Noise Considerations in Microwave Operational Transconductance Amplifiers (OTAs)

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Acknowledgments

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  - Fan Jiang

- Funding support:
  - Natural Sciences and Engineering Research Council of Canada (NSERC)
  - CMC Microsystems

Outline

- Fundamentals: OTAs and their (mostly) baseband applications
- OTAs in Microwave Circuits and Systems
- Microwave OTA circuit design
- Conclusion

Fundamentals

The basic definition of an OTA

- voltage-in / current-out amplifiers

$$i_{out+} - i_{out-} = g_m (v_{in+} - v_{in-})$$

$$g_m = f(I_{tune}, V_{DD})$$

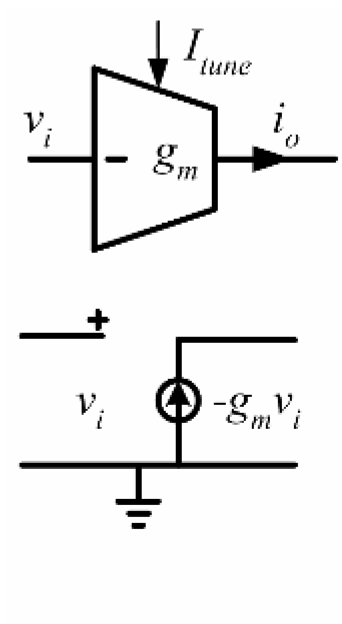
learn to exploit this!

- infinite input resistance

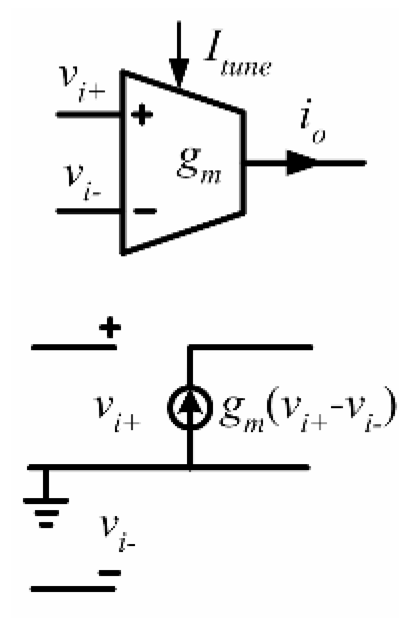
- infinite output admittance

OTA configurations

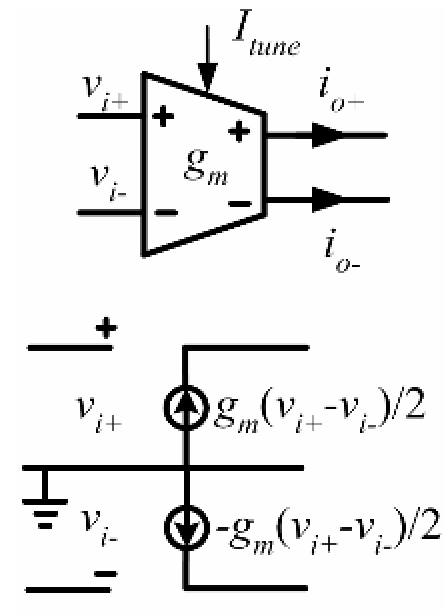
Single-ended



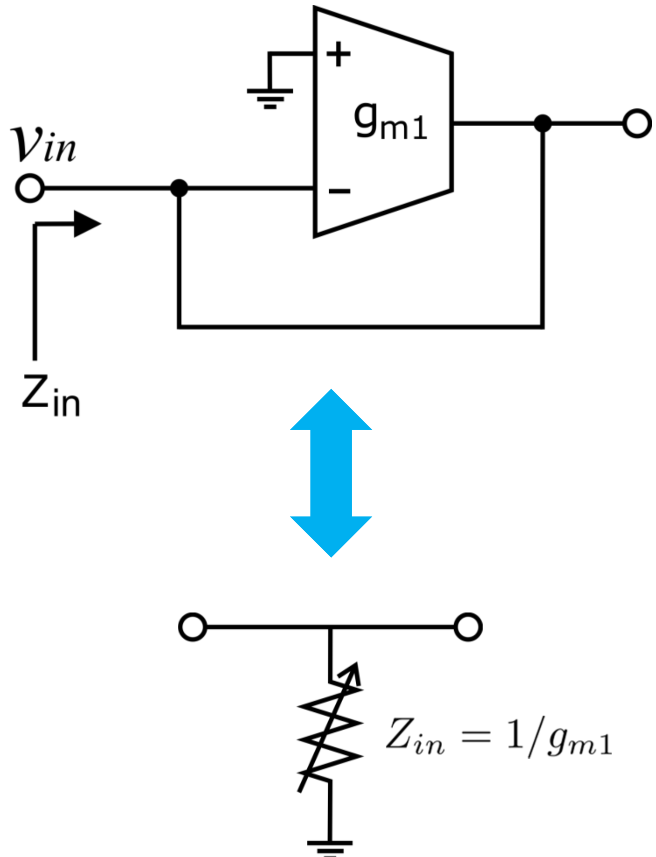
Differential input



Differential input & output

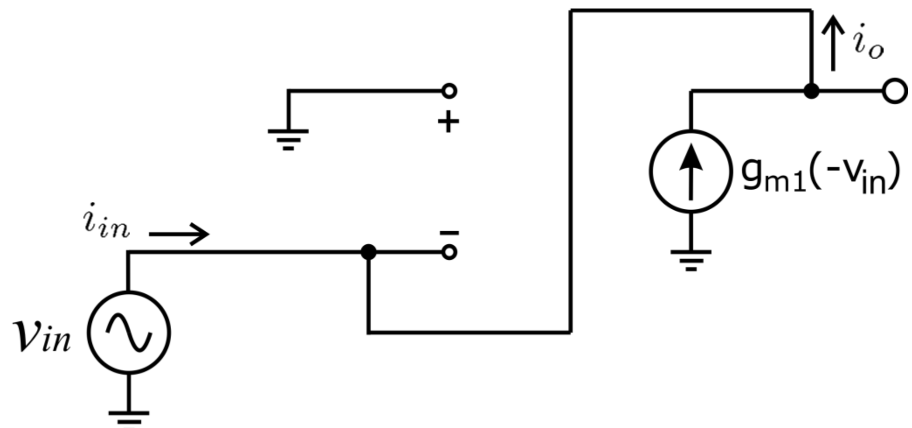


Basic OTA applications



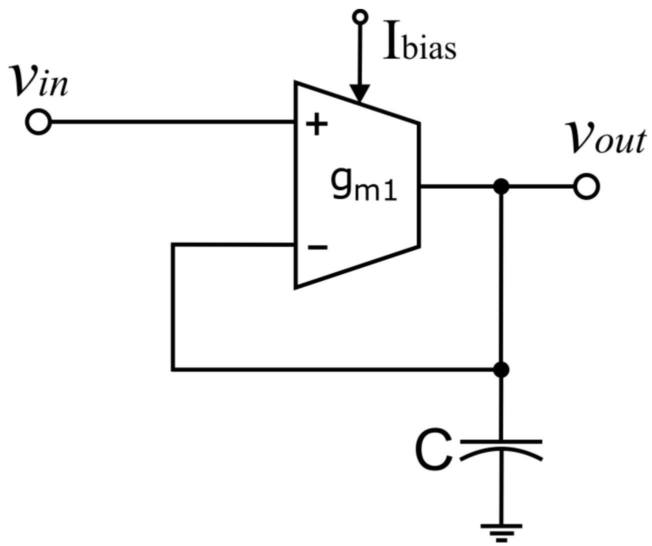
variable resistor

using the simplest possible model……



$$
\begin{aligned}
i_{in} &= -i_o \\
Z_{in} &= v_{in}/i_{in} \\
&= v_{in}/(-i_o) \\
&= v_{in}/(-(-g_{m1}v_{in})) \\
&= 1/g_{m1}
\end{aligned}
$$

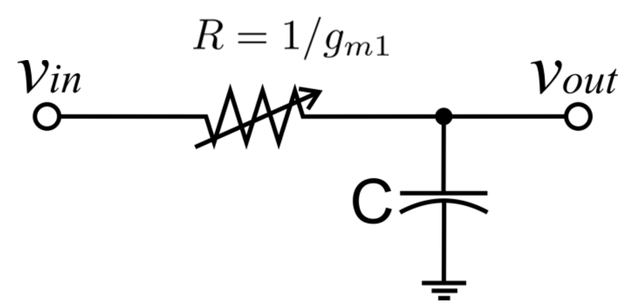
Basic OTA applications

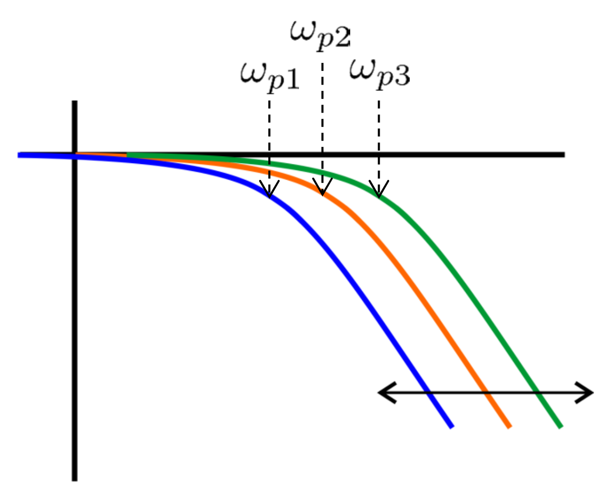


$$H(s) = \frac{v_{out}(s)}{v_{in}(s)} = \frac{g_{m1}}{g_{m1}+sC}$$

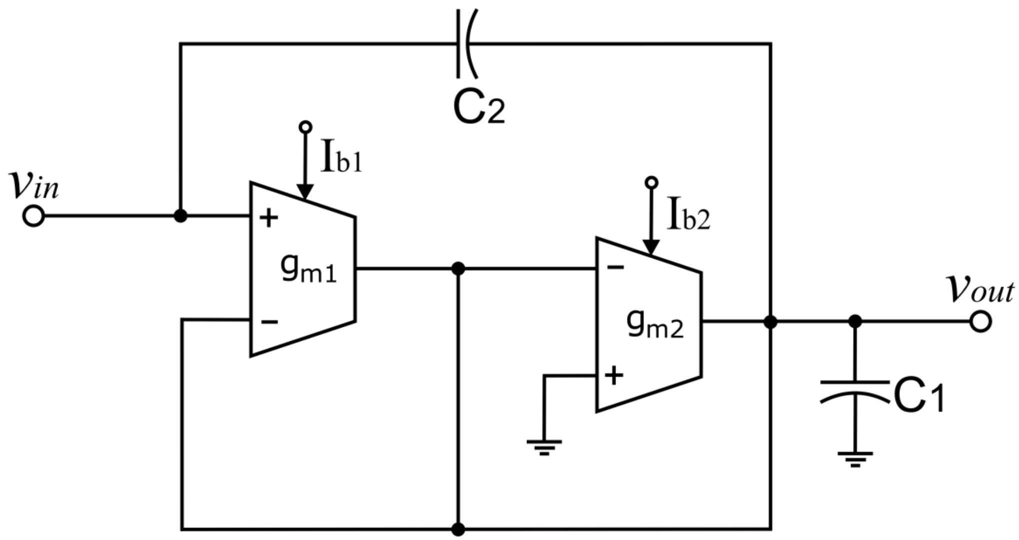
$$= \frac{1}{1+sRC}$$

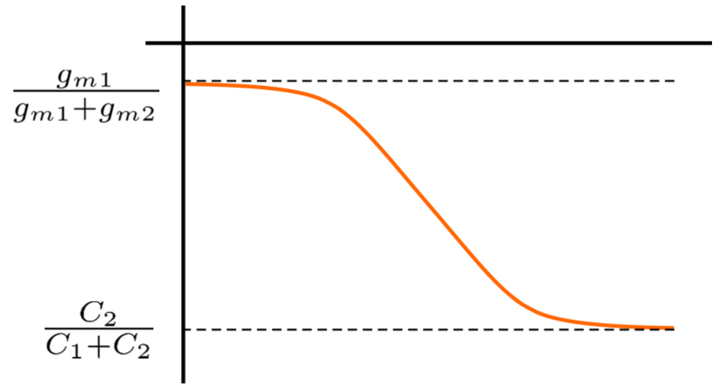
$$\omega_p = \frac{g_{m1}}{C}$$

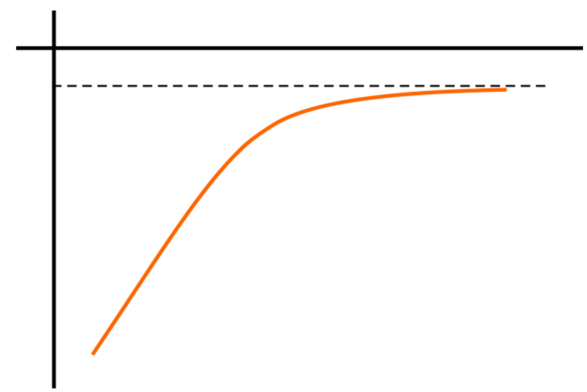




Basic OTA applications

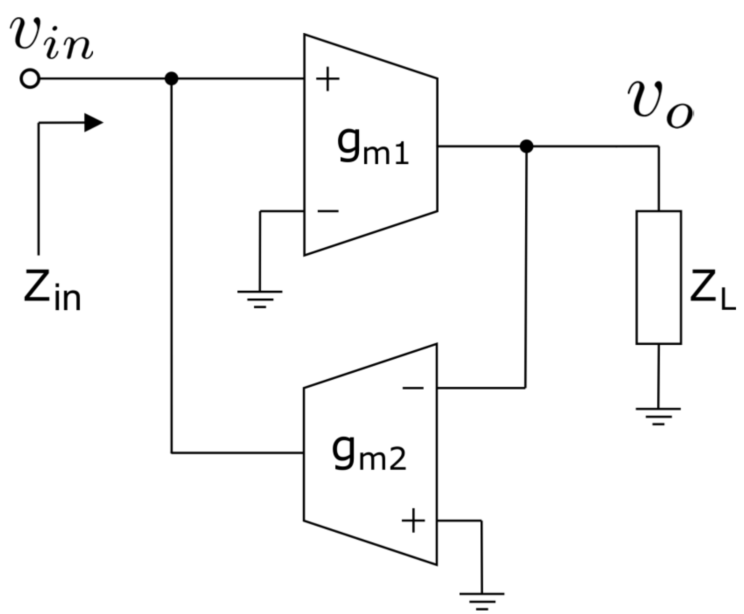






$$\frac{v_{out}}{v_{in}} = \frac{g_{m1}+sC_2}{s(C_1+C_2)+g_{m1}+g_{m2}}$$

Basic OTA applications



Impedance inverter

At the output,

$$v_o = g_{m1} v_{in} Z_L \quad (1)$$

and through the feedback path,

$$v_{in} = g_{m2} v_o Z_{in}$$

$$v_o = v_{in}/(g_{m2} Z_{in}) \quad (2)$$

making eqn. (1) = eqn. (2),

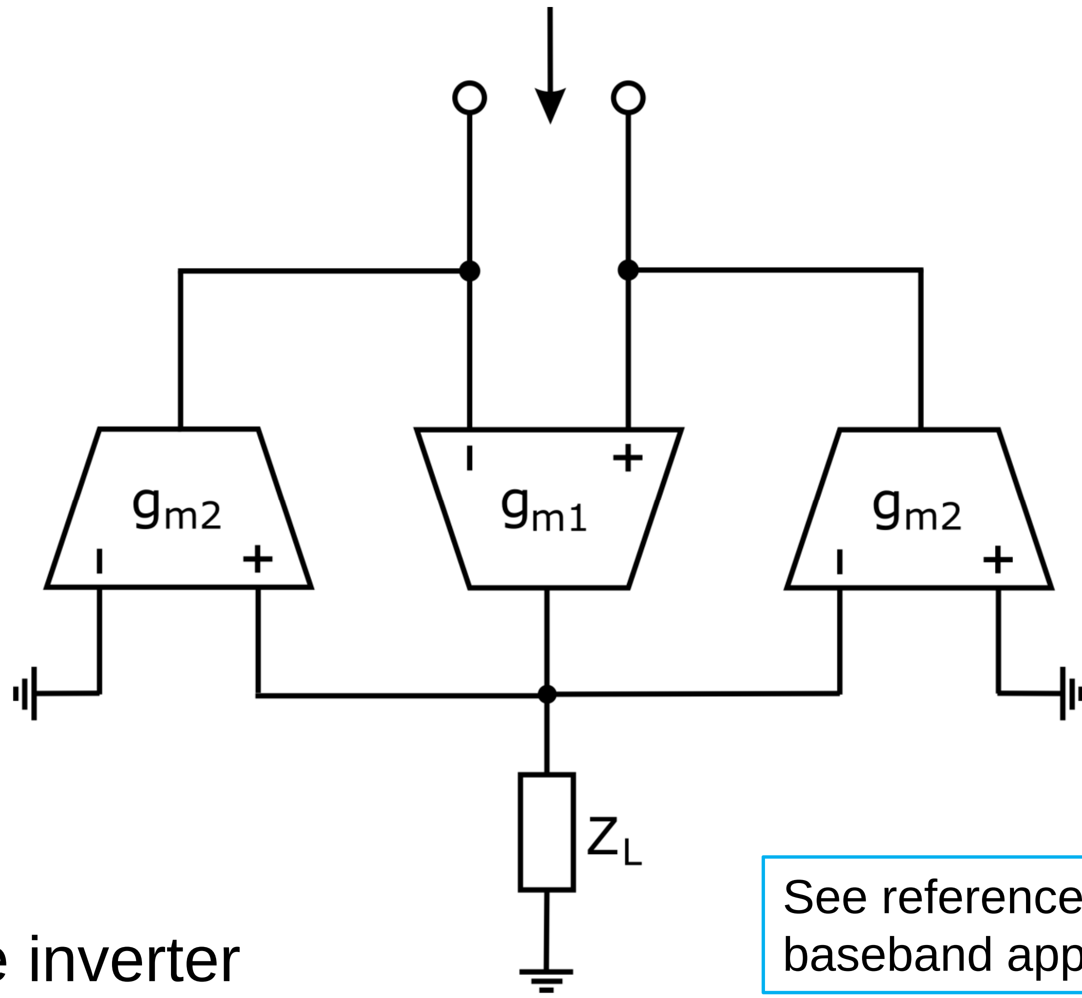
$$g_{m1} v_{in} Z_L = v_{in}/(g_{m2} Z_{in}) \quad (3)$$

and solving (3) for Z_{in} yields

$$Z_{in} = 1/(Z_L g_{m1} g_{m2}) \quad (4)$$

Basic OTA applications

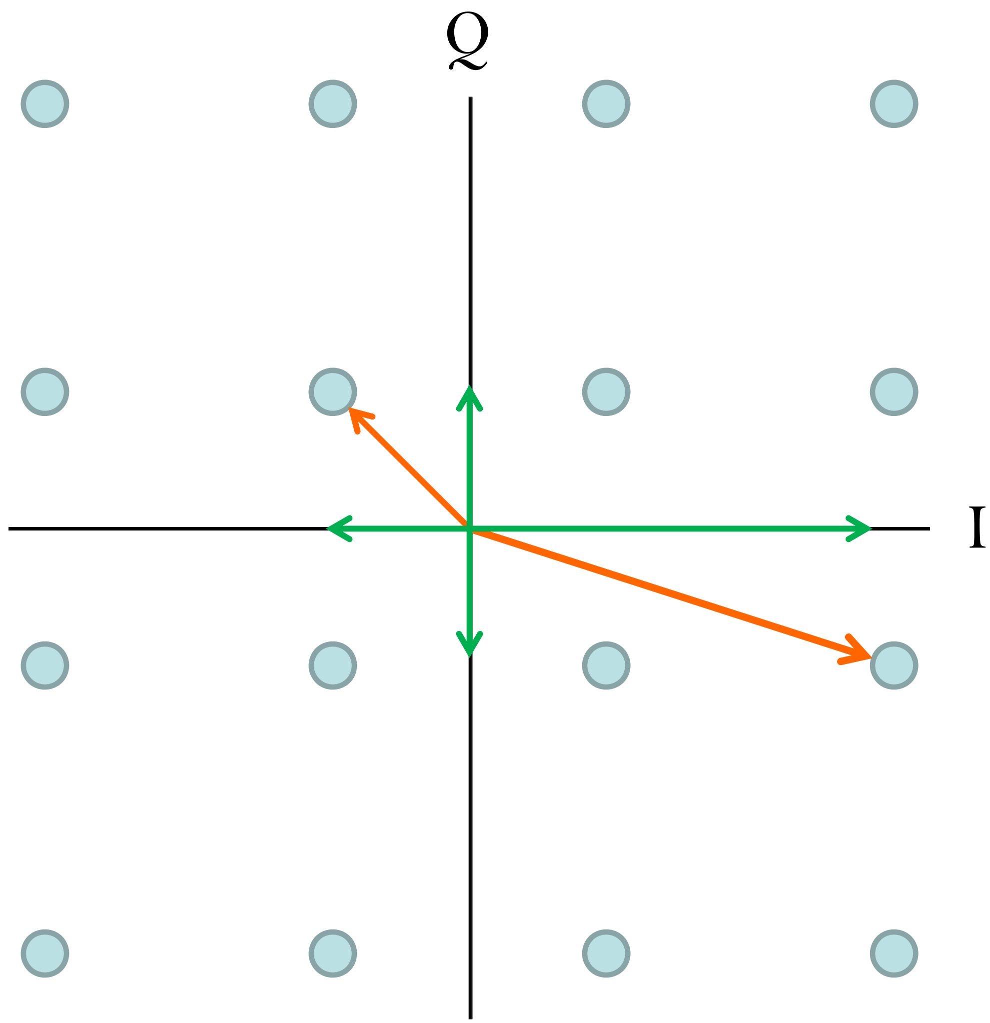
$$Z_{in} = 1/(Z_L g_{m1} g_{m2})$$



Differential
impedance inverter

See reference [1] for more baseband applications of OTAs.

OTAs in Microwave Circuits and Systems


Q
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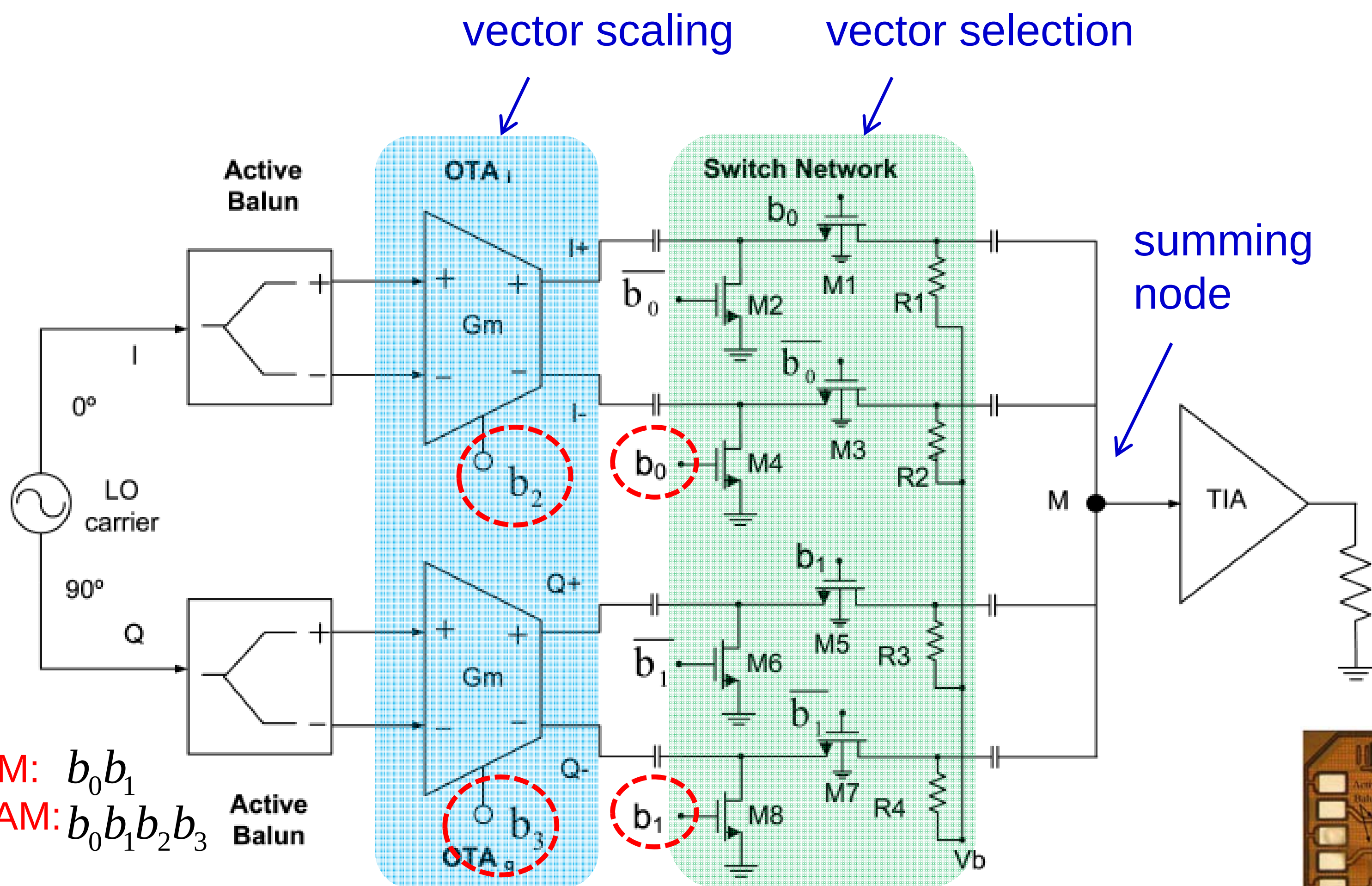
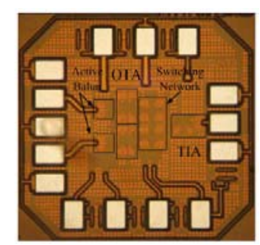
Multi-order QAM circuit

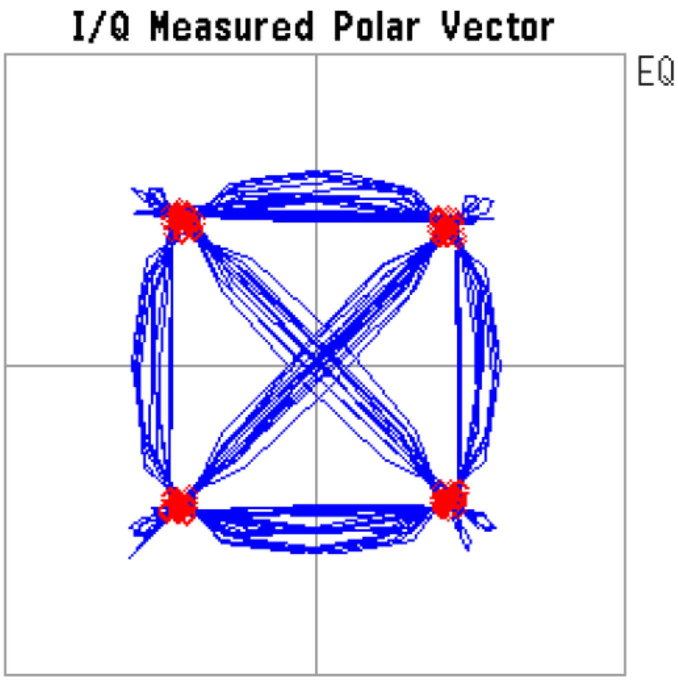


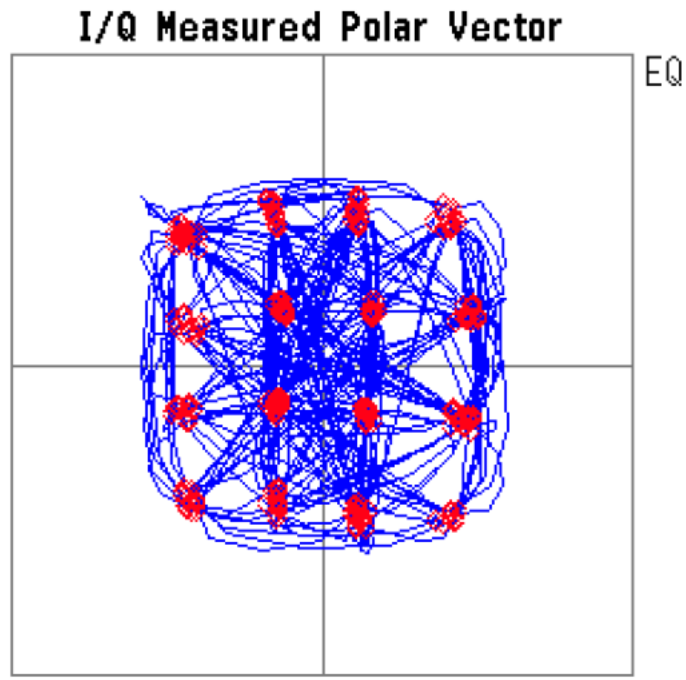
For 4-QAM: b_0b_1

For 16-QAM: $b_0b_1b_2b_3$



Multi-order QAM circuit

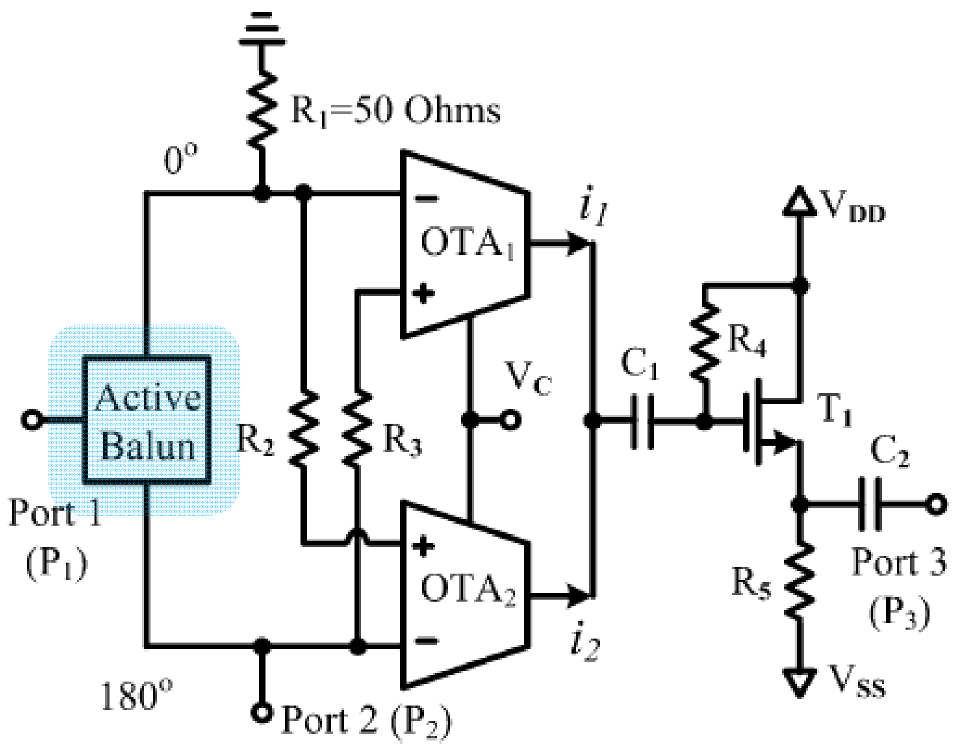


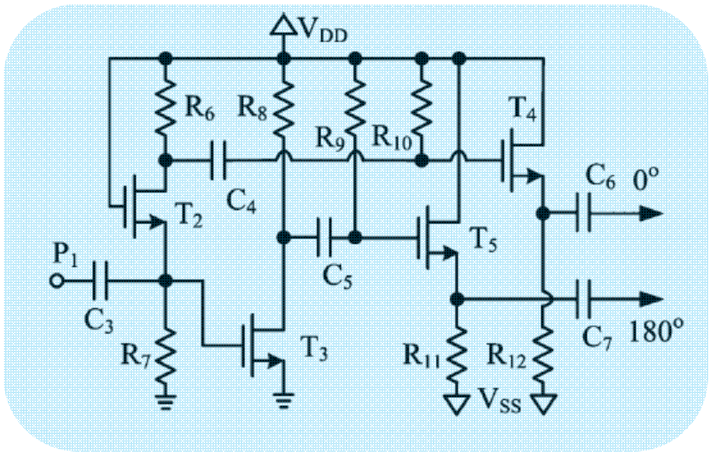


Modulation Scheme	EVM (%)	Mag Error (%)	Phase Error degree	Freq Error (Hz)	DC offset (dB)	SNR (dB)	Output Power (dBm) $@P_{in} = -19dBm$
QPSK	2.33	1.43	1.12	-12.59	-22.13	32.14	-27.99
16-QAM	6.20	4.40	4.05	-139.96	-26.16	21.23	-21.59

For further details see [2].

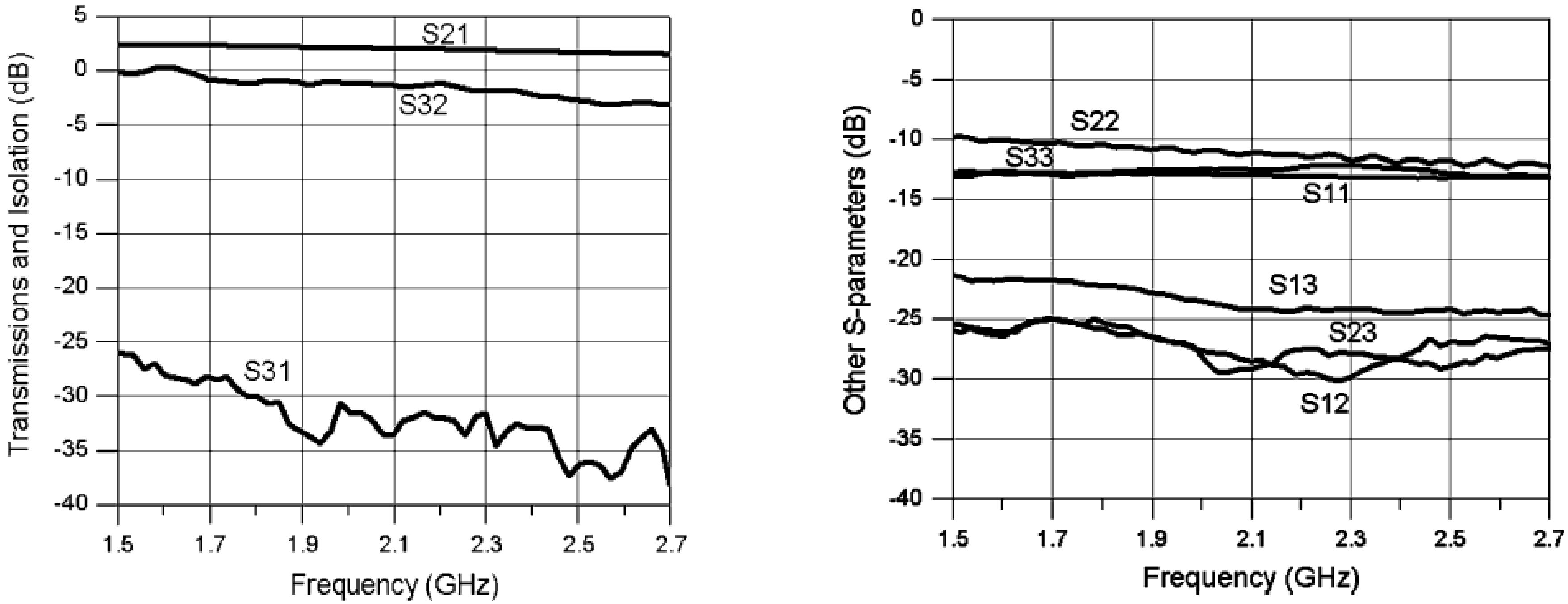
Active quasi-circulator





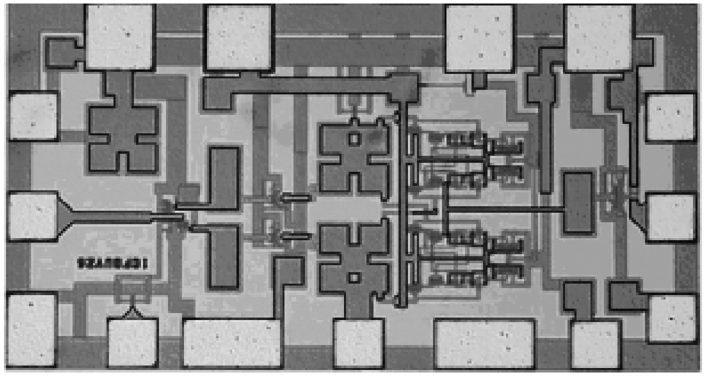
active balun

Active quasi-circulator



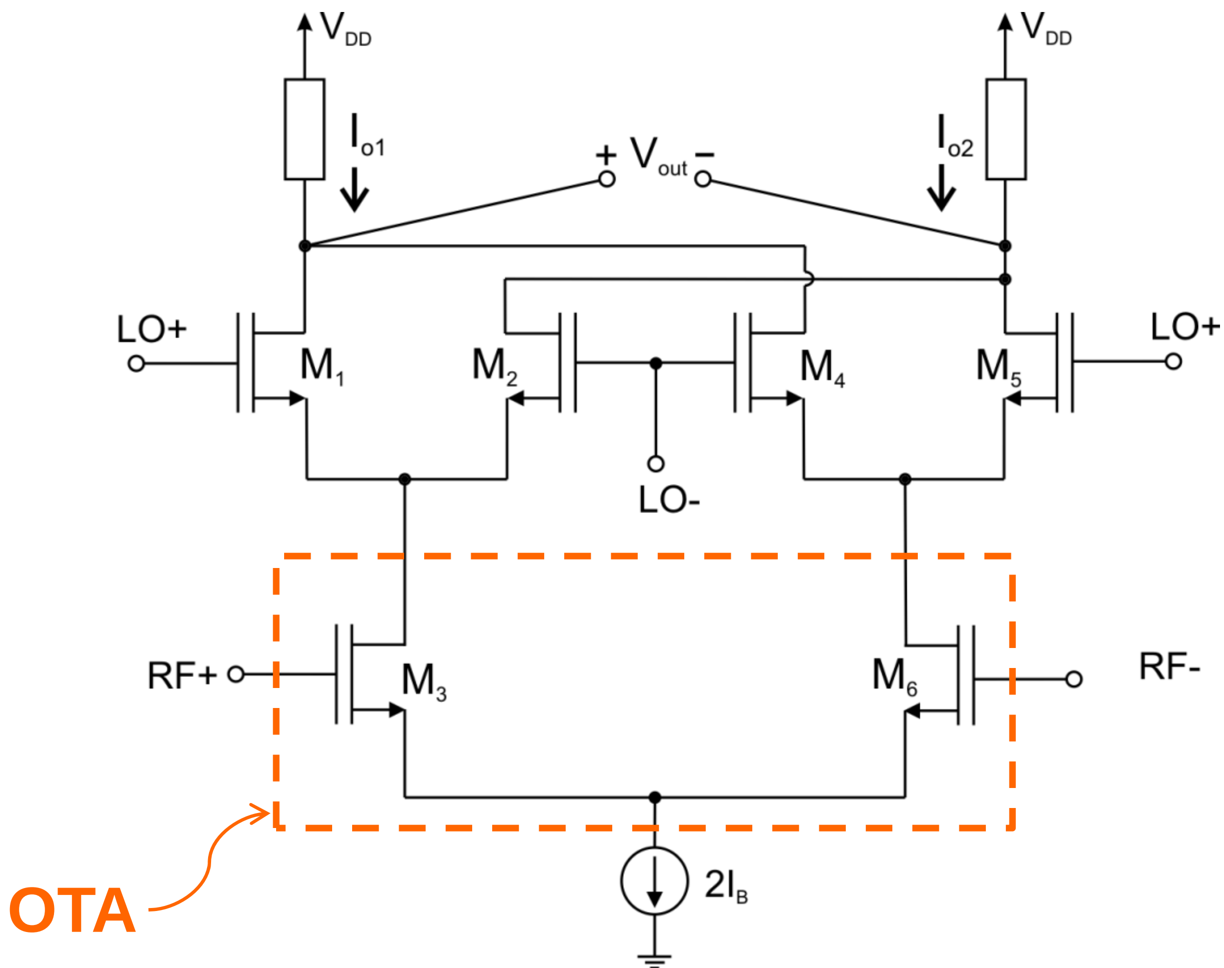
Active Quasi-Circulator

Parameter	Value
IP_{1dB}	-6.4 dBm
IIP3	+1.2 dBm
NF	10.4±0.2 dB
DC power	86 mW
Core size	0.25 sq. mm.
Technology	180 nm CMOS



For further details see [3].

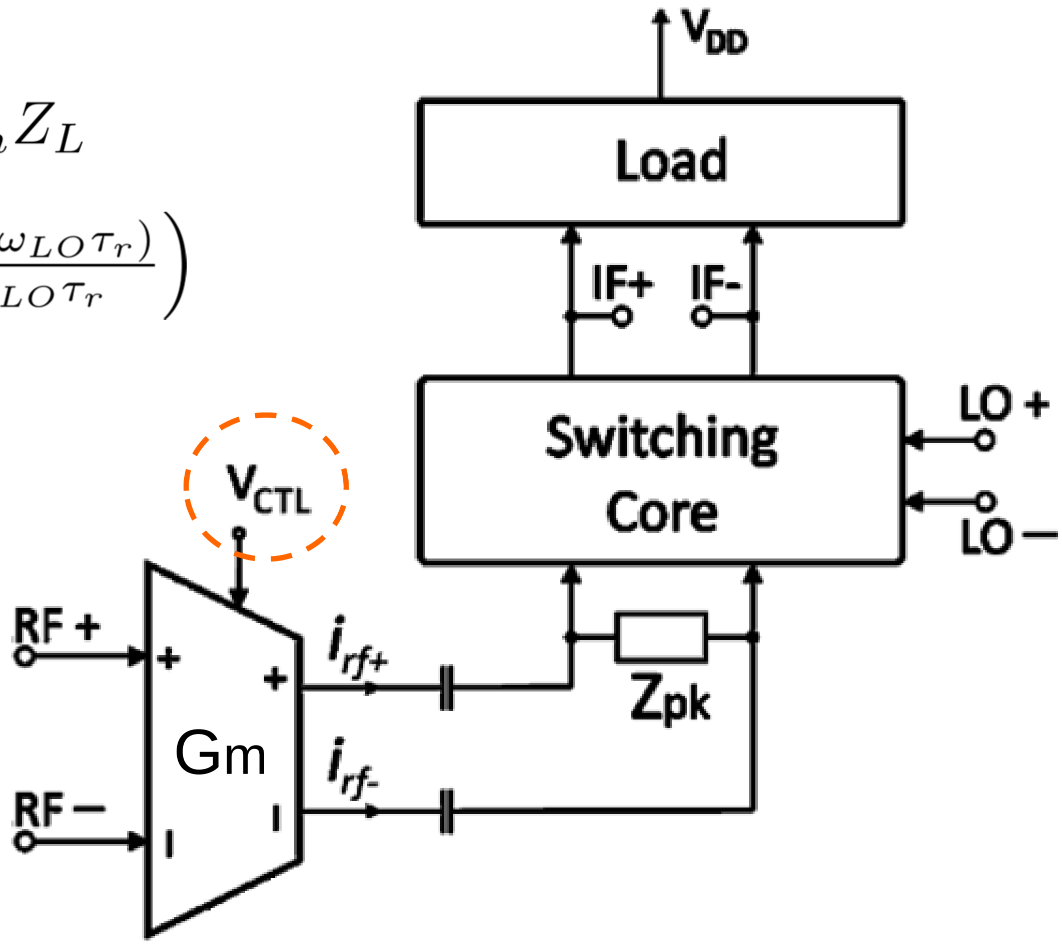
OTAs in active mixers

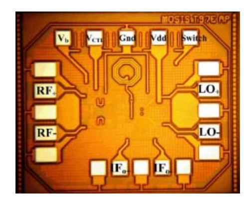


Variable conversion gain mixer

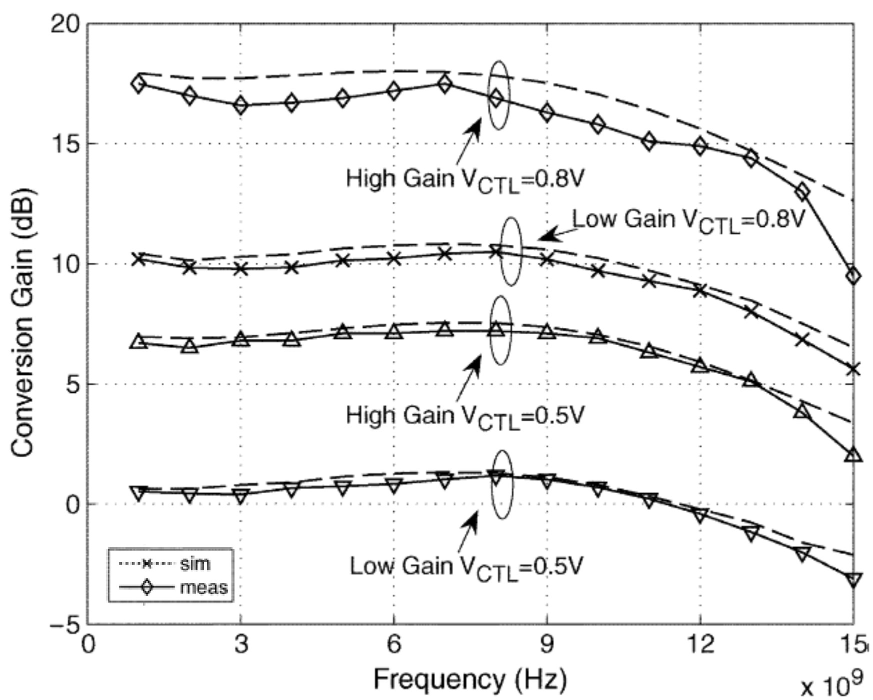
$$CG = \kappa G_m Z_L$$

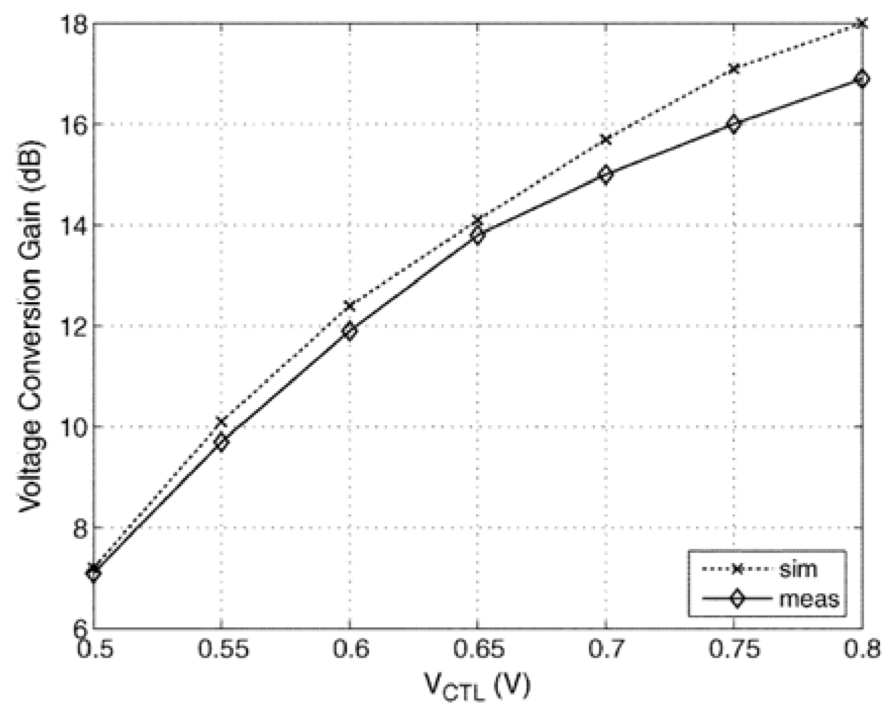
$$\kappa = \frac{2}{\pi}\left(\frac{\sin(\omega_{LO}\tau_r)}{\omega_{LO}\tau_r}\right)$$





VCG mixer





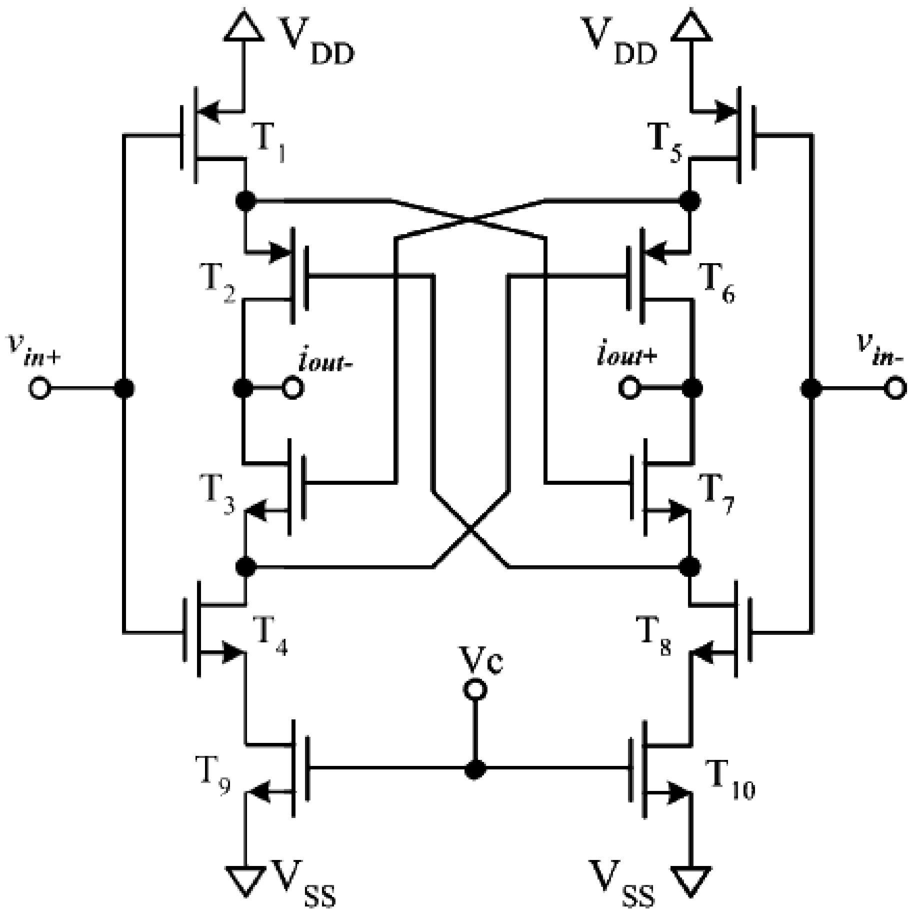
For further details see [4].

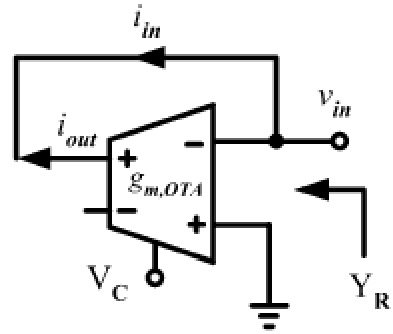
VCG mixer

Parameter		Value
RF frequency input	(GHz)	1 to 12 GHz
Conversion gain	(dB)	+1.2 to +17 dB
Input P_{1dB}	(dBm)	-3.7 (max) -12 (min)
Input IP3	(dBm)	+8.6 (max) +2.5 (min)
DSB noise figure	(dB)	11 (min) >19 (max)
DC power	(mW)	1.8 (min) 5.9 (max)
Vdd	(V)	1.2
Chip core area	(sq. mm.)	0.105
CMOS node	(nm)	130

Microwave OTA Circuit Design

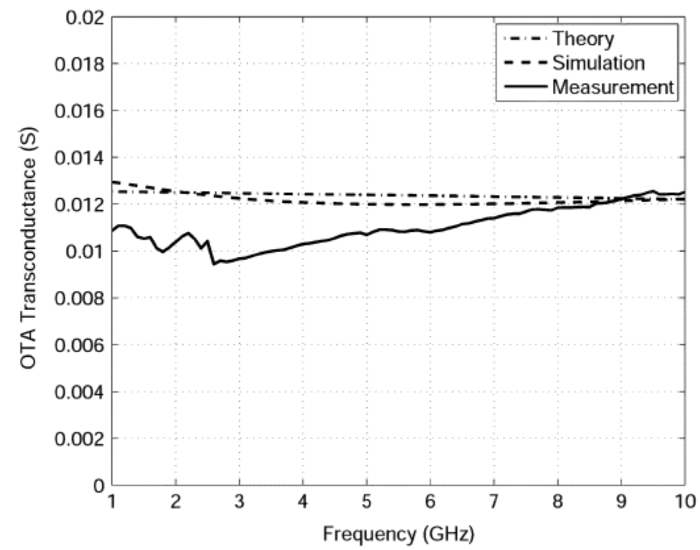
Full CMOS version





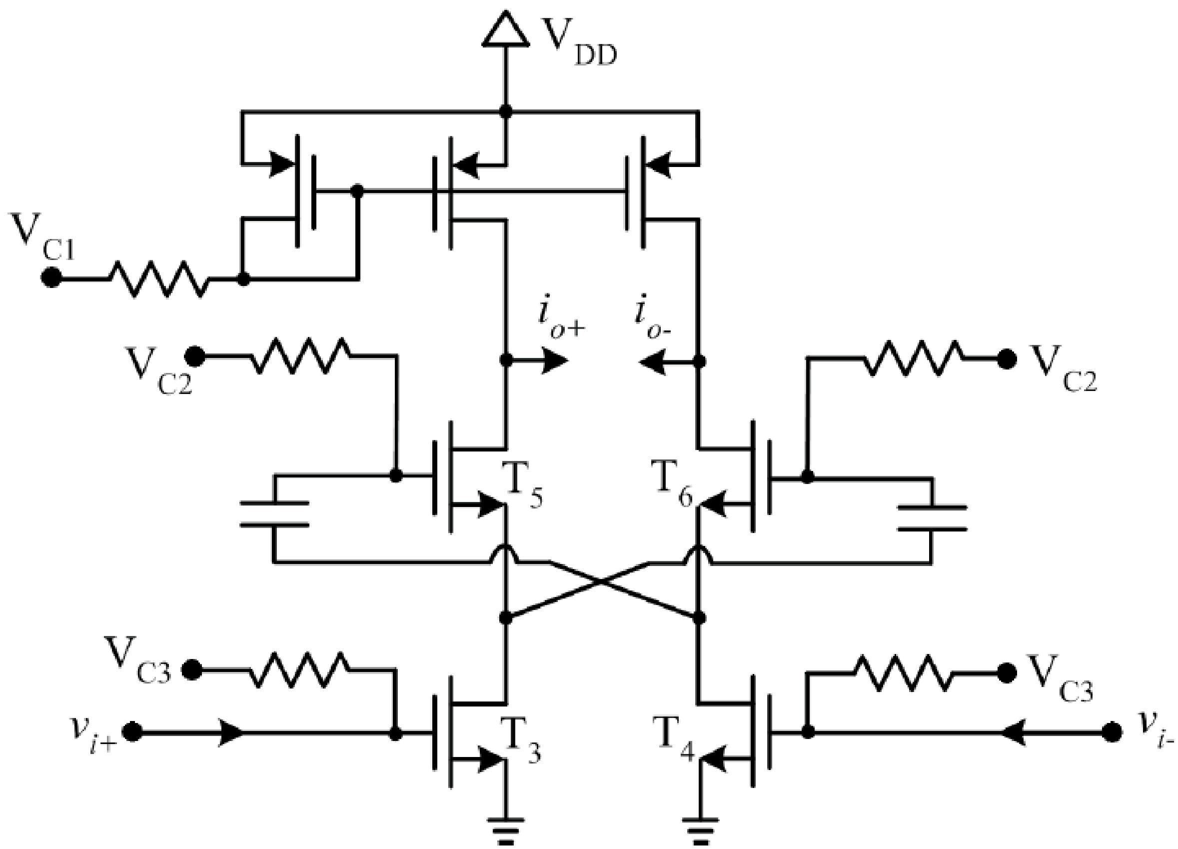
$$Y_R = Y_0\left(\frac{1-S_{11}}{1+S_{11}}\right)$$

$$|g_{m,\mathrm{OTA}}| \approx \mathrm{Re}(Y_R)$$



For further details see [5].

The feedforward regulated cascode OTA



In the ideal case of a perfectly balanced circuit:

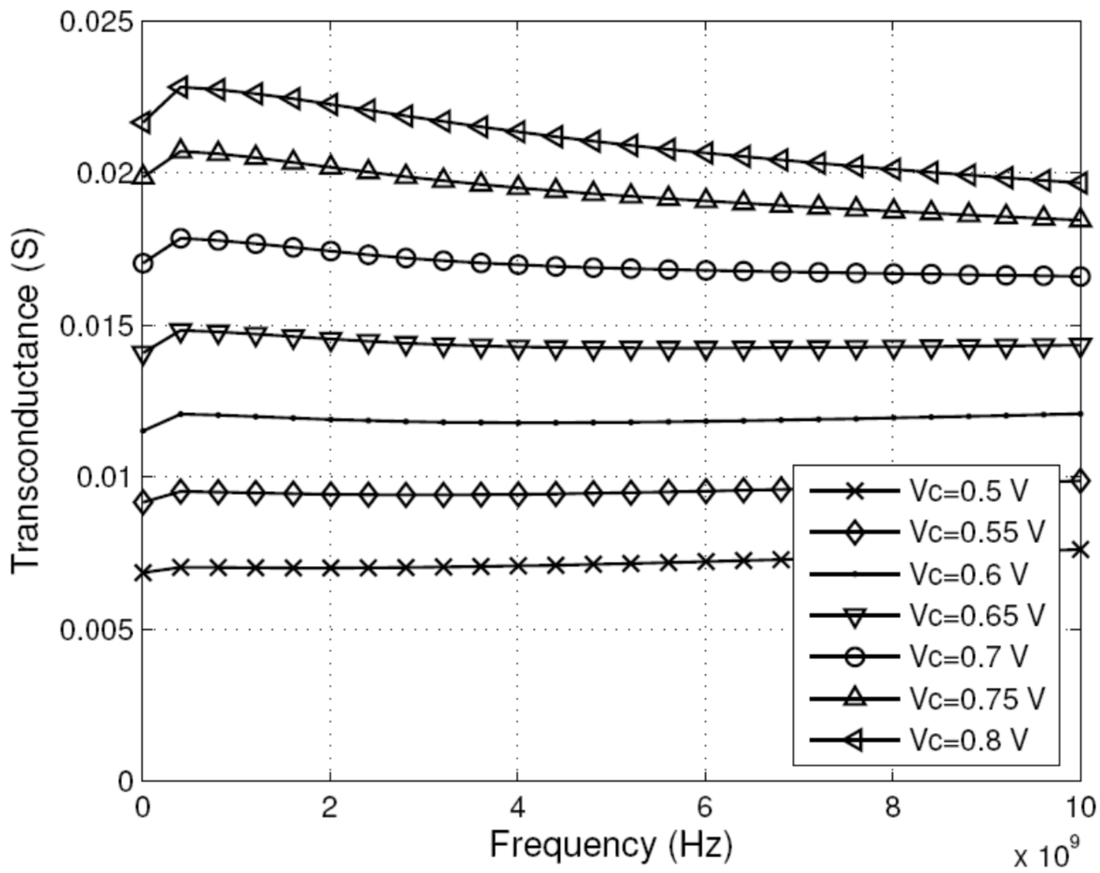
$$G_m = \frac{i_{o+} - i_{o-}}{v_{i+} - v_{i-}}$$

$$= g_{m3}\left[\frac{\frac{1}{r_{o5}} + 2g_{m5}}{\frac{1}{r_{o3}} + \frac{1}{r_{o5}} + 2g_{m5}}\right]$$

$$R_o = 2r_{o3} + 2r_{o5} + 4g_{m5}r_{o3}r_{o5}$$

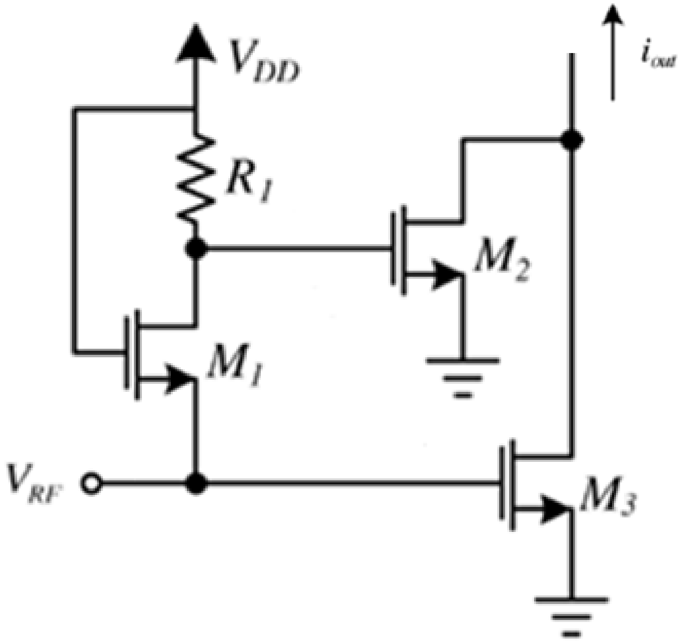
For further details see [6-8].

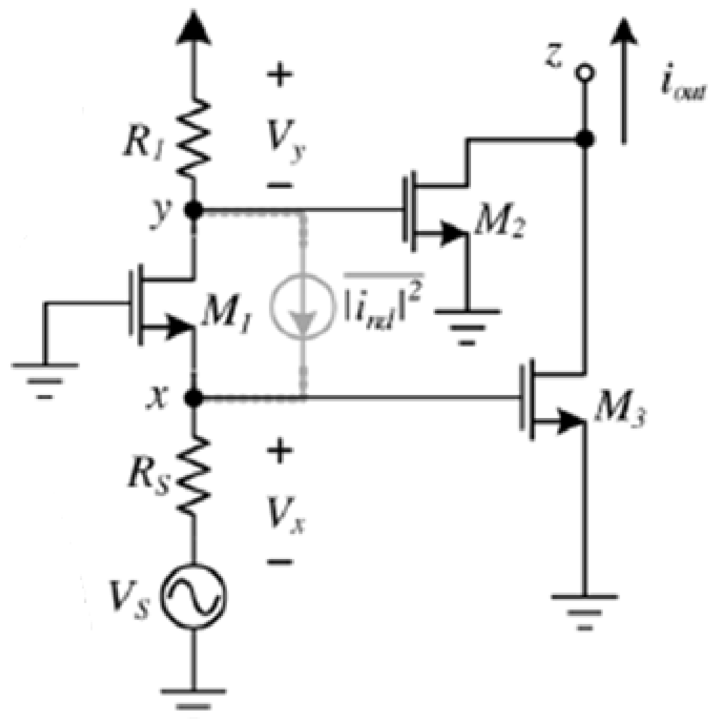
Frequency response



How to make a low-noise OTA?

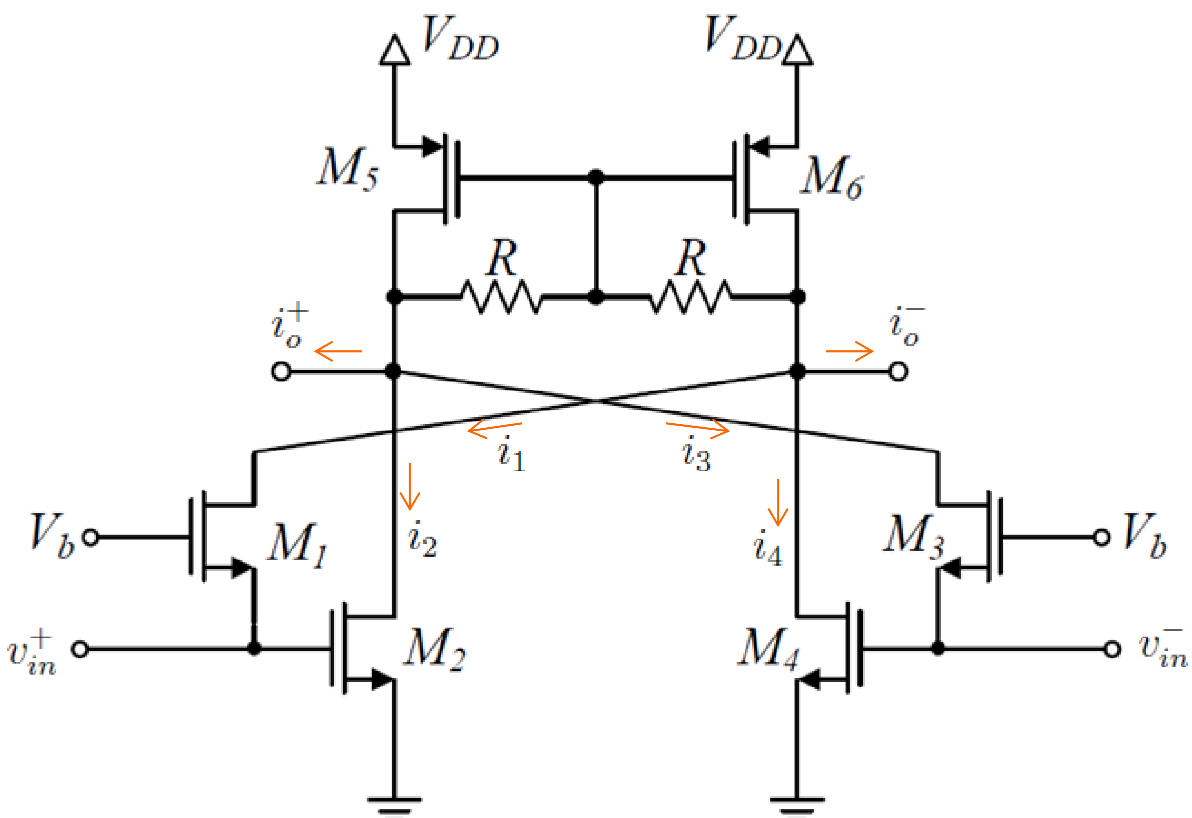
Start with the noise-cancelling method [9] used in LNAs:





Low-noise OTA (LNTA)

Cross-couple the basic cells to get:



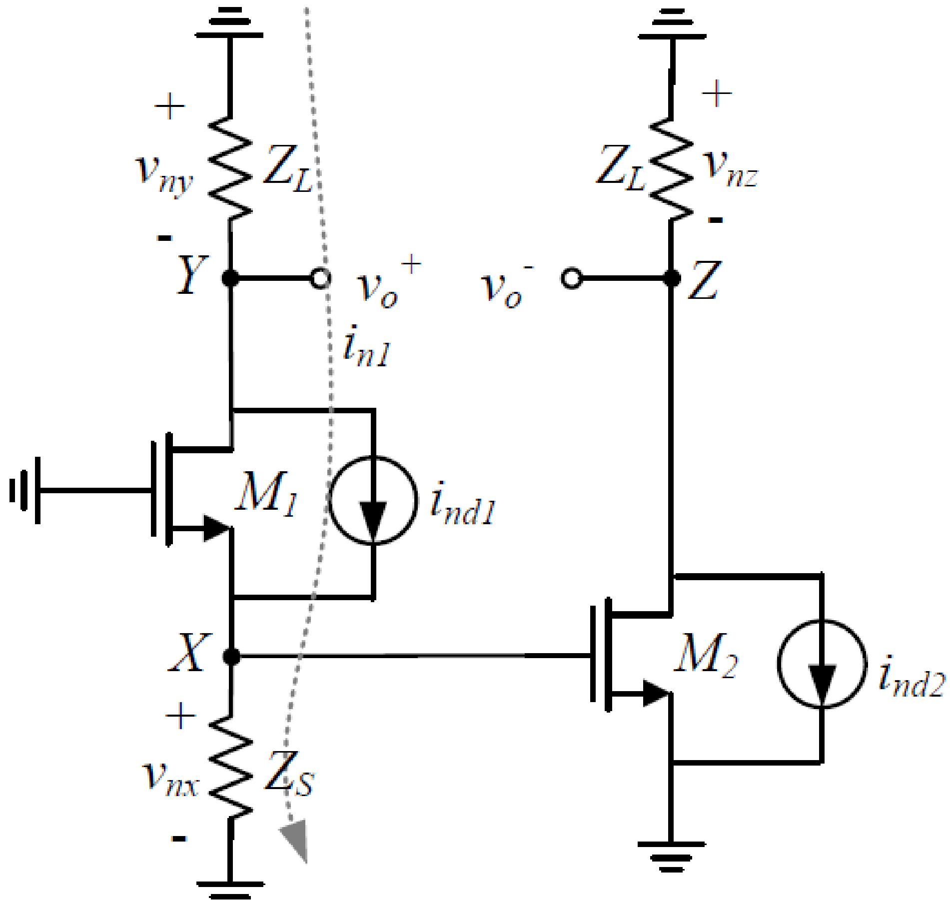
$$i_o^+ = i_2 + i_3 = g_{m2}v_{in}^+ - g_{m3}v_{in}^-$$

$$i_o^- = i_1 + i_4 = -g_{m1}v_{in}^+ + g_{m4}v_{in}^-$$

$$G_m = \frac{i_o^+ - i_o^-}{v_{in}^+ - v_{in}^-} = g_{m,CG} + g_{m,CS}$$

For further details see [10,11].

The CG-CS pair



Output noise voltages:

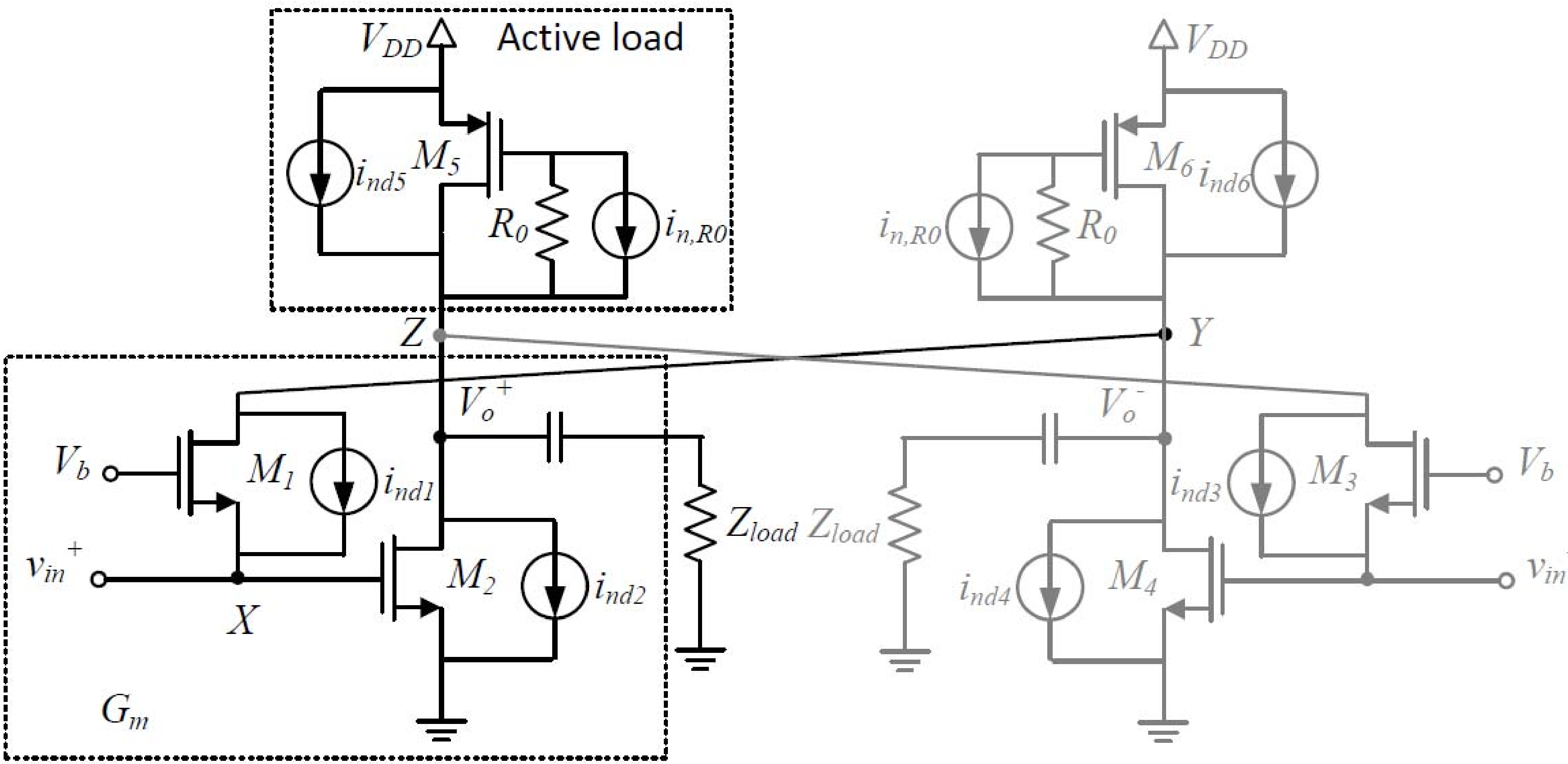
$$v_o^+ - v_o^- = v_{ny} - v_{nz}$$

$$= i_{n1}(1 - g_{m2}Z_s)Z_L$$

For cancellation:

$$g_{m2} = 1/Z_s = g_{m1}$$

The LNTA noise circuit model



Noise Factor (thermal noise only)

Definition:

$$F = \frac{SNR_{in}}{SNR_{out}} = 1 + \frac{\overline{|i_{n,added}|^2}}{G^2_{m,eff}\overline{|v_{ns}|^2}}$$

the added noise current is:

$$\overline{|i_{n,added}|^2} = \overline{|i_{n,G_m}|^2} + \overline{|i_{n,actLoad}|^2}$$

$$\begin{aligned}
\overline{|i_{n,G_m}|^2} &= \overline{|i_{n1}|^2}(g_{m2}Z_s - 1)^2 + \overline{|i_{nd2}|^2} \\
&= \overline{|i_{n1}|^2}(g_{m2}Z_s - 1)^2 + 4kT\gamma_n g_{m2} \\
\overline{|i_{n,actLoad}|^2} &= \overline{|i_{nd5}|^2} + \overline{|i_{n,R_0}|^2} = 4kT\gamma_p g_{m5} + \frac{4kT}{R_0}
\end{aligned}$$

Noise Factor

the source noise voltage is:

$$v_{ns} = \sqrt{4kTR_s}\frac{Z_{in,eff}}{R_s + Z_{in,eff}}$$

where,

$$Z_{in,eff} \approx \frac{r_{o1} + Z_L}{1 + (g_{m1} + g_{mb1})r_{o1}}$$

$$G_{m,eff} \approx \frac{1 + (g_{m1} + g_{mb1})r_{o1}}{r_{o1} + Z_L} + \frac{g_{m2}r_{o2}}{r_{o2} + +Z_L}$$

and substituting…

$$F = 1 + \frac{\overline{|i_{n1}|^2}(g_{m2}R_s - 1)^2}{4kTR_s^{-1}(R_s \parallel Z_{in,eff})^2 G_{m,eff}^2} + \frac{r_n g_{m2} + r_p g_{m5} + R_0^{-1}}{R_s^{-1}(R_s \parallel Z_{in,eff})^2 G_{m,eff}^2}$$

$$F = 1 + 4\frac{r_n g_{m2} + r_p g_{m5} + R_0^{-1}}{R_s G_{m,eff}^2} = 1 + 4\frac{r_n g_{m2} + r_p g_{m5} + R_0^{-1}}{\left[\frac{1+(g_{m1}+g_{mb1})r_{o1}}{Z_L + r_{o1}} + \frac{g_{m2}r_{o2}}{Z_L + r_{o2}}\right]^2 R_s}$$

Conclusion

- Fully differential OTAs offer the greatest versatility and system design possibilities.
- OTAs can be used to implement more complex microwave circuits while keeping chip dimensions small.
- Reducing the NF of OTAs continues to be an active area of investigation.

References

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