} - V_t)E_{sat}\right)}{\partial V_{gs}} \approx \frac{\mu_n C_{ox} W.E_{sat}}{2}$$

Device Performance at high frequencies

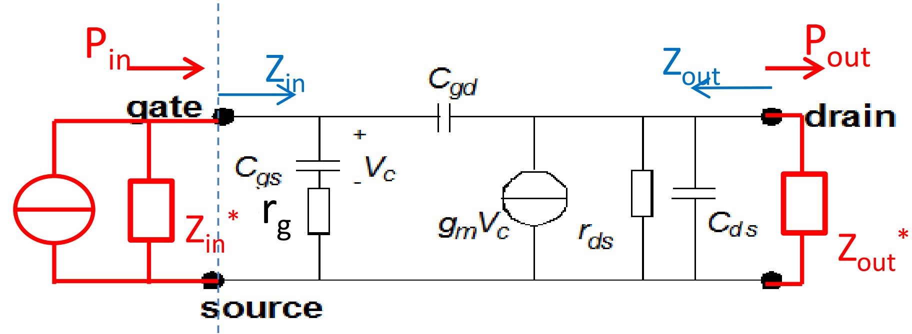
- **f_T** → frequency where current gain becomes unity
  (Not so realistic circuit condition, but very simple)
  - *High ohmic source ($Z_S = \infty$),*
  - *Low-ohmic load ($Z_L \sim 0$)*

f_T condition BJT device

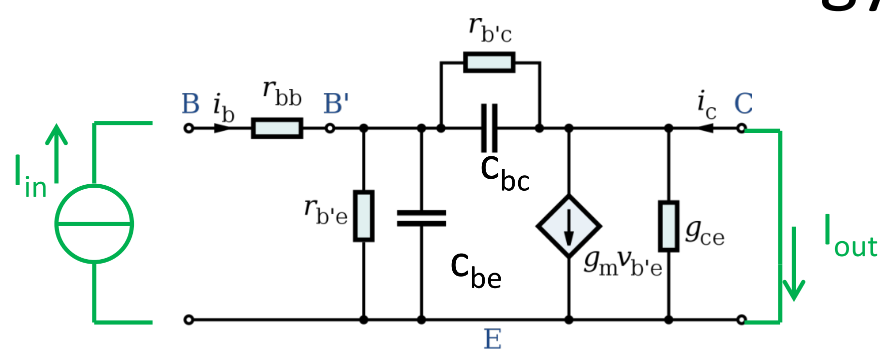


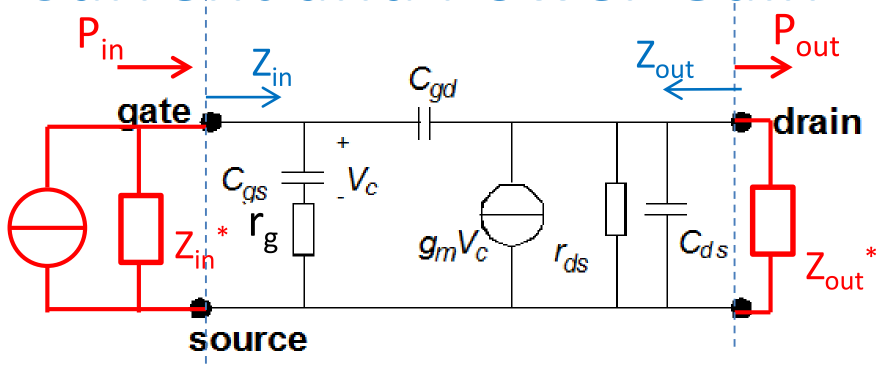
- **f_{Max}** → frequency where power gain becomes unity
  (Also highest frequency of oscillation, more useful)
  - *Assumes conjugate matched conditions*
  - *Contains information on feedback element & Ohmic losses in input*

f_{Max} condition FET device



@RF: Providing Gain or Power at higher frequencies takes even more Energy!, Current and Power Gain





Strongly simplified equivalent circuit BJT "Configured" for current-gain testing

Strongly simplified equivalent circuit FET Configured for power-gain testing

ω_T or f_T = (rad.) freq,. @ which **current gain ($|h_{21}|$ =1)**

$$\omega_T = \frac{g_m}{(c_{be} + c_{cb})}$$

With: $c_{be} \approx A_e.2.C_{je} + g_m.\tau_F$

$$c_{bc} \approx A_e.C_{jc}$$

C_{je}=zero bias depletion base-emitter capacitance per unit area
C_{jc}=zero bias depletion base-collector capacitance per unit area
A_e = effective area multiplication factor

$$\omega_T = \frac{g_m}{(c_{gs} + c_{gd})}$$

With (in saturation):

$$c_{gs} \approx (2/3).W.L.C_{ox} + W.C_{ov}$$
$$c_{gd} \approx W.C_{ov}$$

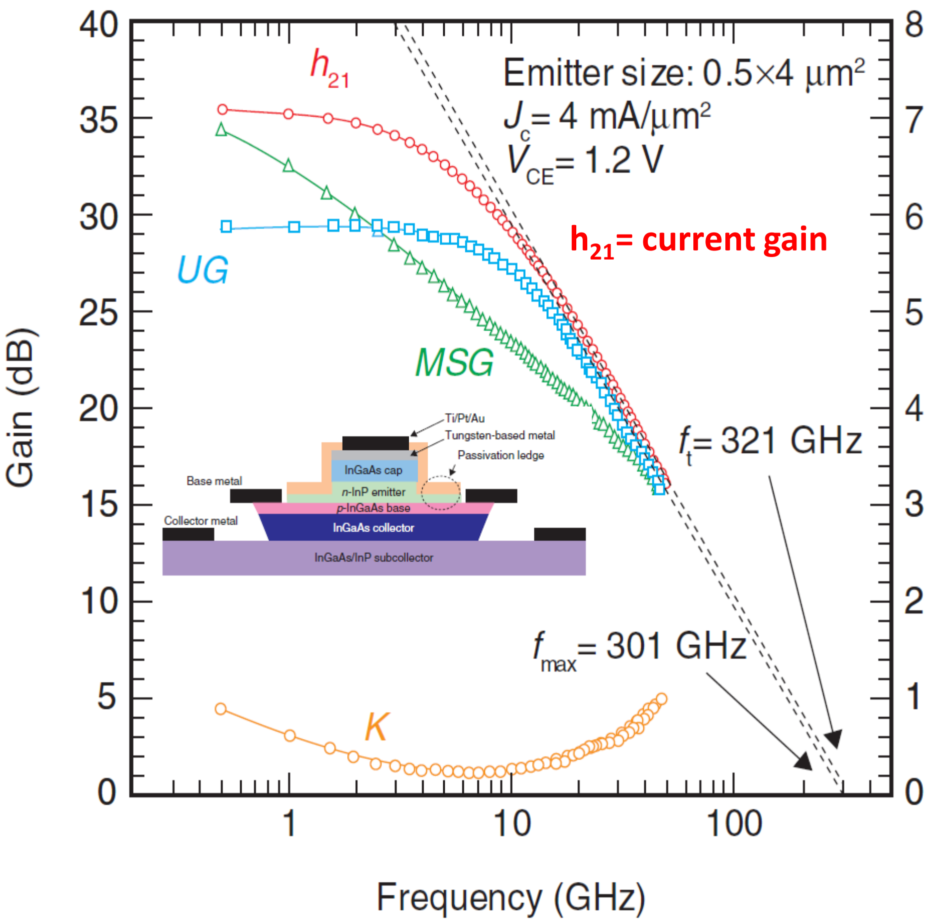
C_{ox}=oxide capacitance per m² area (saturation)
C_{ov}= overlap capacitance per m gate length (saturation)

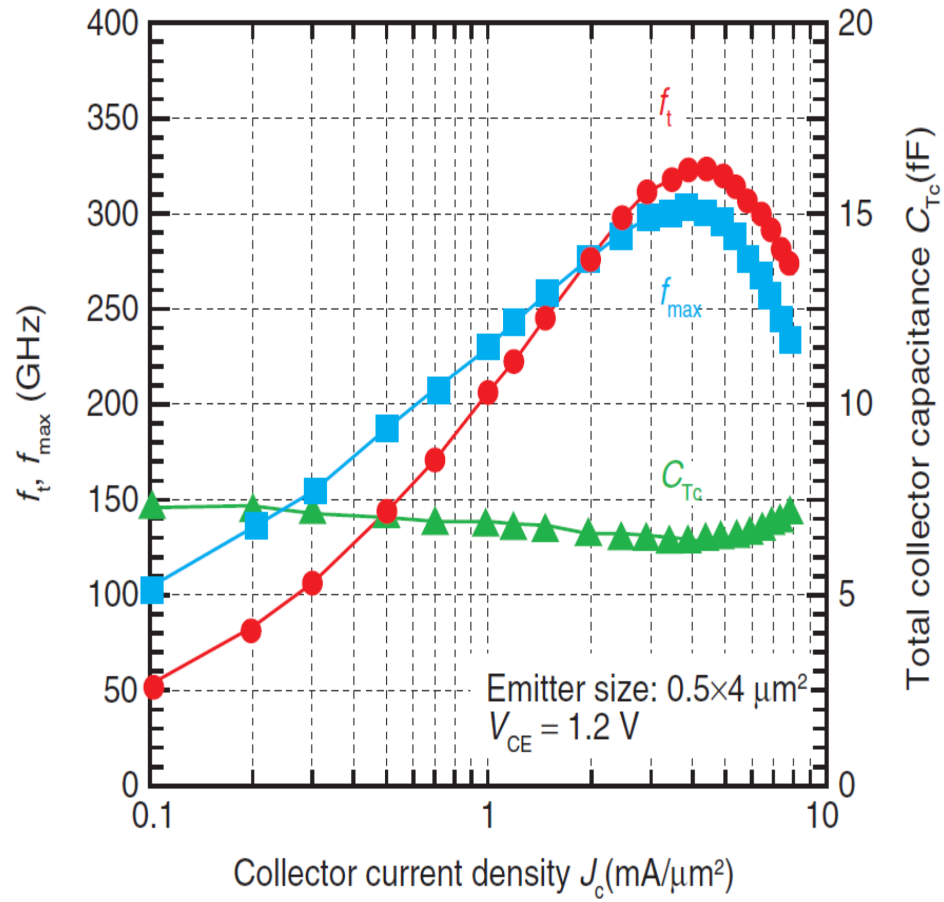
ω_{Max} or f_{Max} = (rad) freq,. @ which **power gain =1:**

$$\omega_{max} = \frac{1}{2}\sqrt{\frac{\omega_T}{r_b c_{bc}}}$$

$$\omega_{max} = \frac{1}{2}\sqrt{\frac{\omega_T}{r_g c_{gd}}}$$

@RF: Providing Gain or Power at higher frequencies takes even more Energy!, "Gains" InP HBT transistor

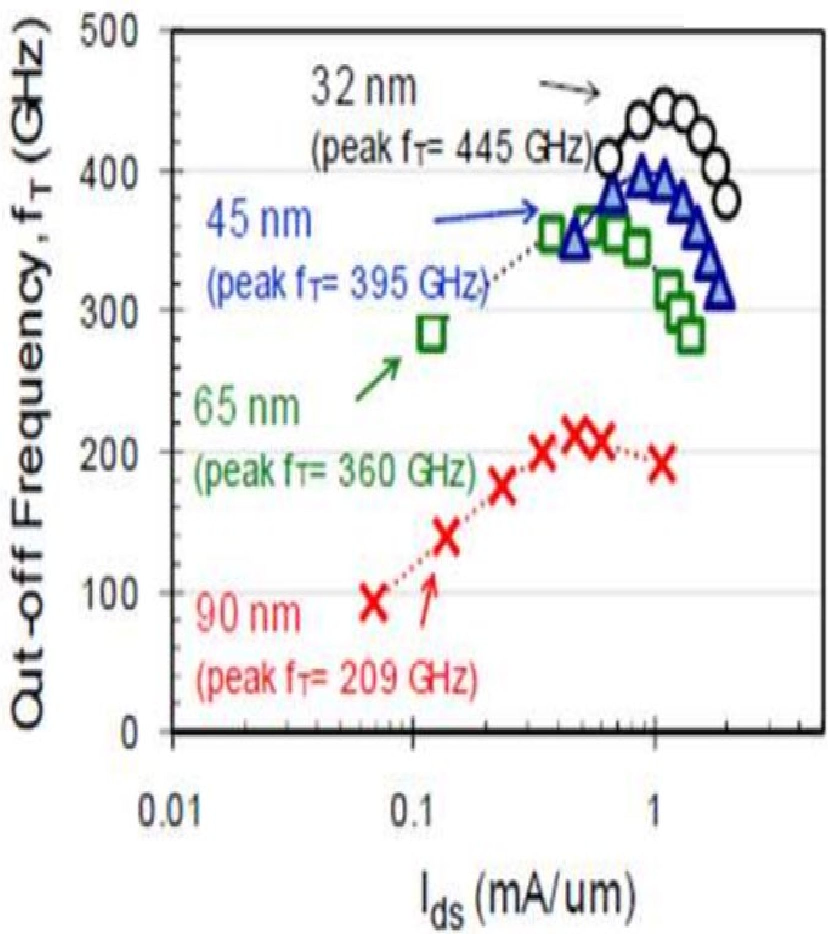




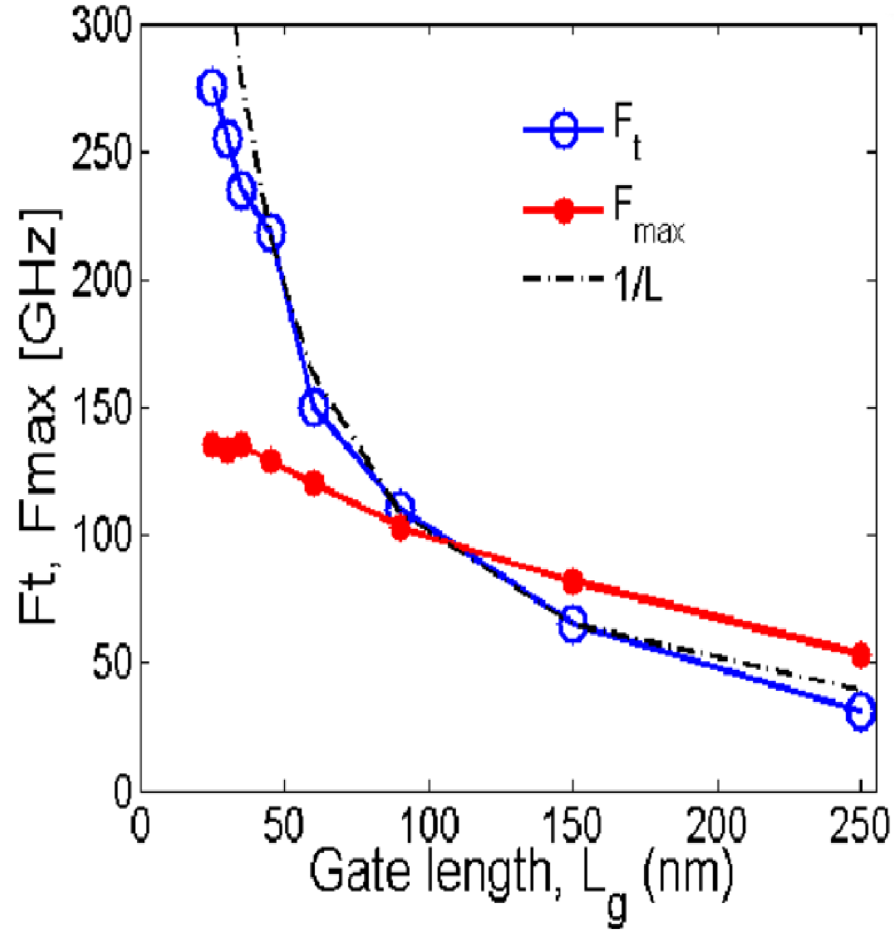
- Gain roll-off vs. frequency,
  at higher freq. there is simply less gain!

- High f_T and f_{max} requires high currents!

f_T and f_{Max} NMOS devices



f_T (NMOS) vs. current density



f_T and f_{Max} vs. gate length SOI tech.

Why are CMOS devices so popular?

Question (4) Why are CMOS devices so popular?
(select the correct statements)

1. They provide the highest gain at RF
2. They offer the highest output impedance at RF for a given power level
3. They provide the best switch like performance
4. They do not require an input current
5. They offer the lowest noise in a practical RF circuit

Why are CMOS devices so popular?

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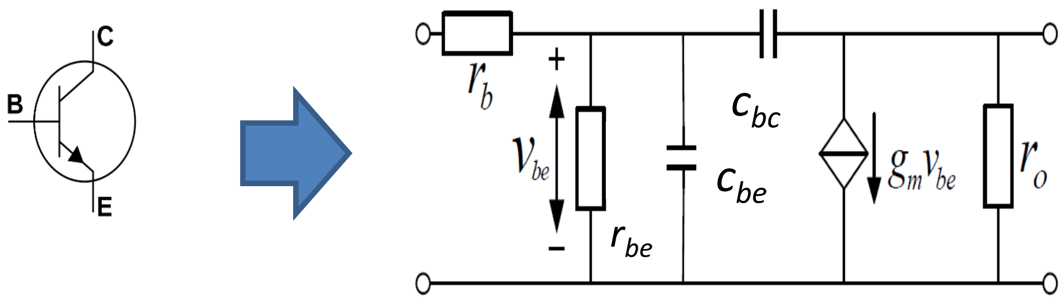
True

Active Devices and their (simple) black-box description



(Similar considerations hold for FET devices)

$$[ABCD]_{BJT}=\begin{bmatrix}1 & r_b\\ 0 & 1\end{bmatrix}\cdot\frac{1}{sc_{bc}-g_m}\cdot\begin{bmatrix} sc_{bc}+g_o & 1\\ g_m\left(\frac{sc_{bc}+g_o}{\beta}+sc_{bc}\right)+\left(sc_{bc}+g_o\right)\left(sc_{bc}+sc_{be}\right)-s^2c_{bc}c_{be} & \frac{g_m}{\beta}+sc_{bc}+sc_{be}\end{bmatrix}$$

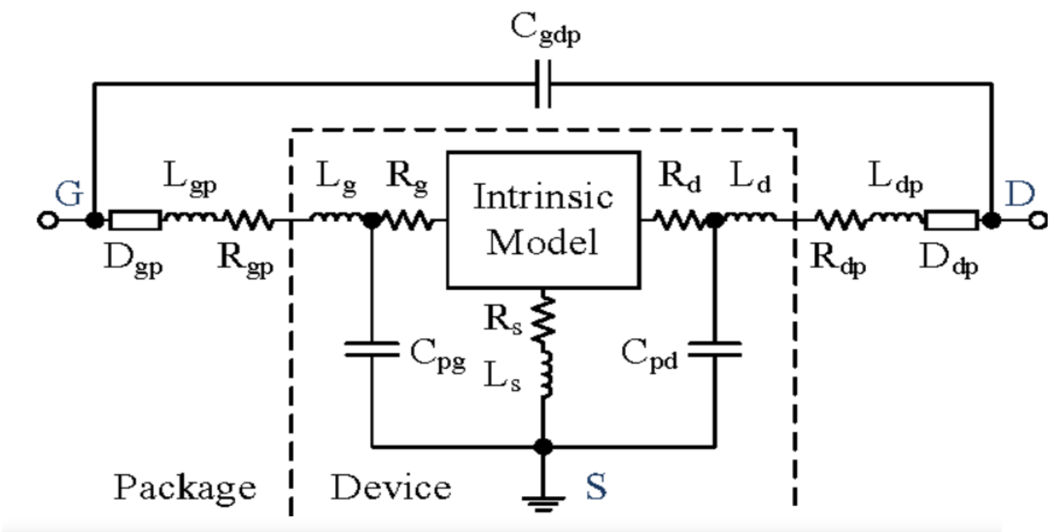
When $s.c_{bc}$~0, this expression simplifies to: $$[ABCD]_{BJT}=\begin{bmatrix}1 & r_b\\ 0 & 1\end{bmatrix}\cdot\frac{-1}{g_m}\cdot\begin{bmatrix} g_o & 1\\ g_o\left(\frac{g_m}{\beta}+sc_{be}\right) & \frac{g_m}{\beta}+sc_{be}\end{bmatrix}$$

When g_m is large *(and β is large (e.g. 100) and g_o is small)*, this expression simplifies to:

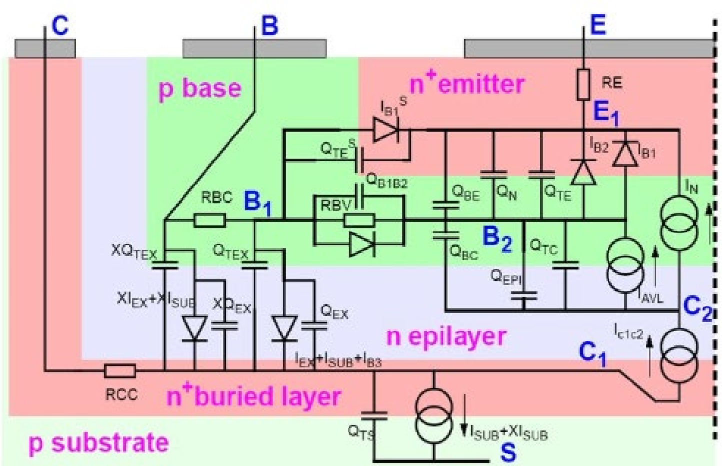
$$[ABCD]_{BJT}=\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix}$$

Null-or approximation!
In analog design

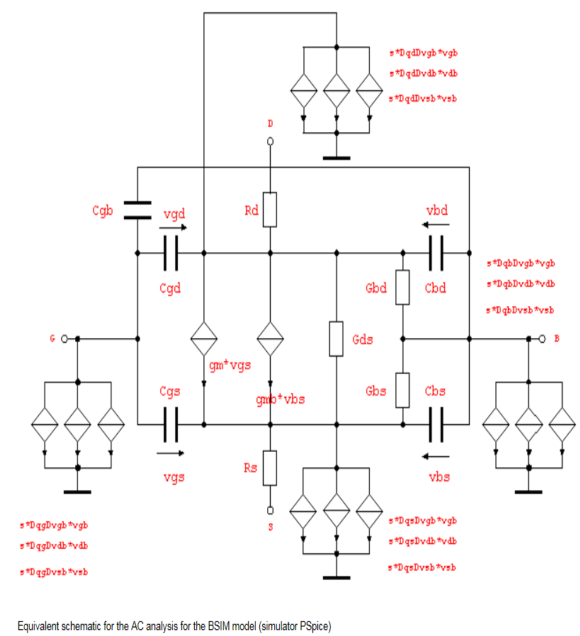
@RF: It is a bit more complicated!



RF uses dedicated design techniques to handle the increased complexity
→ Taught in RF Design track!

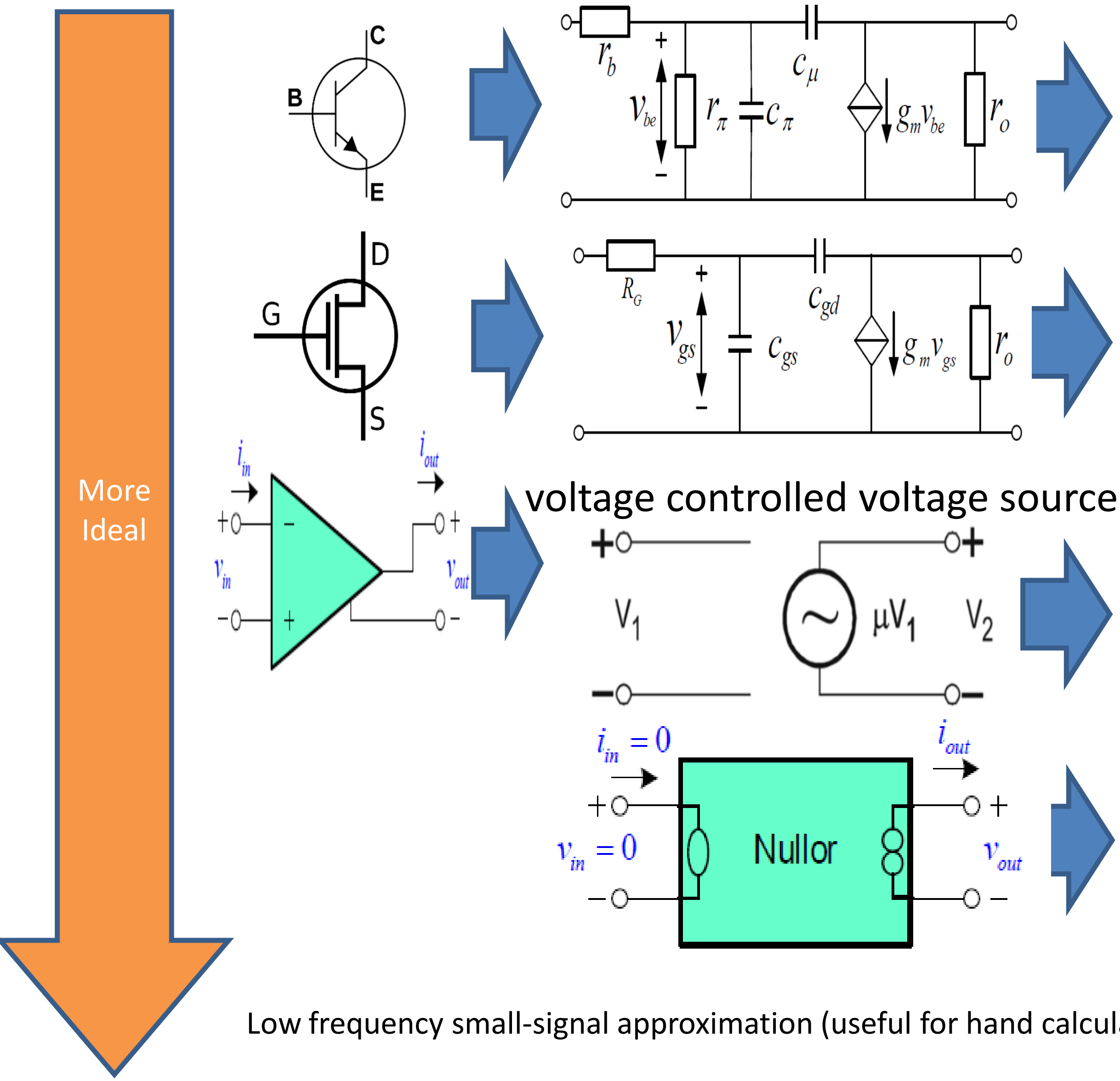


Mextram (Bipolar) Large signal Model



BSMIM 3 (FET) AC equivalent model

(Active) Devices and Their Simplest Small-Signal Black-Box Description



$$[ABCD]_{BJT}$$

$$[ABCD]_{FET}$$

$$[ABCD] = \begin{bmatrix} \frac{1}{\mu} & 0 \\ 0 & 0 \end{bmatrix}$$

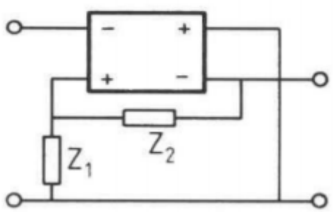
$$\begin{pmatrix} v_{in} \\ i_{in} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v_{out} \\ i_{out} \end{pmatrix}$$

Low frequency small-signal approximation (useful for hand calculations and conceptual considerations)

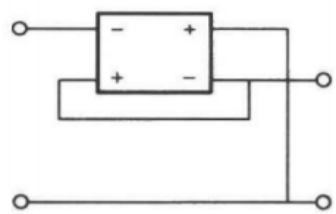
Defining Transfer Functions, Analog Way

- "single loop" feedback topologies

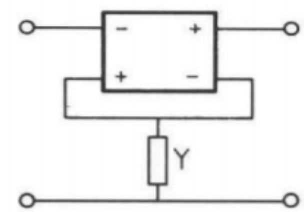
Single-loop amplifiers with zero or infinite input and output impedances



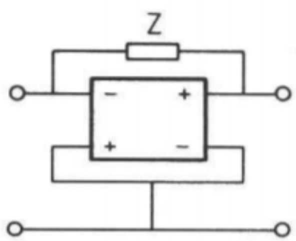
a. $\mu = +(1+Z_2/Z_1)$
(voltage amplifier)



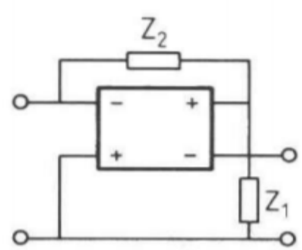
b. special case: $\mu = 1$
(voltage follower)



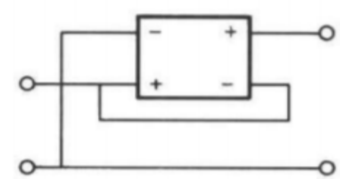
c. $\gamma = -Y$
(transadmittance amplifier)



d. $\zeta = -Z$
(transimpedance amplifier)



e. $\alpha = +(1+Z_2/Z_1)$
(current amplifier)



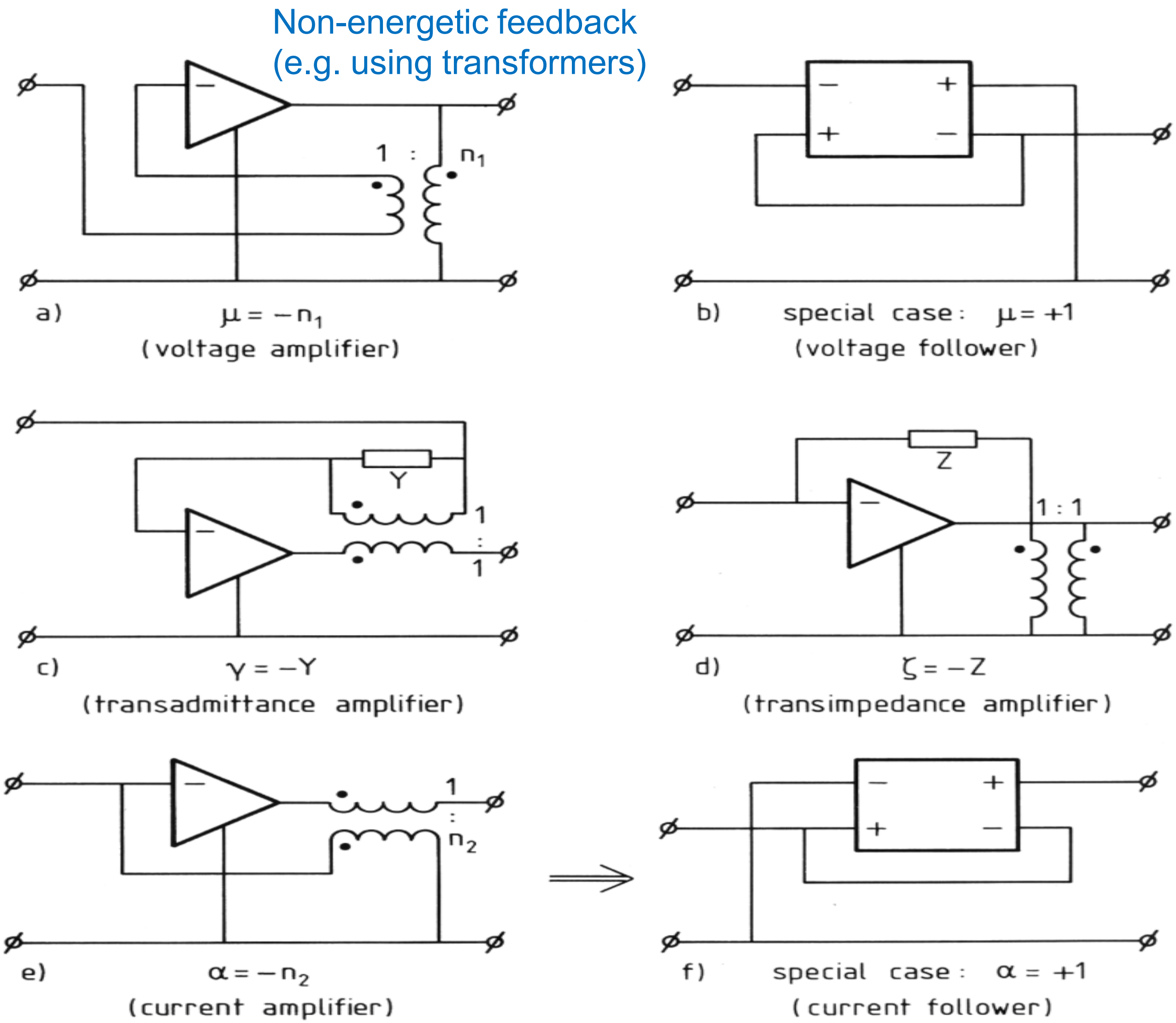
f. special case: $\alpha = +1$
(current follower)

With:

$$\mu = \frac{1}{A} = \left(\frac{u_o}{u_i}\right)_{i_o=0}, \quad \gamma = \frac{1}{B} = \left(\frac{i_o}{u_i}\right)_{u_o=0}, \quad \zeta = \frac{1}{C} = \left(\frac{u_o}{i_i}\right)_{i_o=0}, \quad \alpha = \frac{1}{D} = \left(\frac{i_o}{i_i}\right)_{u_o=0},$$

From "The design of high-performance negative feedback amplifiers", by Ernst Nordholt

Defining Transfer Functions, Analog Way



Single-loop amplifiers with zero or infinite input and output impedances

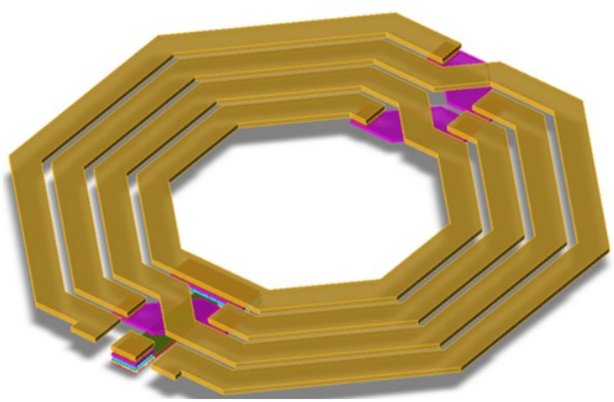
(Taken from "The design of high-performance negative feedback amplifiers", by Ernst Nordholt)

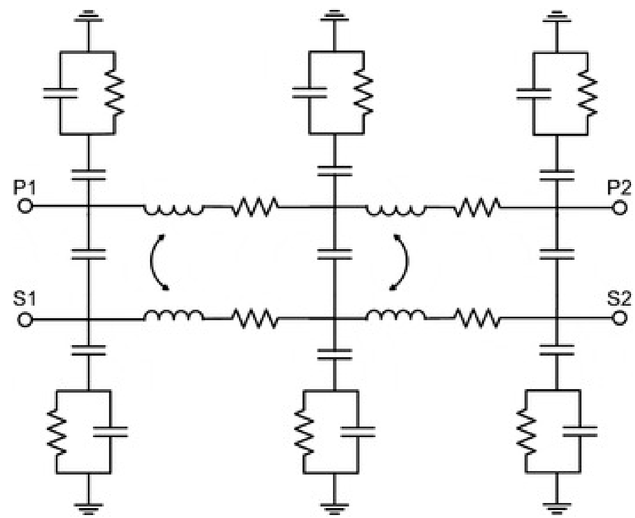
With:

$$\mu = \frac{1}{A} = \left(\frac{u_o}{u_i}\right)_{i_o=0}, \quad \gamma = \frac{1}{B} = \left(\frac{i_o}{u_i}\right)_{u_o=0}, \quad \zeta = \frac{1}{C} = \left(\frac{u_o}{i_i}\right)_{i_o=0}, \quad \alpha = \frac{1}{D} = \left(\frac{i_o}{i_i}\right)_{u_o=0},$$

Transformer feedback (The reality)

- Transformers as feedback element works very well in simulation but are in practice **BIG & lossy,** have **limited turn ratios, poor coupling (k<1)** → far-from-ideal)



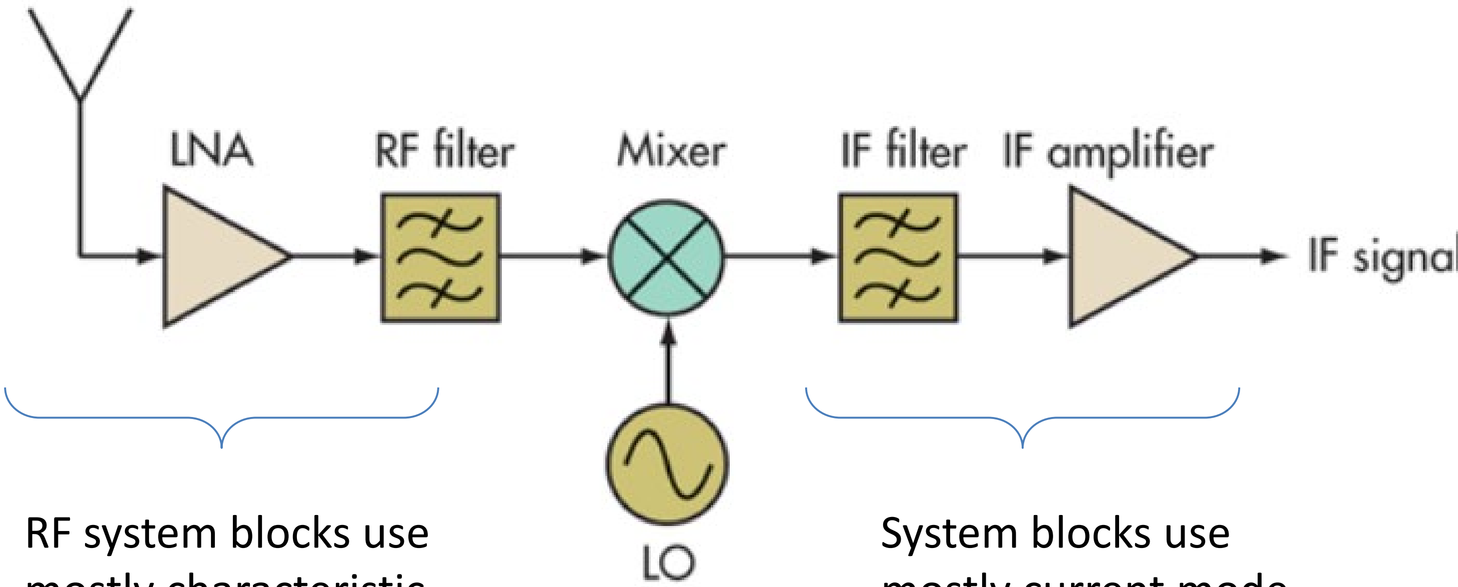


Strongly simplified equivalent “transformer” schematic

- Inductors (L) and capacitors (C) are much simpler to use as feedback but makes the circuit transfer strongly frequency dependent.

- *@RF transformers are used for (on chip) oscillators, baluns etc. inductive coupling etc..*

Defining Transfer Functions, RF way



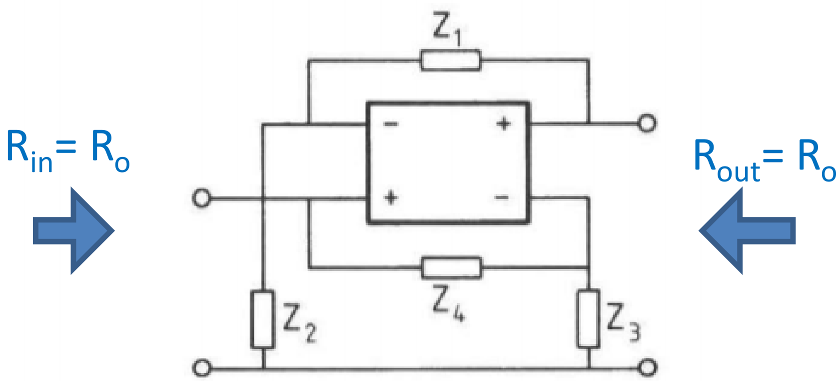
RF system blocks use mostly characteristic impedances

System blocks use mostly current mode connections to limit voltage swings (→ improved linearity)

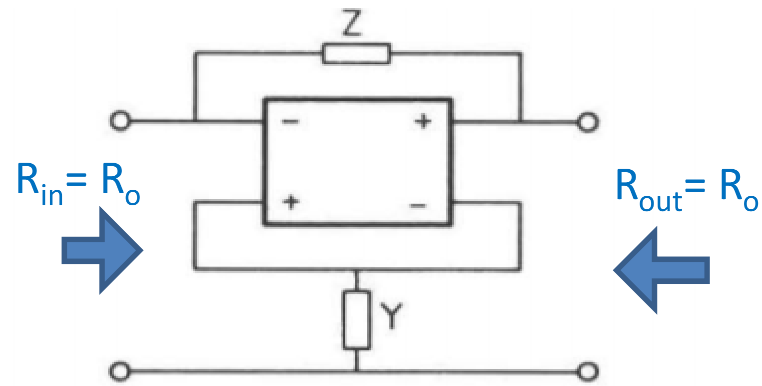
→ How to do <u>impedance matching</u>, achieve good <u>noise</u> and <u>linearity</u> performance in these RF system blocks?

Defining Transfer Functions, Analog Way

- Dual-loop feedback topologies with resistors, for "power-to-power" **impedance matched** applications with well defined "characteristic" impedance levels at in and output.



$$\mu = (Z_2+Z_1)/Z_2, \quad \gamma = \infty$$
$$\zeta = (Z_1+Z_2)(Z_3+Z_4)/(Z_2+Z_3),$$
$$\alpha = (Z_3+Z_4)/Z_3$$



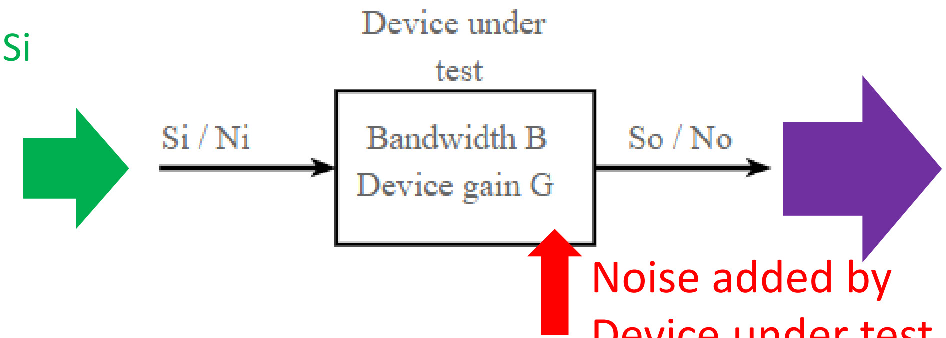
$$\mu = 1 - YZ, \quad \gamma = (1-YZ)/Z$$
$$\zeta = (1-YZ)/Y, \quad \alpha = 1 - YZ$$

Exercise, proof that the condition for a characteristic impedance match is: $\dfrac{Z}{Y} = R_o^2$

Note that; Z, Y, can be ohmic but also complex

The Noise Figure “F”

(Desired) input signal, Si
(Undesired) noise, Ni



(Desired) output signal, So
(Undesired) output noise, No

Noise added by Device under test

- For circuits with well defined input and out impedances, <u>the noise Figure</u> gives the ratio of the: *“signal-to-noise ratio at the input”* vs. *“signal-to-noise ratio at the output”,*

$$F = \frac{P_{Si} / P_{Ni}}{P_{So} / P_{No}} \Leftrightarrow F = \frac{P_{Ni\_source} + P_{N\_network\_input\_refered}}{P_{Ni\_source}}$$

$In\ which:$

Si is the input signal power

Ni is the input noise power

So is the output signal power

No is the output noise power

More about the noise figure F in the RF design track

→ The noise figure is used to specify the noise performance of LNAs, Mixers etc.

Design example, an "RF" LNA based on Analog (1) and RF design techniques (2)

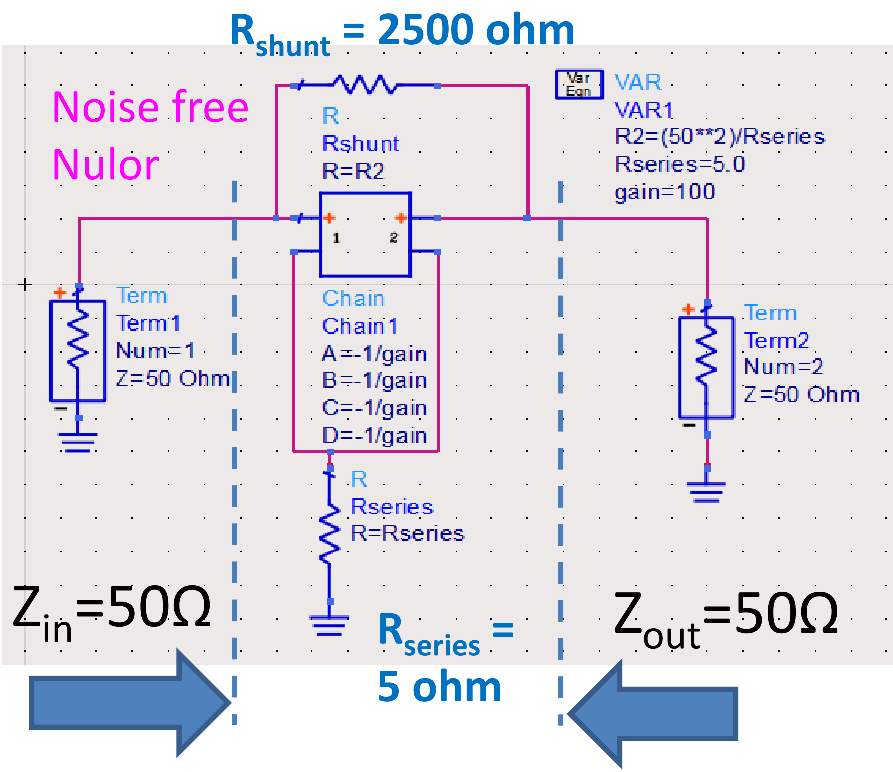
Issues to address are: Gain, noise,
DC power/current needed, matching and **Stability**!

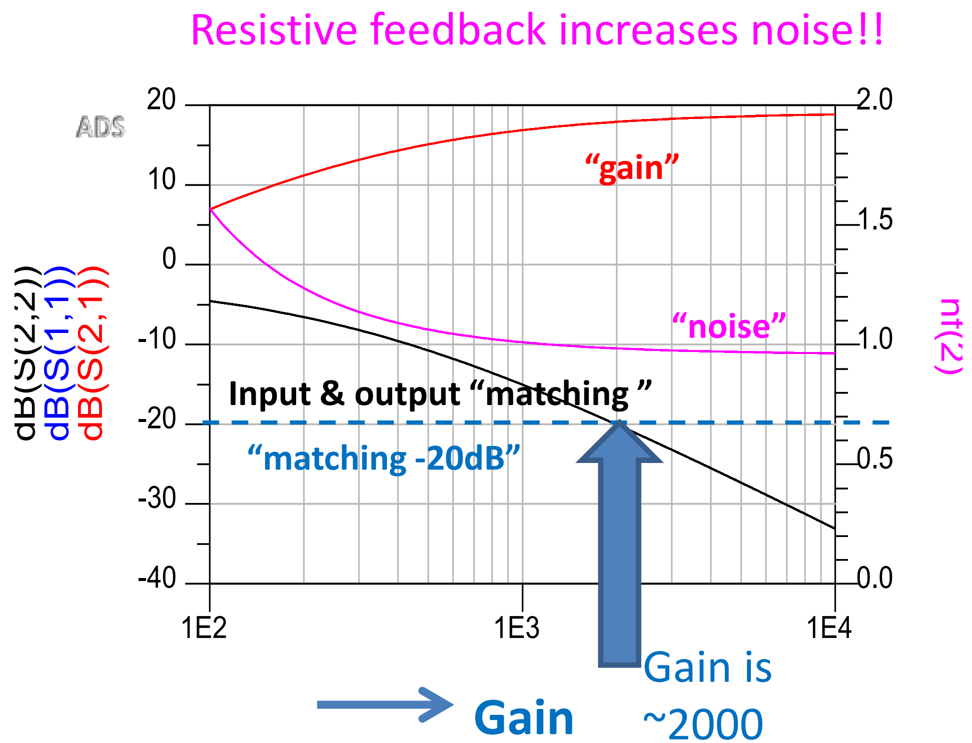
Aim LNA;

- Design freq. (f_{design})= 2GHz
- "Gain" @f_{design} S_{21} = 20dB of
- 50 ohm input
  ("Matching" S_{11}~S_{22} better than -20 dB @f_{design})
- Noise Figure F below 1.5 dB
- Technology bipolar transistor (f_T= ~ 30 GHz)

Analog design methods used **@RF**, "How much (loop) gain is needed?"

- Example power-to-power amplifier with resistive feedback, provides matched input and output (50 ohm)



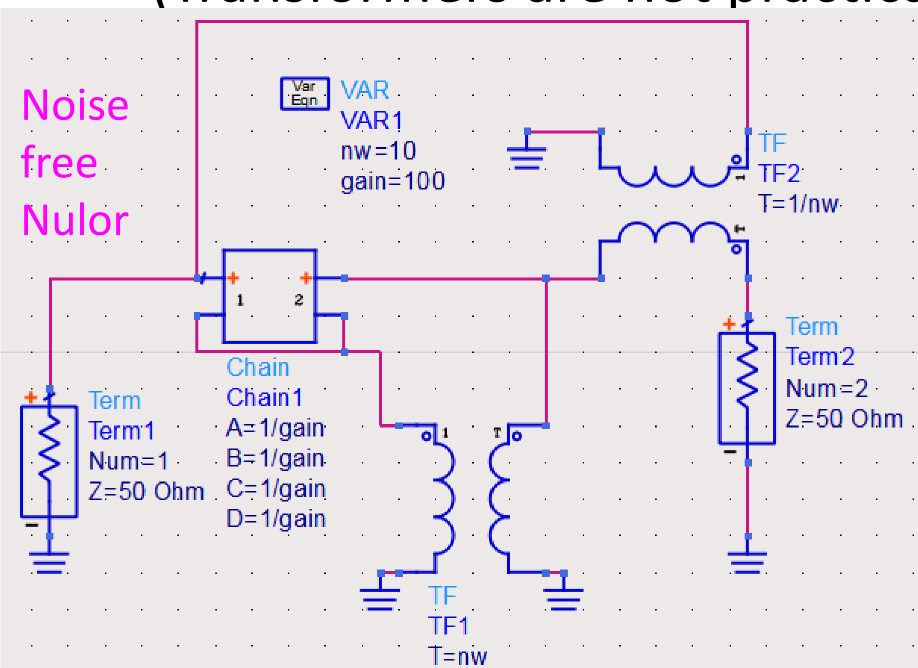


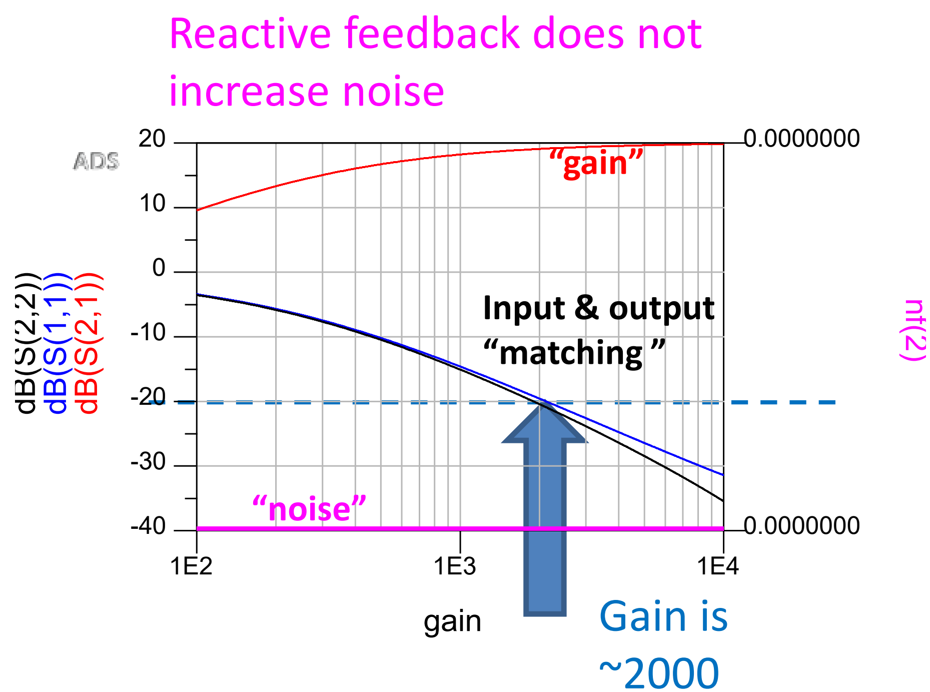
All transfer gains set equal (voltage, current, transimpedance, transconductance) **A=B=C=D=1/gain**

Question (open question) Why does the noise reduces with increasing gain?

Analog design methods used **@RF**, "How much (loop) gain is needed?"

- Example power-to-power amplifier with transformer feedback, provides matched input and output (50 ohm). (Transformers are not practical at low freq. → better @RF)





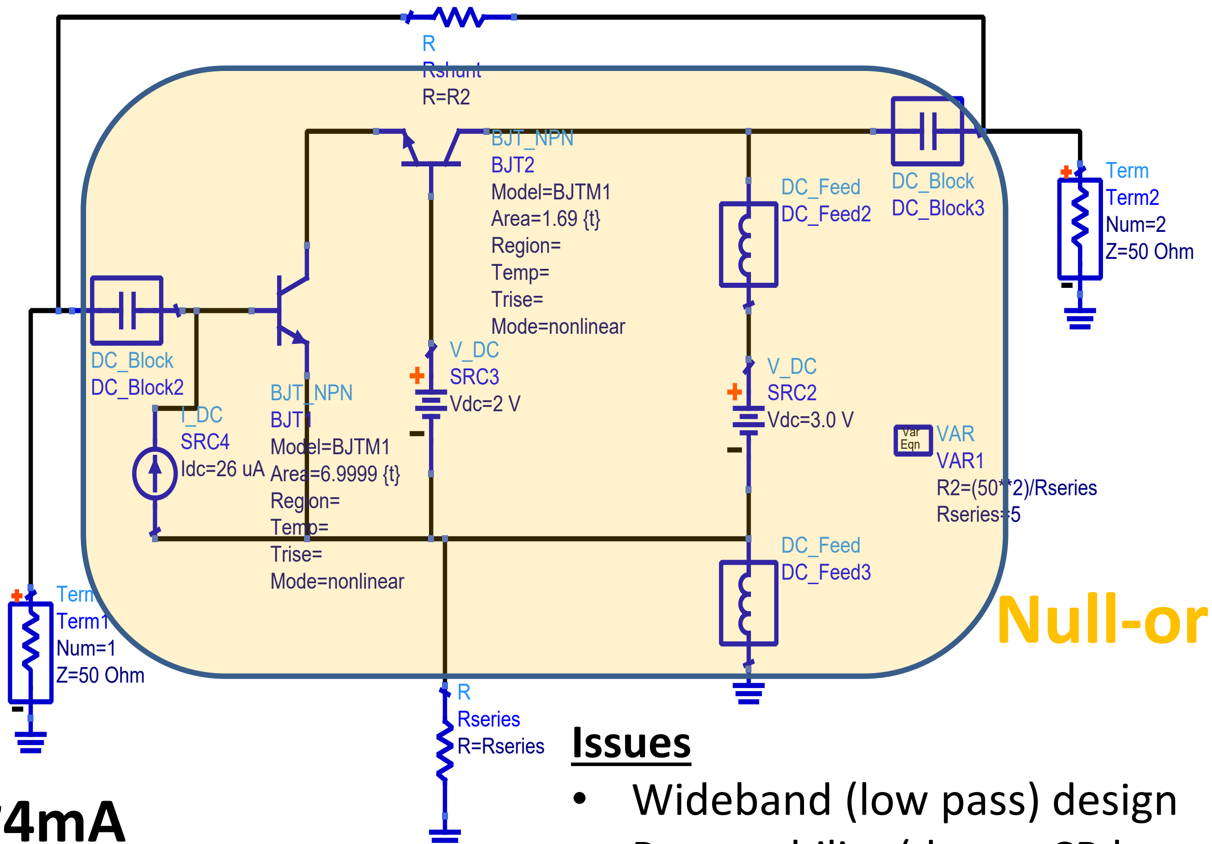
All transfer gains set equal (voltage, current, transimpedance, transconductance)

A=B=C=D=1/gain

Example, Simple RF LNA based on

Analog design techniques (1)

Use of overall feedback approach in most straight forward manner



I_c~4mA

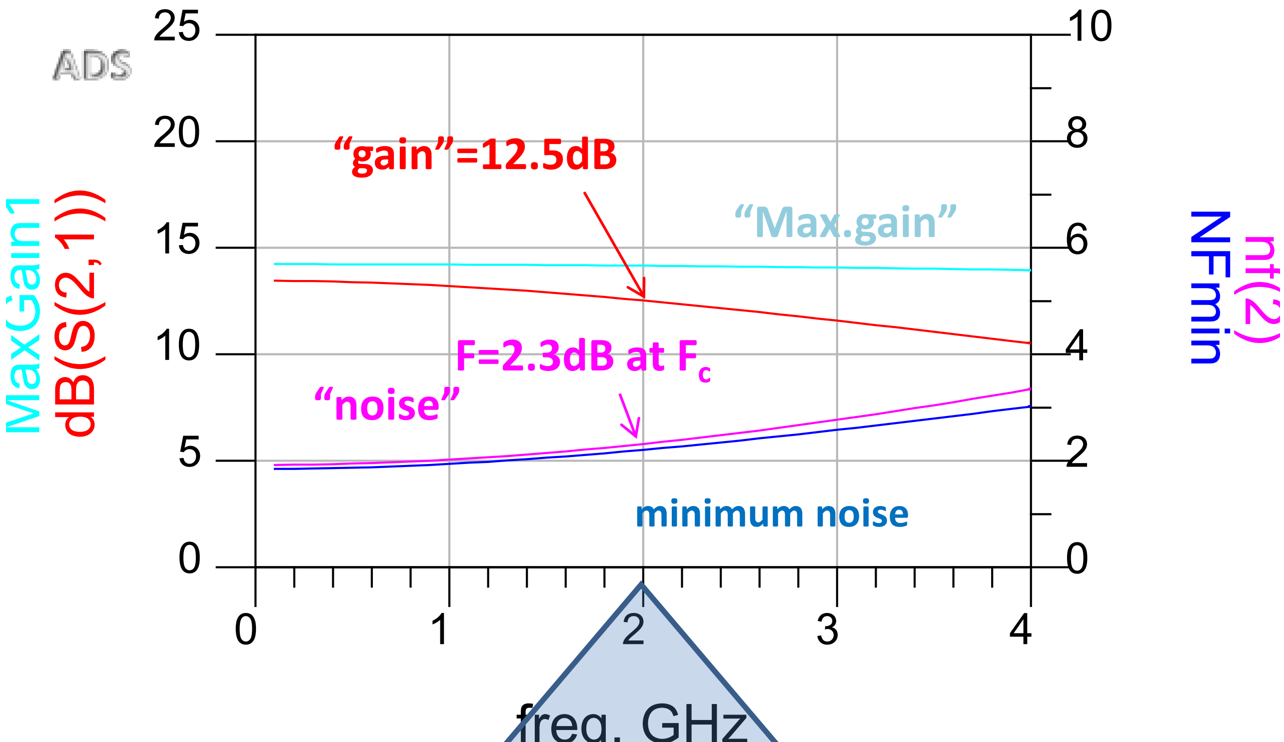
R_{series}= 7 ohm

Issues

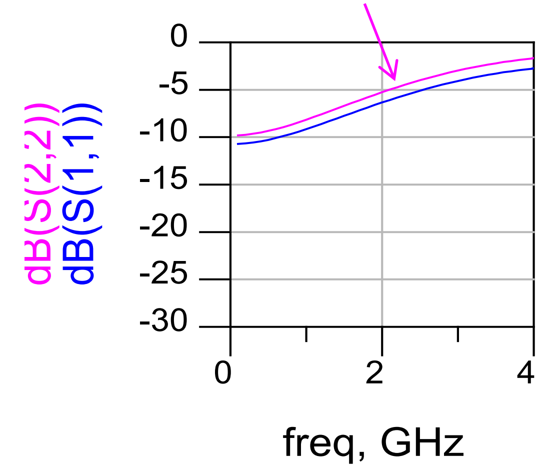
- Wideband (low pass) design
- Poor stability (due to CB base connection to hot terminal)
- Resistive feedback elements → Poor noise performance
- One cascode → not enough loop gain!

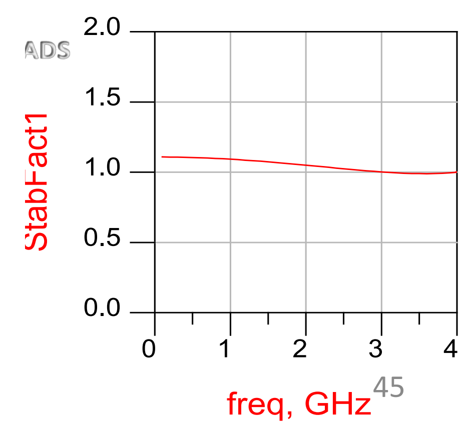
Example, Simple LNA based on
Analog design techniques (1)

→ Poor Gain, input and output imp. matching + noise match



Input & output "matching"= -5dB





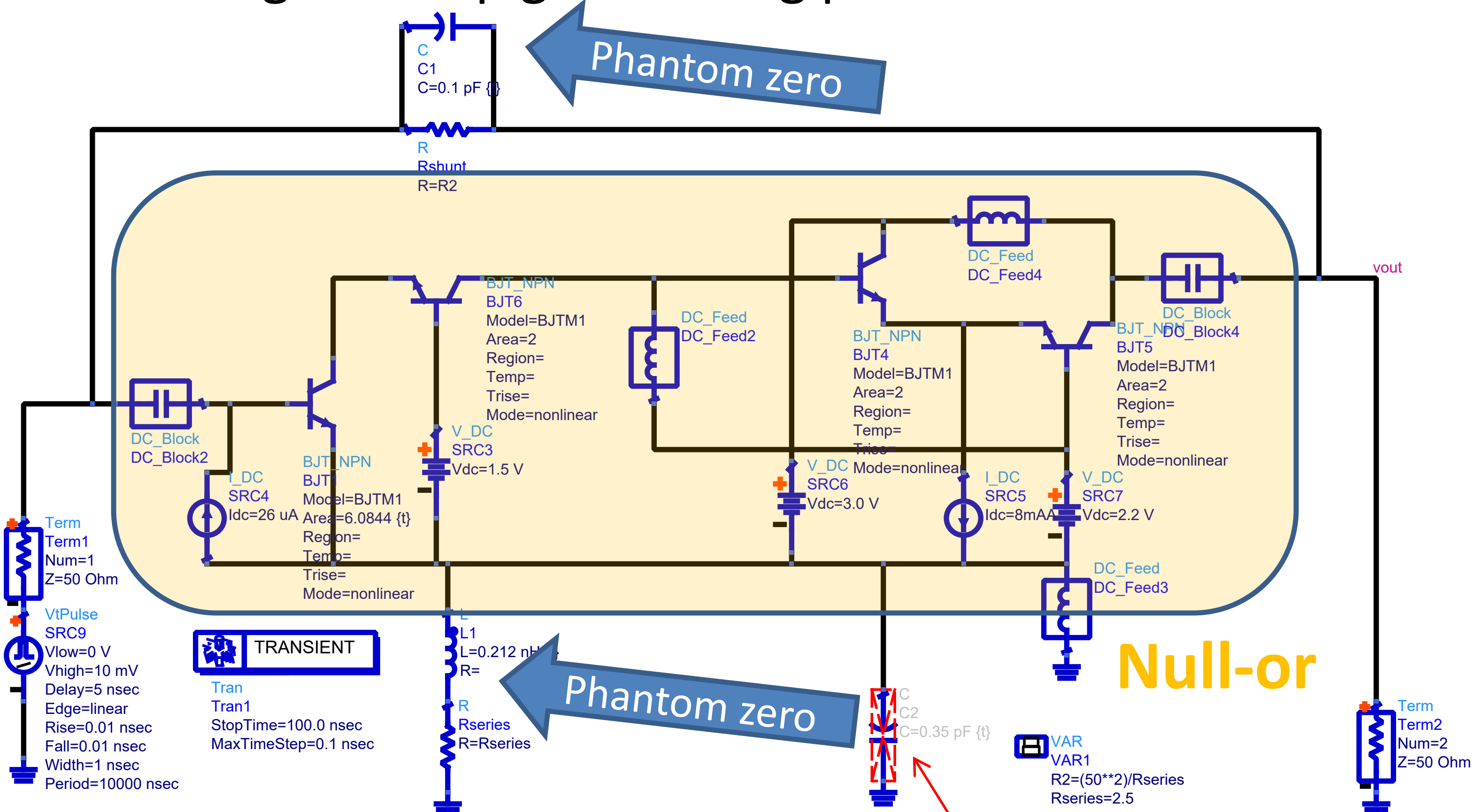
I_c~4mA
R_{series}= 7 ohm

Design frequency

Wideband design
Poor stability
Poor noise
Poor Impedance match
Poor gain

Example, Simple RF LNA based on
Analog design techniques (2)

→ Boosting the loop gain + using phantom zeroes !!!



I_c~12mA

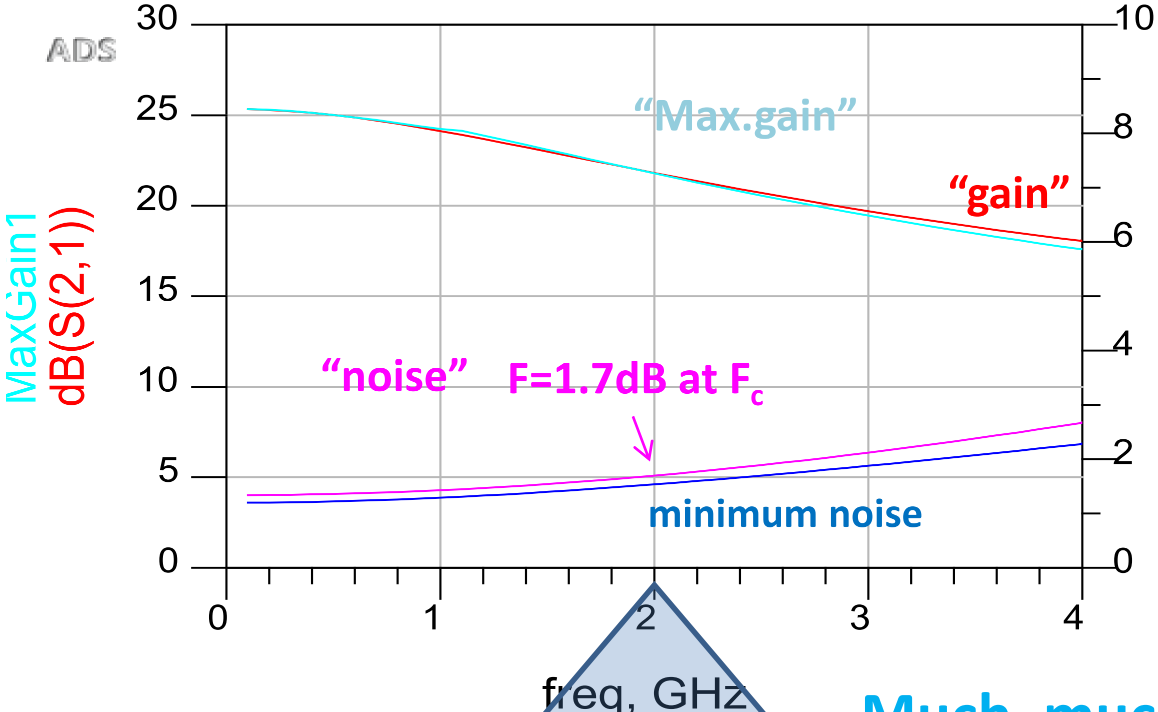
R_{series}= 2.5 ohm

Parasitic capacitive loading (350fF)

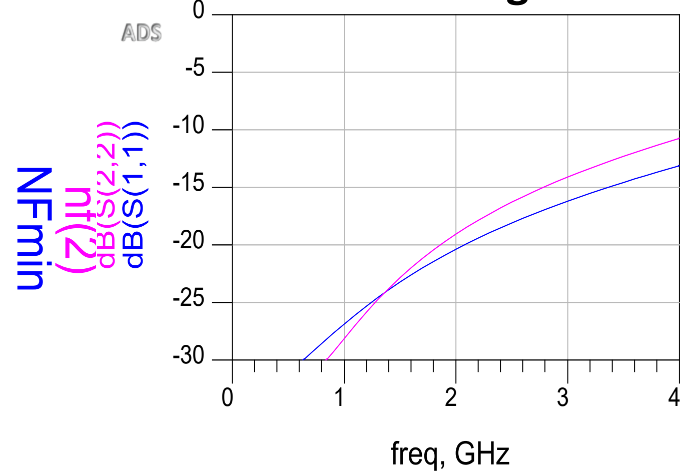
Example, Simple RF LNA based on

Analog design techniques (2)

→ Boosting the loop gain + using phantom zeroes !!!

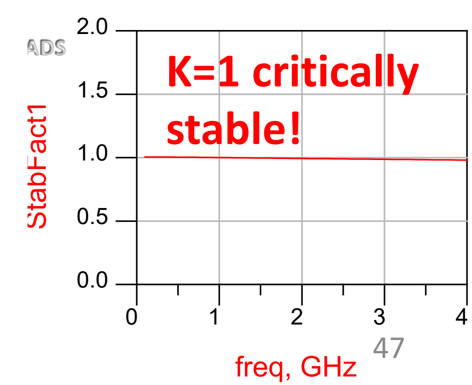


Input & output "matching"



Much, much nicer !!!

But at the cost of higher DC current!



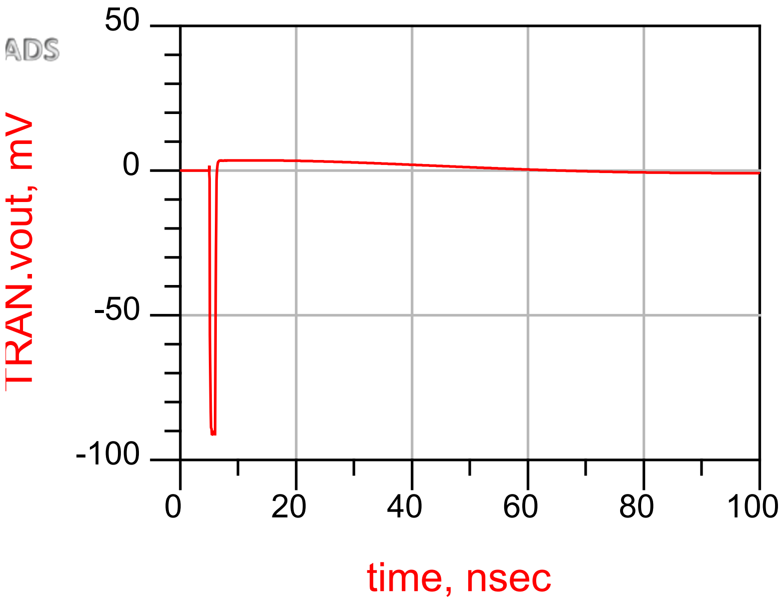
I_c~12mA

R_{series}= 2.5 ohm

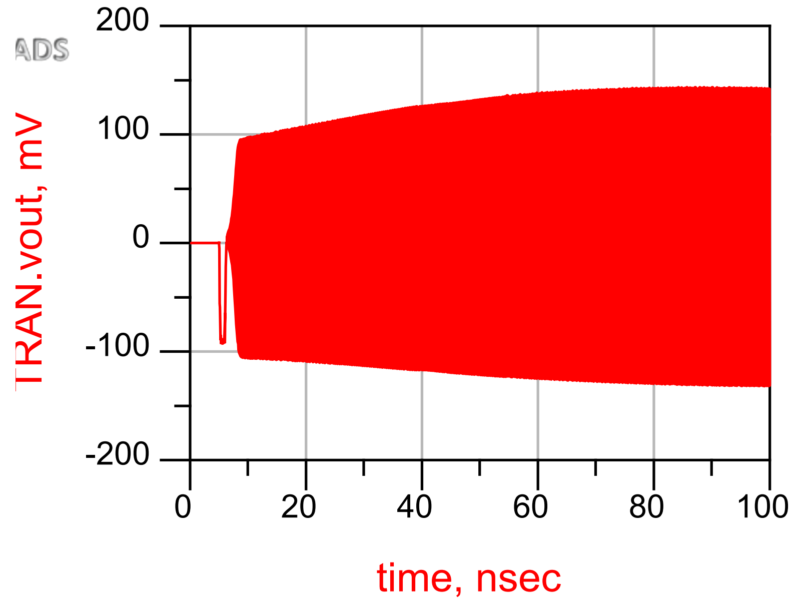
Design frequency

Example, Simple RF LNA based on Analog design techniques (2)

→ However, very sensitive to oscillations, → not practical……



NO parasitic capacitive loading



When parasitic capacitive loading (0.3 5pF) is taken into account the circuits oscillates!!!

In practice there will be many more parasitics….

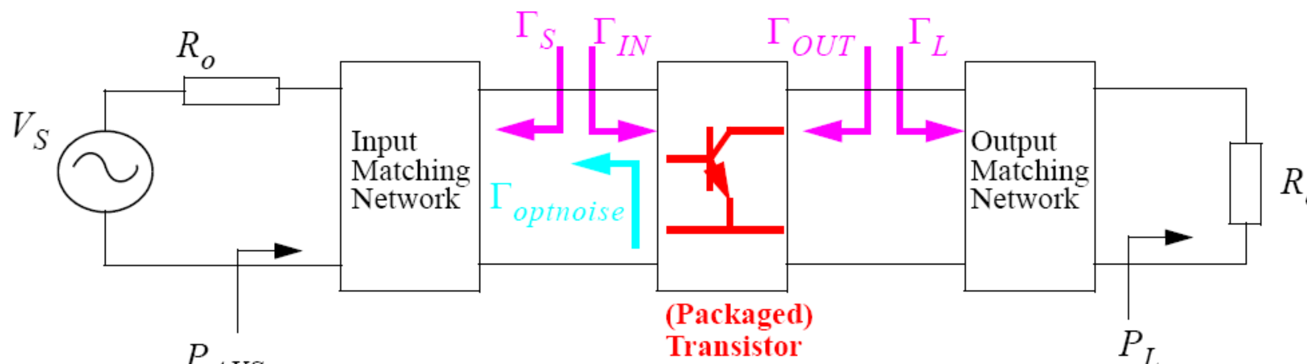
@RF, The RF way

Matching a major principle!

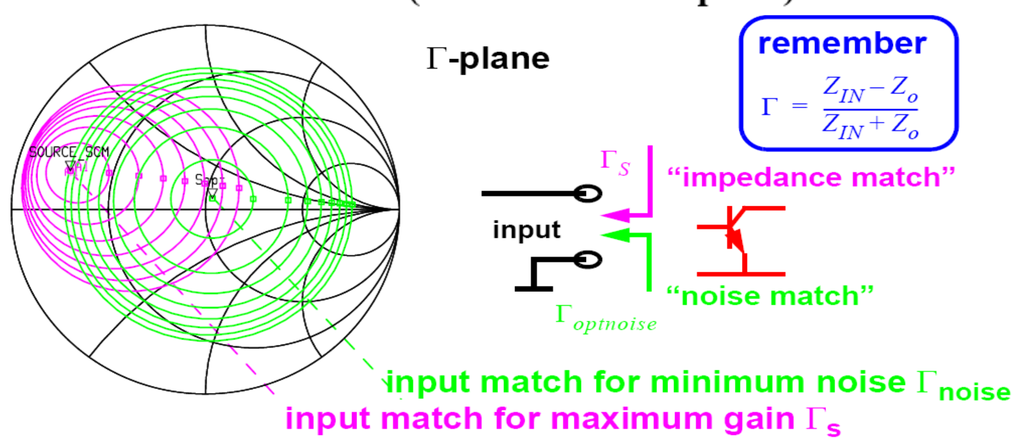
- Add matching networks using “lossless” components
- Make use of graphical design tools → **Introduced in RF track!**

<u>It can provide:</u>

•Lower reflections
•Higher gain
•Lower noise
•Higher linearity
•Higher output power
•Lower power consumption
•Higher efficiency



(Black-box description)



Smith chart -> Graphical relation between impedance and reflection coefficient

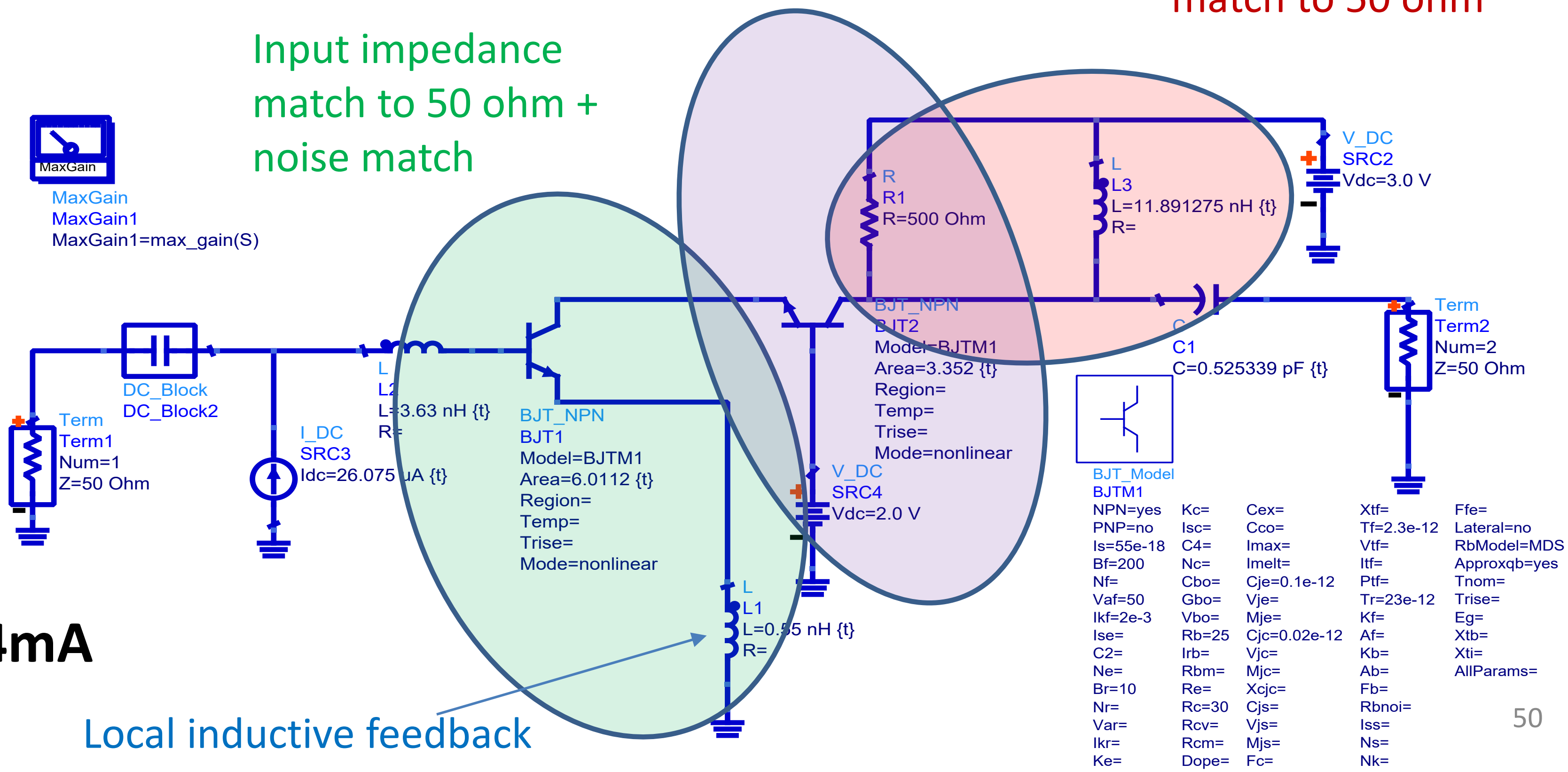
Example, Simple LNA based on RF design techniques (2)

→Gain, input and output imp. matching + noise match

Enhance output-to-input isolation
→ improve stability

Output impedance match to 50 ohm

Input impedance match to 50 ohm + noise match

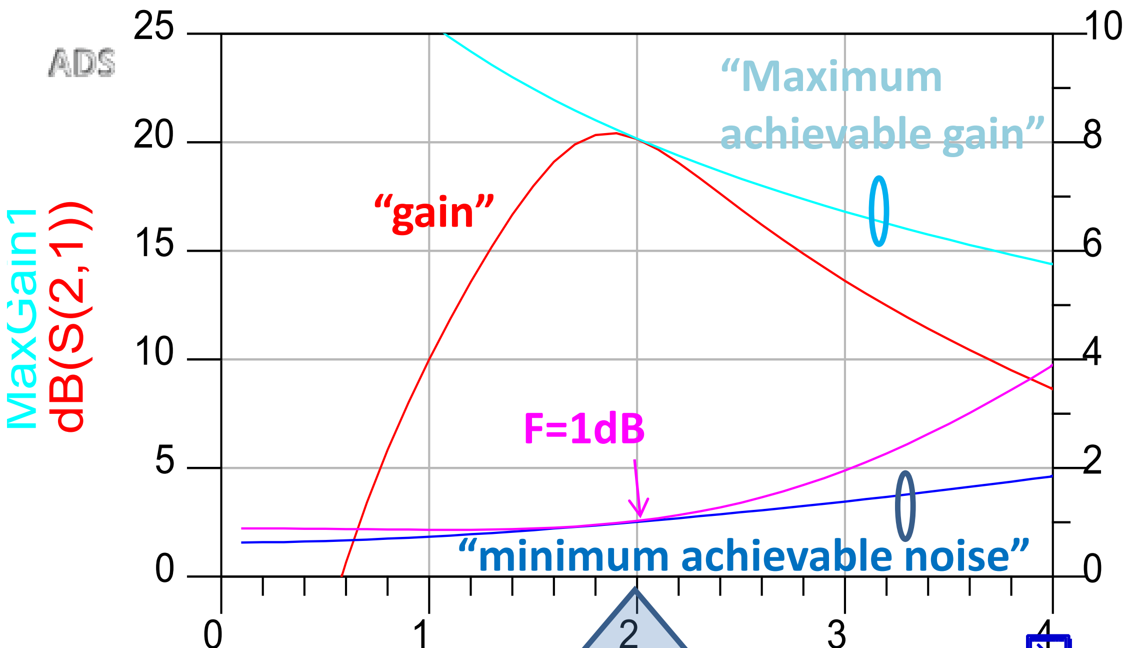


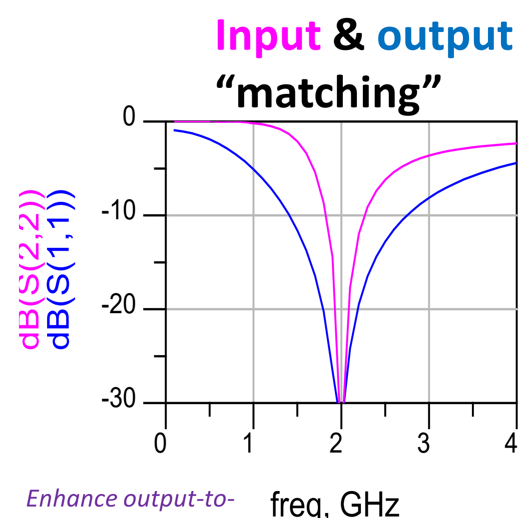
I_c~4mA

Local inductive feedback

Example, Simple LNA based on
RF design techniques (2)

- Gain, impedance input and output matching + noise matching

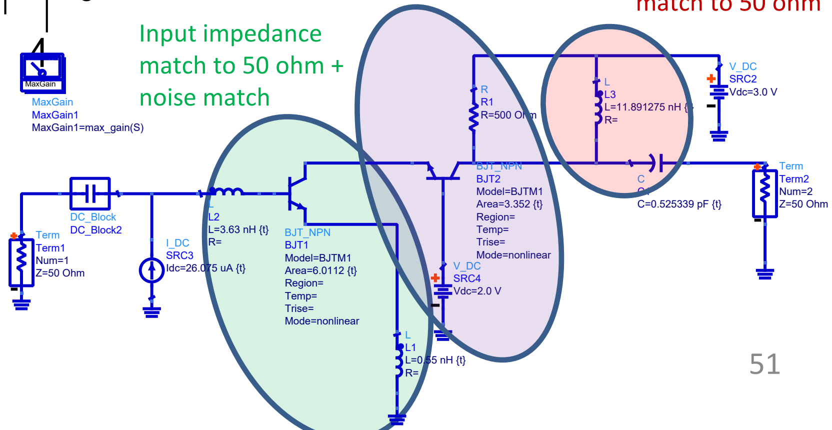




Enhance output-to-input isolation → improve stability

Output impedance match to 50 ohm

Input impedance match to 50 ohm + noise match



K>50
Very stable!

I_c~4mA

Design frequency

Conclusions, RF LNA based on
Analog (1) & RF design (2)

Analog (1)

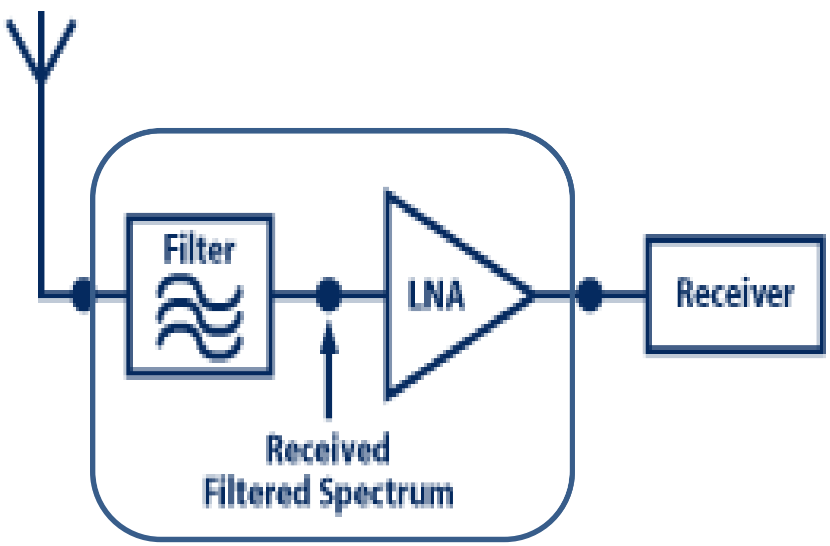
- low pass
- Gain / matching accuracy depends on: feedback elements and (high) loop gain
- High risk of oscillation due to overall feedback
- No Reactive matching for noise

RF design (2)

- Bandpass
- Gain / matching accuracy depends on component values and bias current accuracy & feedback
- Low risk of oscillation, since stability factor (K) dictates design strategy
- Both ohmic and reactive noise matching

Homework related to this course

- Design a: “**RF frontend with band pass filter and “LNA” for 802.11 standards in the 5030-5875 MHz band”**



- Center frequency filter and LNA = 5.5GHz
- BW = 1 GHz
- Gain > 8.5 dB
- Current Budget = 12mA
- Supply voltage = 1.8 V
- Noise Figure = 3 dB @ 290K (standard noise reference temperature)
- S_{11} < -20dB

If time permits

- There is so much more to tell… / learn…

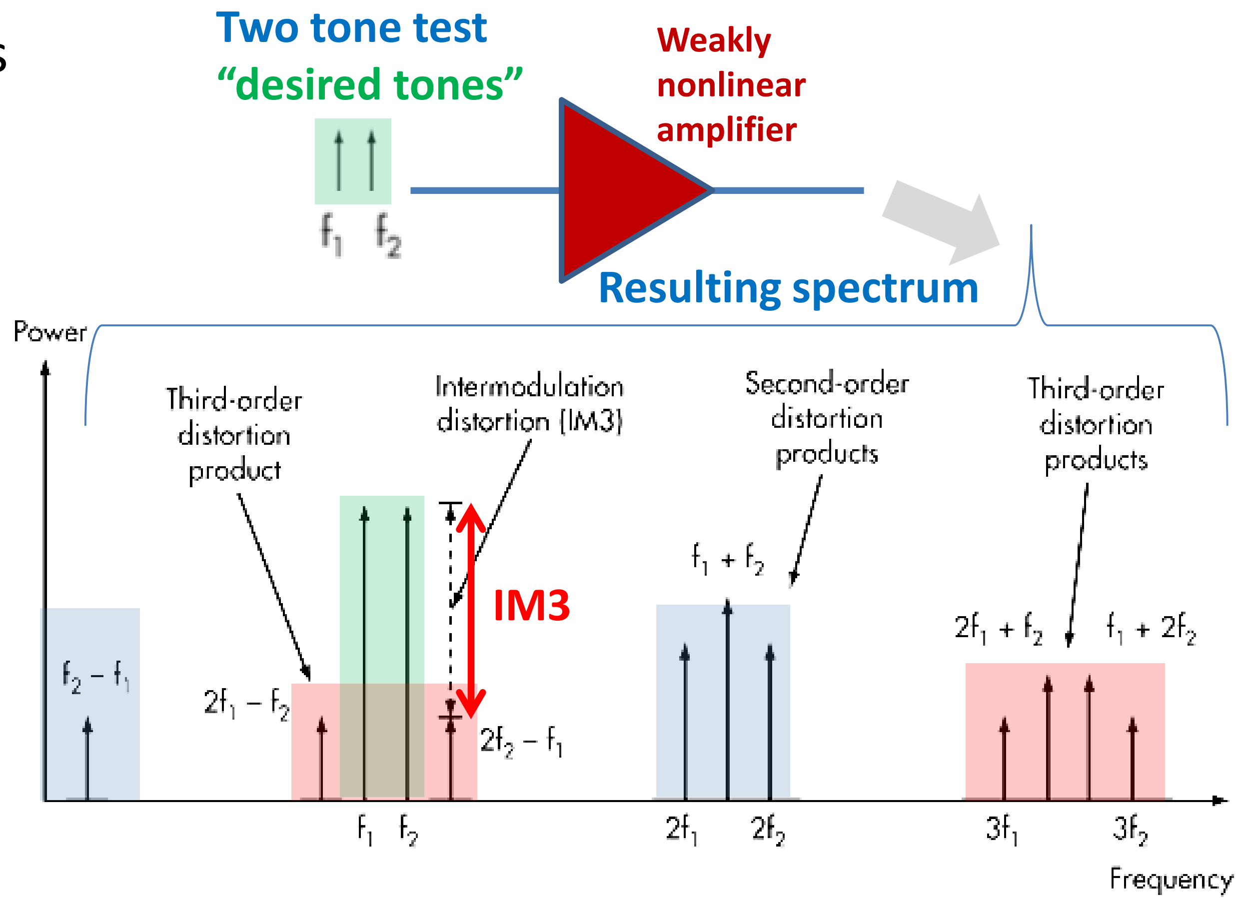
→ RF Education Track

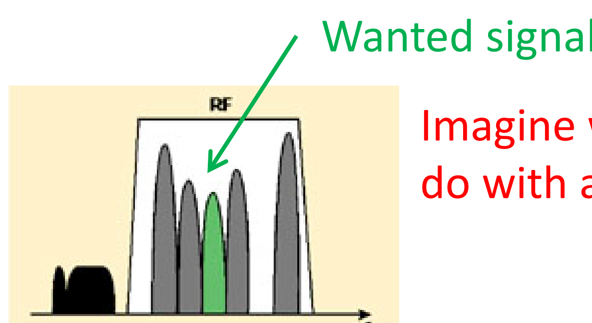
Example: Why is linearity important?

- **A non-linearity** causes freq. comp to mix yielding;
  → New frequency components / spurs

- **Weak nonlinearities;** The frequency components in the circuit are linear combinations of all frequencies fed to the circuit

- **Hard nonlinearities;** (clipping) causes many more strong interferes





Imagine what a non- linearity will do with a realistic RF spectrum!

Linearity, Intercept points

Ratios between intermodulation and fundamental signal,are:

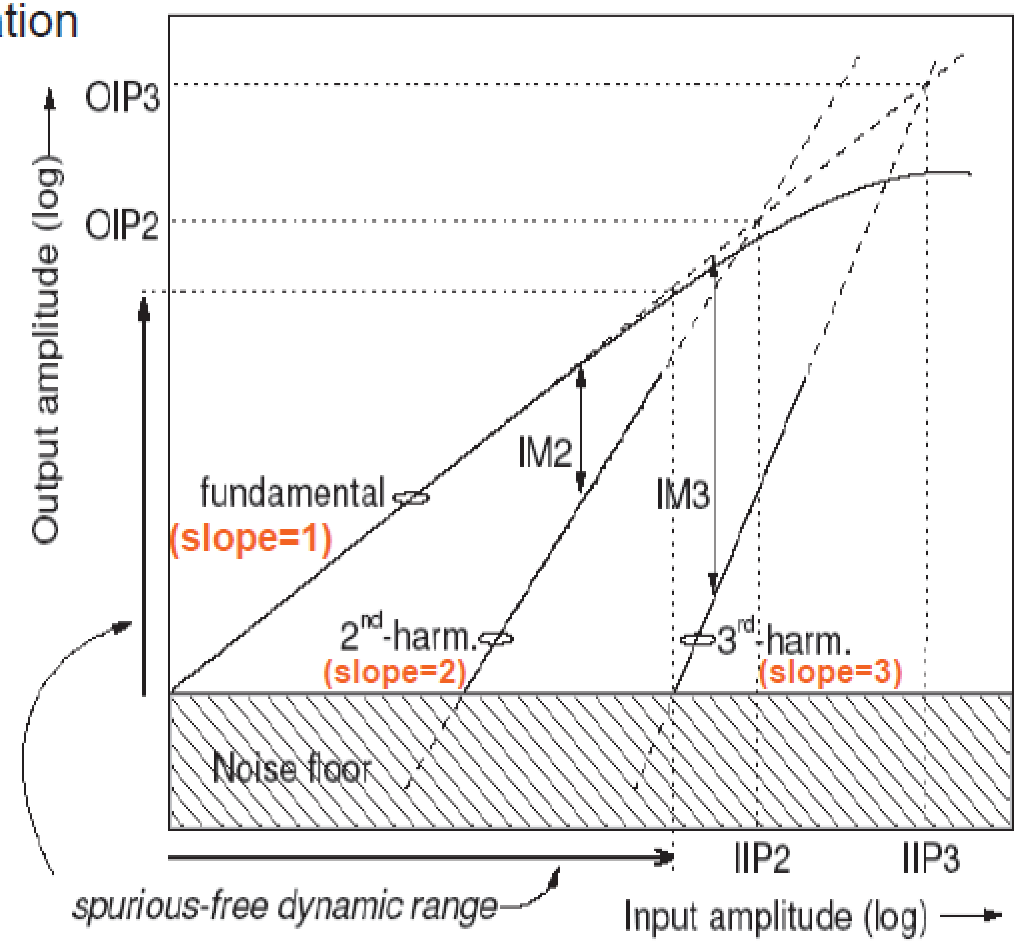
$$IM2 = \left|\frac{a_2}{a_1}\right| A$$

$$IM3 = \frac{3}{4}\left|\frac{a_3}{a_1}\right| A^2$$

Virtual crossing of fundamental with intermodulation products is a measure for the achieved linearity (solve IM_x for A=1)

$$IIP2 = \left|\frac{a_1}{a_2}\right|$$

$$IIP3 = \sqrt{\frac{4}{3}\left|\frac{a_1}{a_3}\right|}$$

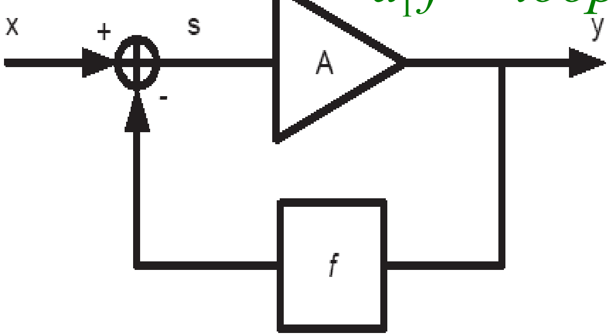


Linearity in Low Noise Amplifiers

Low frequency / Analog approach

- Increase loop gain to reduce error, (@ cost of DC power & risk of oscillation)
- No correction for memory effects (e.g. due to capacitors & inductors)
- Calculation using **Taylor** series

$$a_1 f = loopgain$$



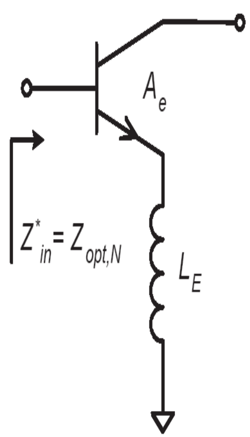
$$IM3_{FB} = \frac{IM3_{AMP}}{(1 + a_1 f)^3}$$

RF approach / conditions

- Not much (loop) gain available
- Memory effects, due to capacitors & inductors, are important
- Calculation using **Volterra series (or HB / Transient simulations)**

Boost linearity by;

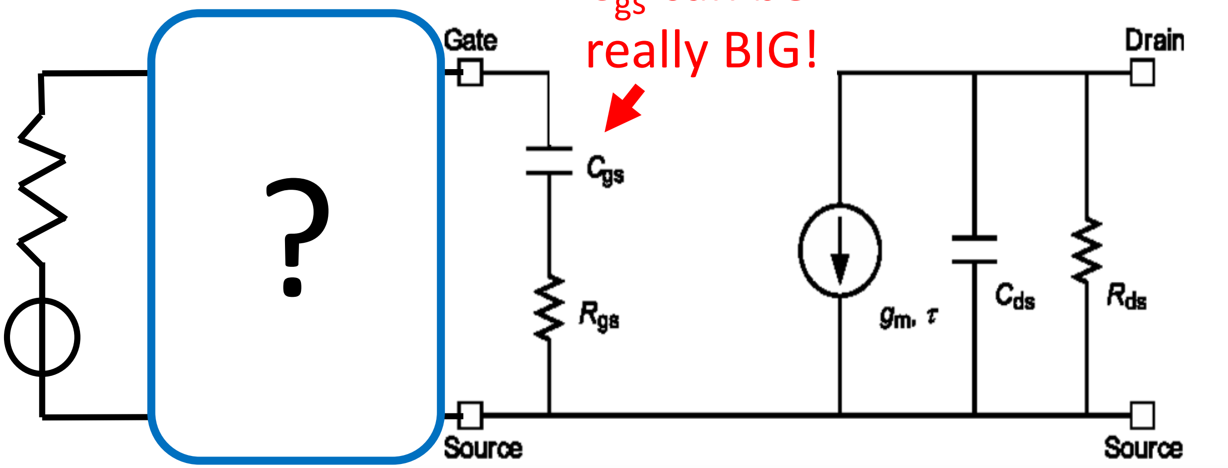
- Shaping of transfer functions → (e.g. derivative super position)
- IF, fundamental and harmonic terminations
- IM3 cancelation techniques → (e.g. out-of-band linearization)



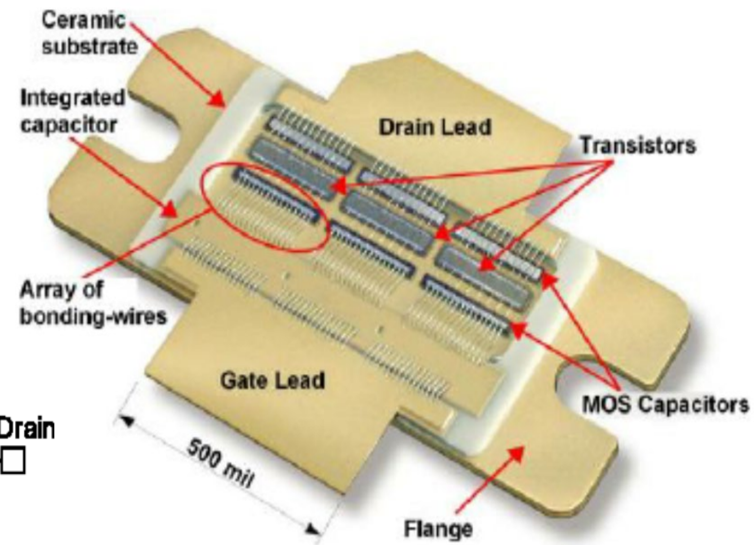
Let's consider two examples!

Matching of a BIG TX Transistor (Example)

C_{gs} can be really BIG!

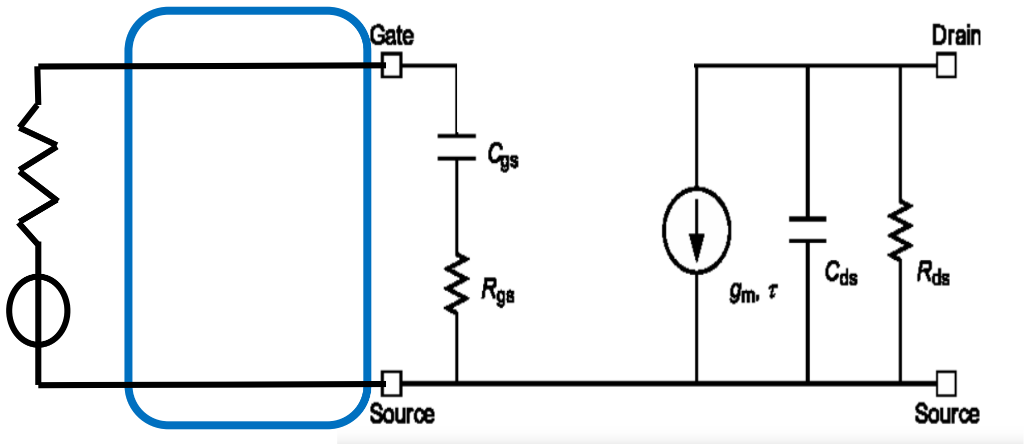


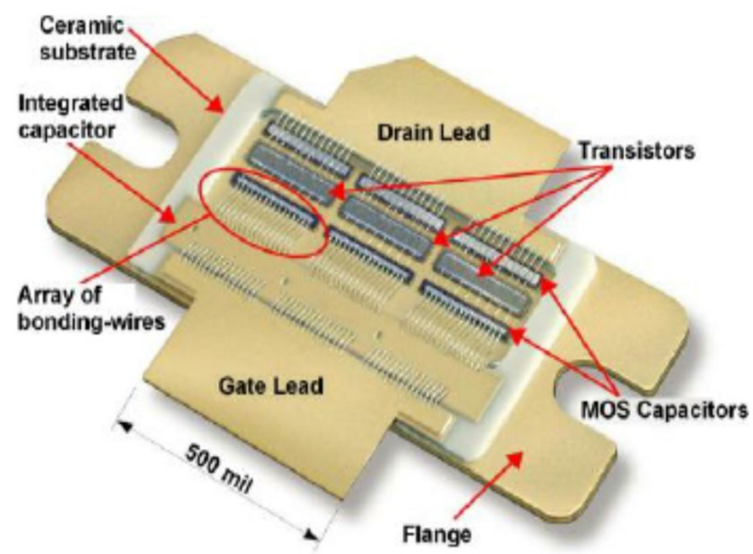
Strongly simplified AC equivalent circuit LDMOS DEVICE



Schematic die cross-section of a LDMOS gate cell. (much bigger than W_g=25mm)

Matching of a BIG Transistor (Example)





Strongly simplified AC equivalent circuit LDMOS DEVICE

C_{gs} ~ 1pF /mm
Rgs ~4 ohm /mm

For a 25 mm
LDMOS device

C_{gs} =25 pF
Rgs =0.16 ohm

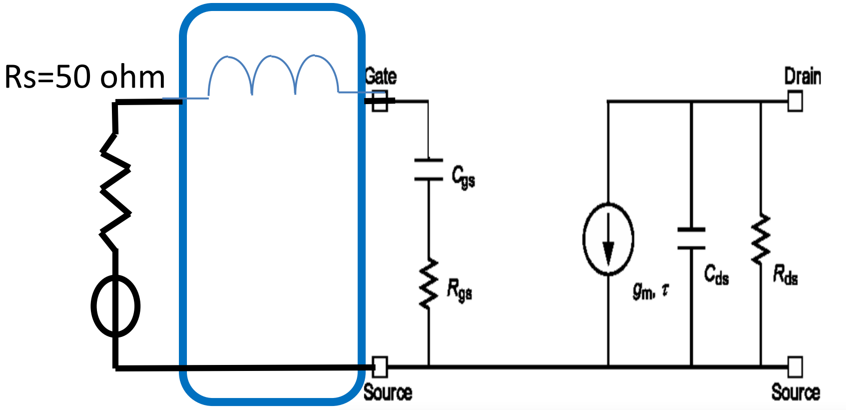
$$Z_{in} = \frac{1}{j\omega C_{gs}} + R_{gs}$$

$$= \frac{1}{j2.\pi.2,1e+9.25e-12} + 0.16 = \boxed{-j3.03 + 0.16}$$

Very low impedance level

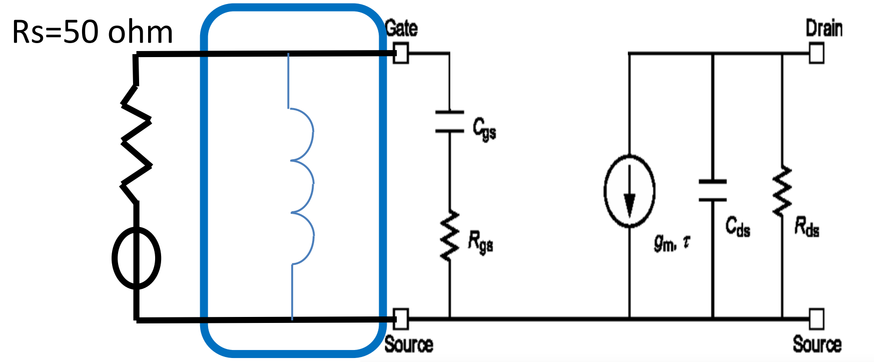
Very low impedance level, difficult to get voltage swing & bandwidth!

Matching of a Transistor (Example)



Configuration I

$$Z_{in} = -j3.03 + 0.16$$



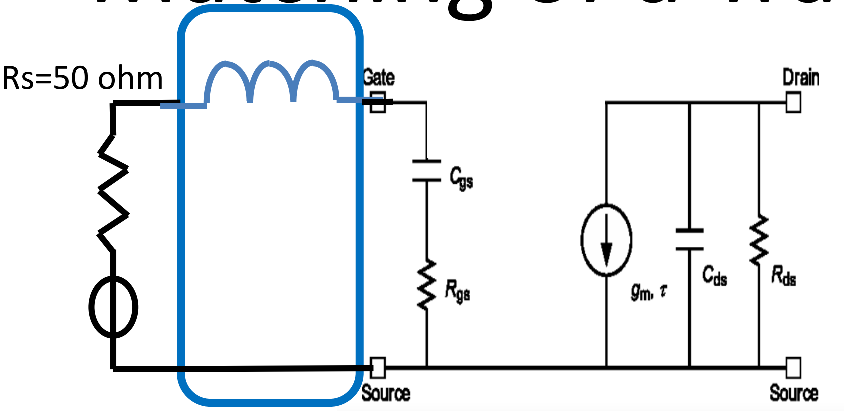
Configuration II

Question (5) Which configuration is better in terms of input matching and bandwidth I or II? (<u>select the best answer</u>)

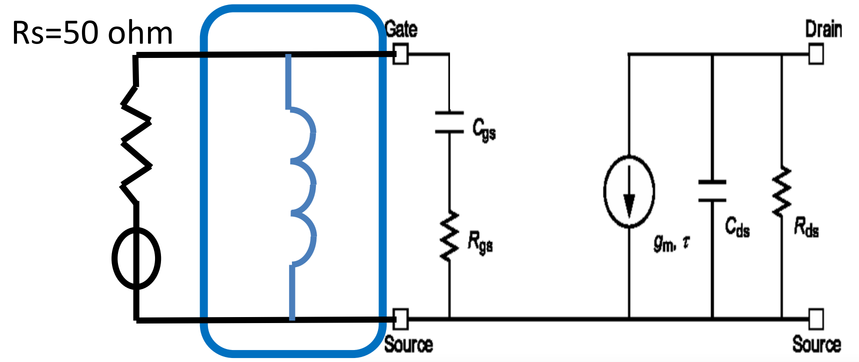
a) **Configuration I** provides highest gain, bandwidth and best impedance match
b) **Configuration II** provides highest gain, bandwidth and best impedance match
c) **Configuration I,** provides highest bandwidth **Configuration II,** provides best gain and impedance match at RF
d) **Configuration II,** provides highest bandwidth **Configuration I,** provides best gain and impedance match at RF

Matching of a Transistor (Example)

$Z_{in} = -j3.03 + 0.16$



Configuration I



Configuration II

Question (5) Which configuration is better in terms of input matching and bandwidth I or II? (select the best answer)

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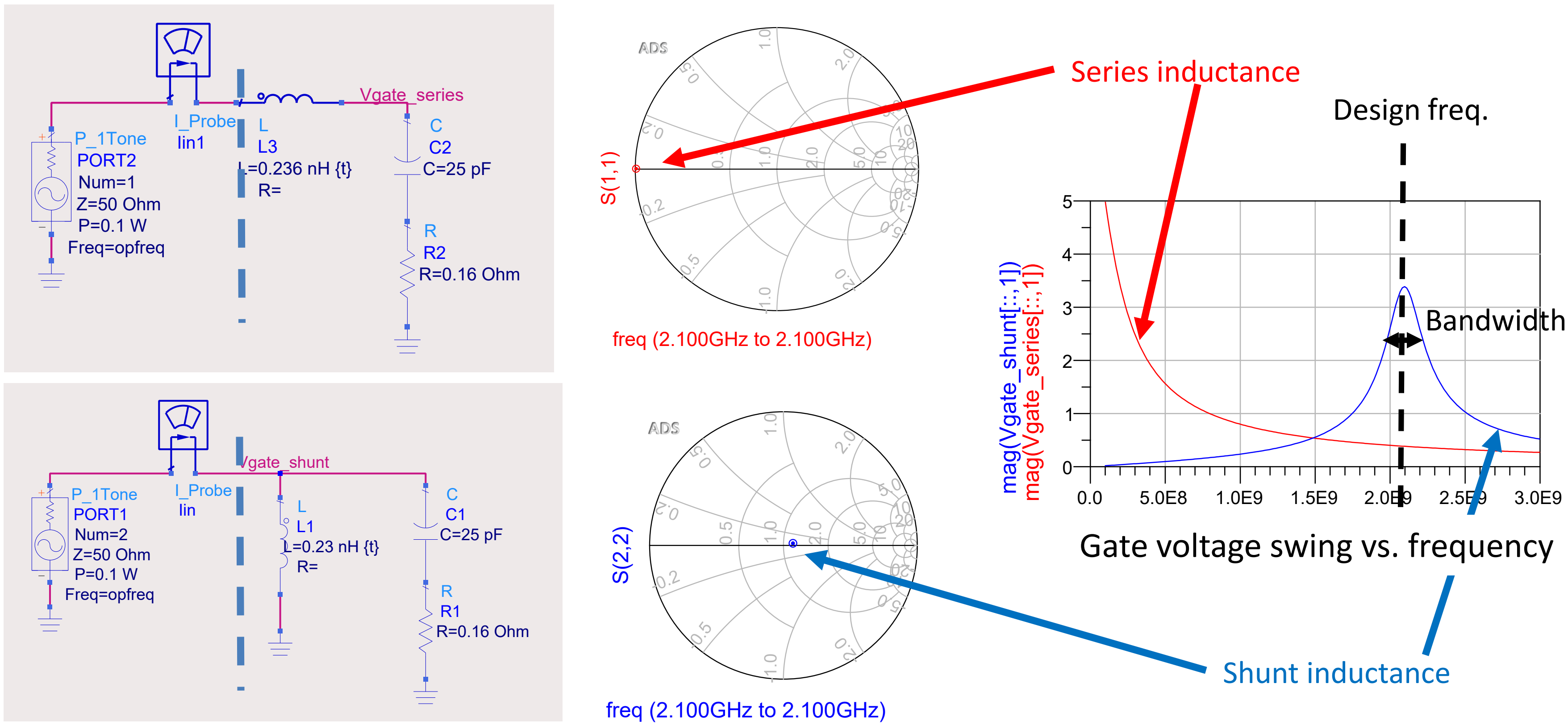
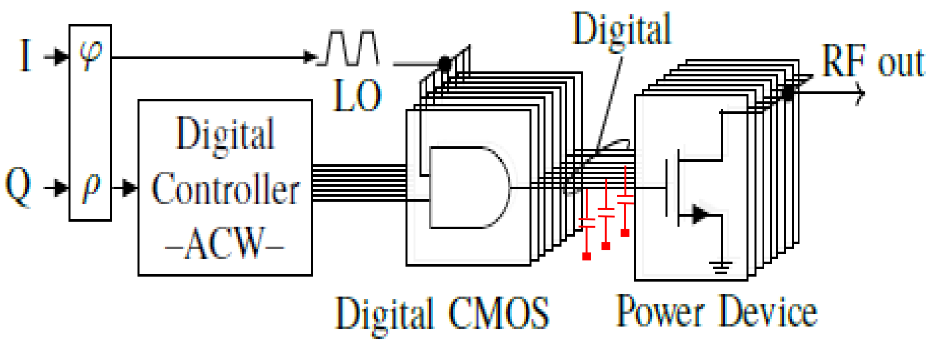
c) **Configuration I,** provides highest bandwidth **Configuration II,** provides best gain and impedance match at RF
d) **Configuration II,** provides highest bandwidth **Configuration I,** provides best gain and impedance match at RF

Matching of a Transistor (Example)

Which configuration is better in terms of input matching and bandwidth I or II?

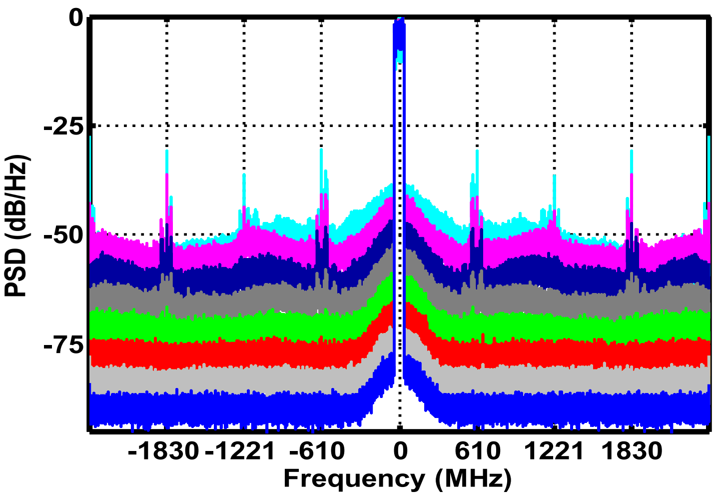


The New Digital RF Way



Strongly simplified Polar Digital transmitter
(there are other concepts as well)

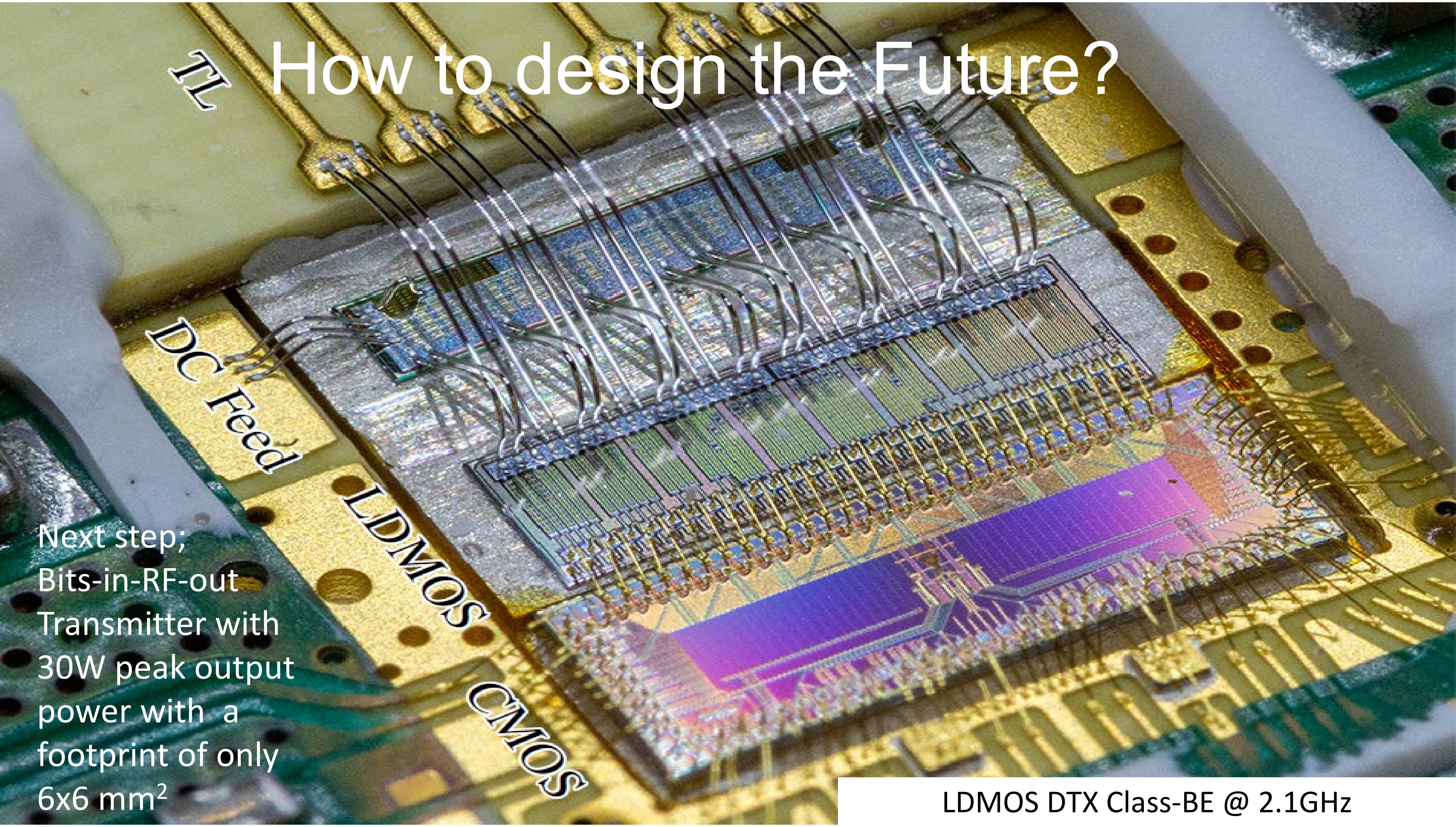
Split the output device / stage in many small devices (small W_g) and control them directly from the digital domain!
→ Higher integration, better control,
Higher Efficiency & **Higher bandwidth!**



Adding more bits reduces the quantisation noise

→ Approximate analogue signal(s) using many gates

How to design the Future?



Next step;
Bits-in-RF-out Transmitter with 30W peak output power with a footprint of only 6x6 mm^2

LDMOS DTX Class-BE @ 2.1GHz

There is so much more to tell..

- The previous slide were only intended to make you aware of differences between Analog and RF (not to provide you with the full story)

- The full story will be taught in the "**RF track!**"
    - **Q2, EE4600,** Fundamentals for RF / Wireless Design
    - **Q3, ET4605,** Integrated Circuits and Systems for Wireless Applications
    - **Q4, ET4371,** Advanced Digital Wireless transceivers

- **Thank you for your time and interest and we hope to see you in class!!!**