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## Differential Structures

Damien Prêle

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A phase portrait in the plane showing a vertical line of symmetry. On the left side, there is a center point (a dot) surrounded by several nested closed orbits. On the right side, there is a saddle point (a point with an 'X') also surrounded by nested closed orbits. Trajectories flow from the top and bottom towards the vertical line, then curve around the centers and away from the saddle point.

# Differential Structures

*nano-electronic school* - Oléron - oct 2022

Damien PRÊLE

## Introduction

### Differential transmissions

- Differential signals
- Differential lines
- Coupling

### Differential amplifier

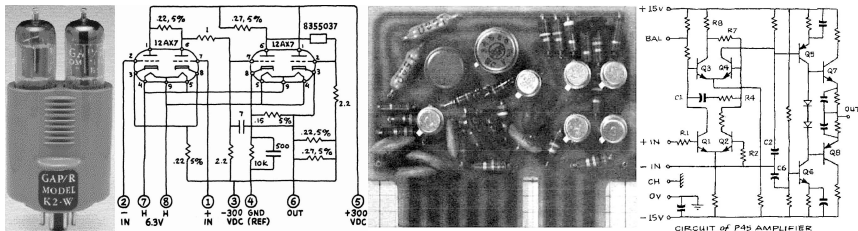
- Single to differential
- Fully differential amplifier
- Differential pair with "transistor load"
- Common Centroid Layout

### Noise and noise rejection



# Introduction: Initial use

- ▶ Differential structures since beginning of **signal transmission**
- ▶ Introduced to **minimize response to common mode signals/noises/interferences**
- ▶ Differential amplifier **circuit** using vacuum tubes in 1937/38  
(common-cathodes dual pentode circuit) used to drive push-pull
- ▶ Also introduced for "analog computing" in the 50s/60s to do **mathematical operations in analog computers**



GAP/R K2-W vacuum tube and solid-state (model P45) op amps

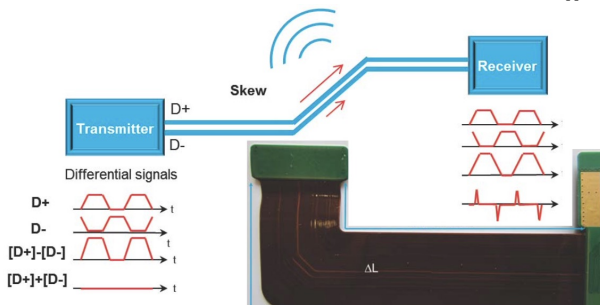


# Introduction: Reduce noise emissions

Electromagnetic compatibility

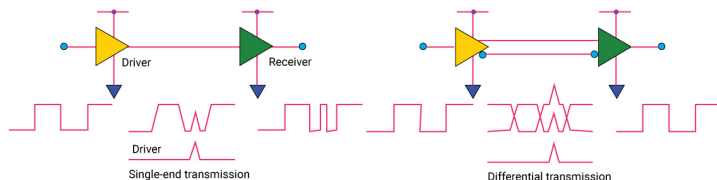


*In our connected world, data exchange very fast ... include high-speed serial links, ... fast transition times and long lines may induce radiations due to common mode noise ... AN4511 Application note*



# Introduction: Reducing common mode noise contamination.

**Low-voltage differential signaling**, or LVDS, is a way to communicate data using a differential signal - **reduce common mode noise contamination** - with a **small voltage swing** : LVDS standardized as ANSI/EIA/TIA 644 offers gigabit speeds at very **low power**



Also true for small/low-noise analog signal transmissions ...



## Introduction

### Differential transmissions

Differential signals

Differential lines

Coupling

### Differential amplifier

Single to differential

Fully differential amplifier

Differential pair with "transistor load"

Common Centroid Layout

### Noise and noise rejection



# Differential signaling

To decouple transmitted signals from "references" and reject external perturbations/emissions :

- ▶ **balanced** line / signal pair
- ▶ **2 conductors** same type  $\neq$  coaxial (return current connected GND)
- ▶ circuits interfacing balanced line must also be balanced :
  - ▶ transformer or ballun / autotransformer
  - ▶ differential to single or single to differential
  - ▶ floating sources or loads
  - ▶ differential sensors
  - ▶ ...
- ▶ **balanced impedances to ground**
- ▶ wires twisted together  $\rightarrow$  each conductor is equally exposed to noise-inducing magnetic fields

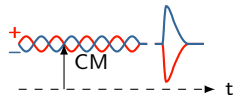
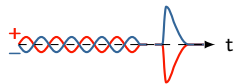
+ Maximum output is twice as much (wrt norm/standard)





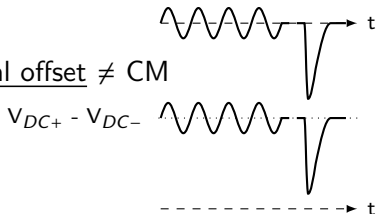
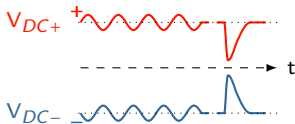
# Transmitting a signal using a pair of opposite signals

- ▶ opposite phase/polarity
- ▶ both same amplitude
- ▶ could be also associated to a common mode "signal"



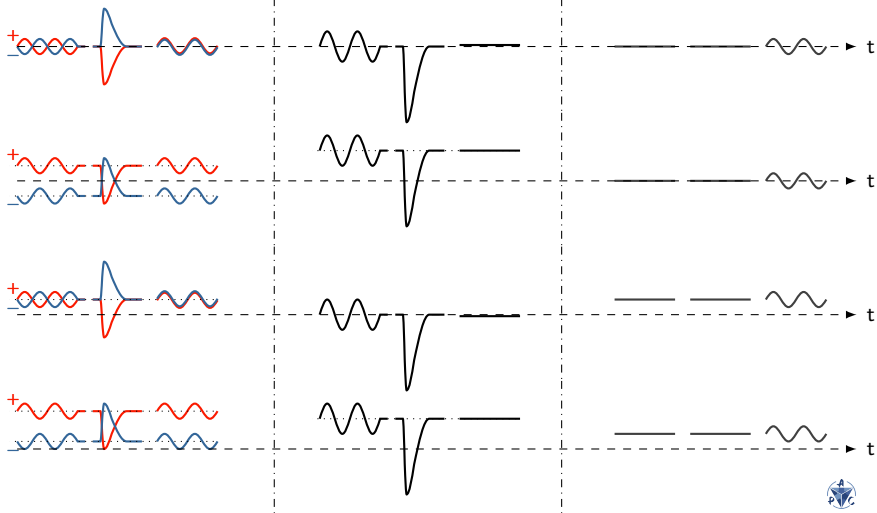
## Differential signal characteristics

- ▶ differential amplitude = twice larger than each opposite signal
- ▶ can be affected by a differential offset  $\neq$  CM



# "Opposite" signals $\Rightarrow$ Differential signal $\Rightarrow$ Common mode

$$\text{Single } V_+ \text{ and } V_- \Rightarrow V_{diff} = V_+ - V_- \Rightarrow V_{CM} = \frac{V_+ + V_-}{2}$$

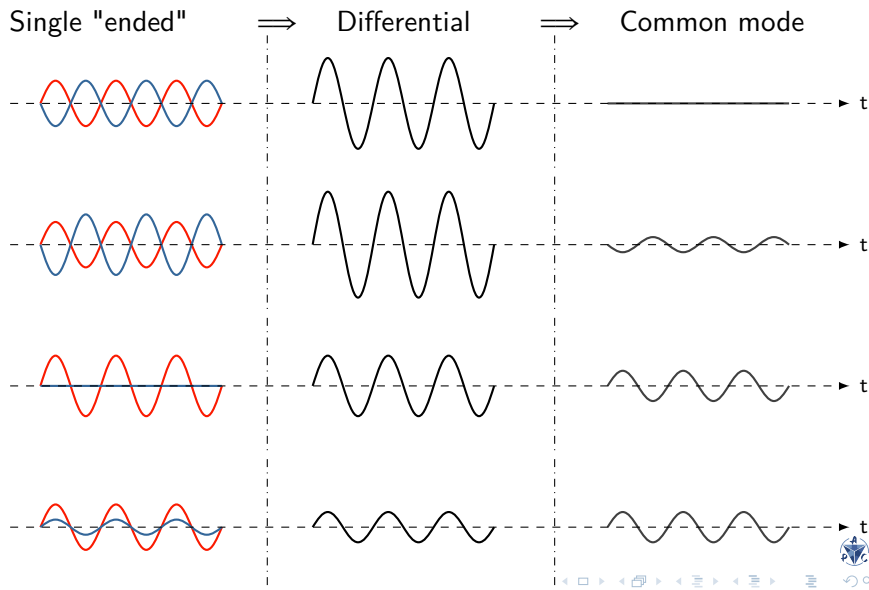


# Causes of imbalance on differential signals

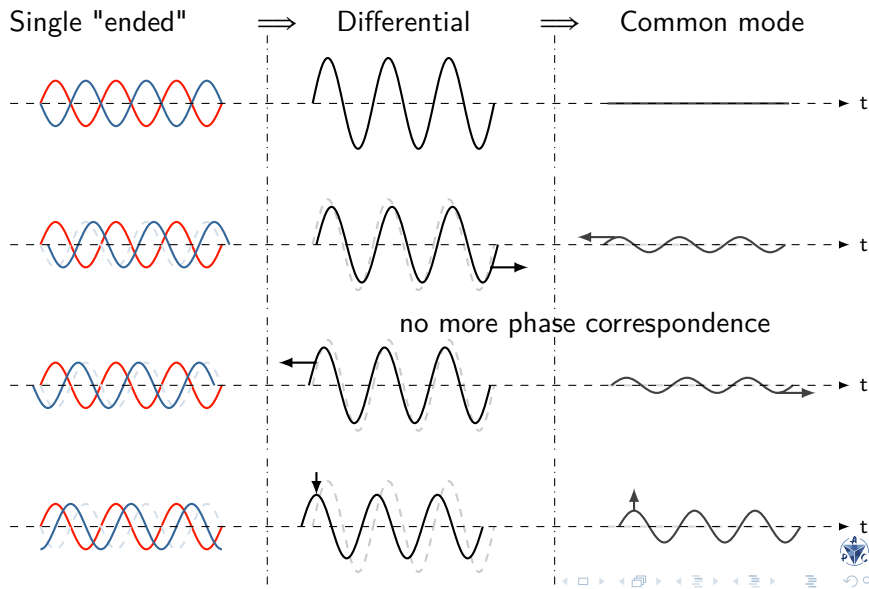
- ▶ Lack of **symmetry** on the device pairs
- ▶ **unbalanced** biasing
- ▶ Differences in routing **length**
- ▶ Differences in routing **widths**
- ▶ Differences in routing **resistivity**
- ▶ Differences in routing **layer/material**
- ▶ Routing through **non-continuous grounding/return**
- ▶ **Coupling** to other traces and grounding inhomogeneities
- ▶ Active devices **timing/BW** asymmetry
- ▶ unbalanced **impedance/matching**



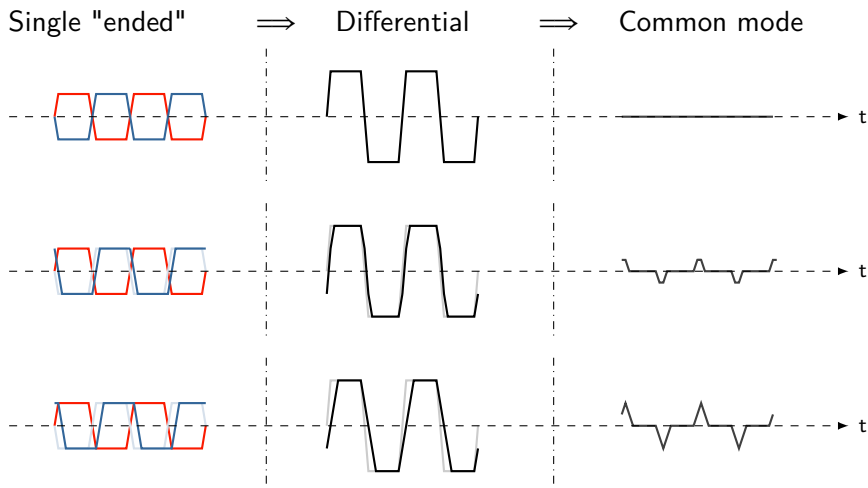
# Unbalanced amplitude: diff. to CM conversion



# Unbalanced phase: diff. to CM conversion



# Skewed: CM glitches & slow transient



# Balanced line/circuit and differential signaling

1. **A balanced line/circuit** shows a symmetry for common-mode rejection

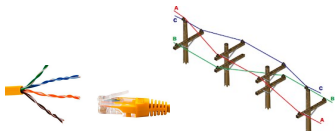


2. **Two wire transmission & "transposition"** was introduced end of the 19th century to improve telegraph/telephone transmissions

in replacement of single-wire earth return affected by ... electric trams interference



3. It as also applied to **tree phase power transmission lines** to restrain induced current in parallel lines and for phase balancing

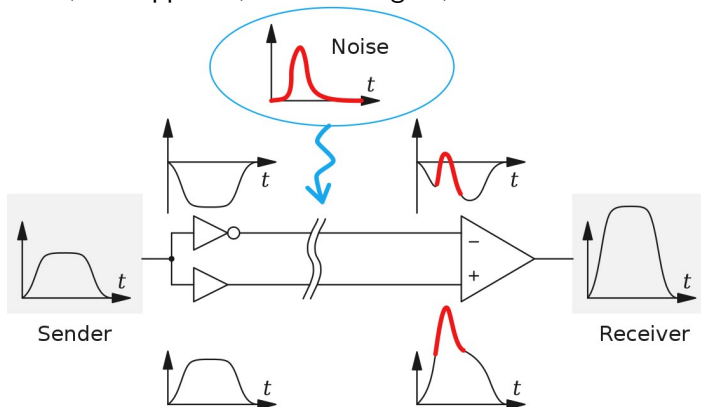


4. **Twisted pairs** - ethernet networks



# Differential signalling

Transmitting information using two complementary signals same, but opposite, electrical signal, each in its own conductor



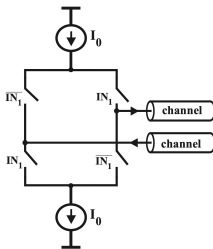
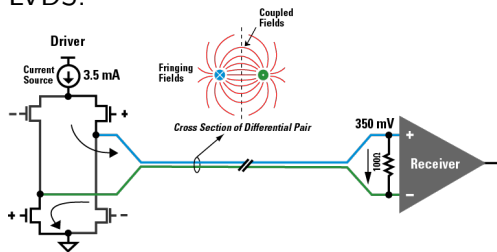
The pair of conductors can be wires in a twisted-pair or ribbon cable or traces on a printed circuit board...





# Differential signalling

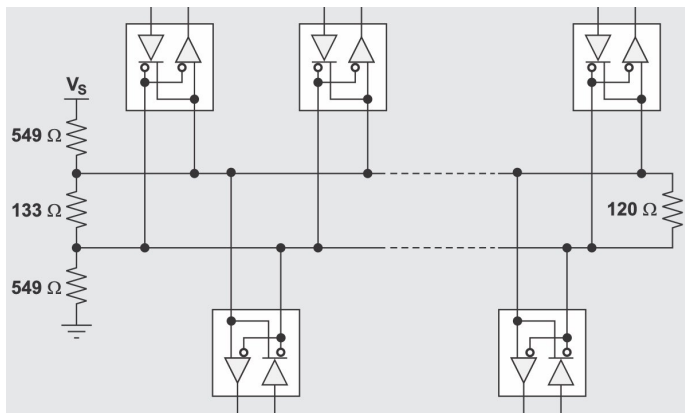
LVDS:



or fully floating:



# Failsafe mode: RS485

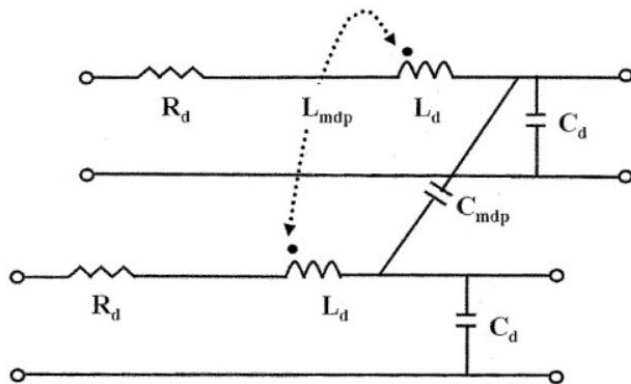


or 2 loads at 120  $\Omega$  and 800  $\Omega$  pull resistors can be also used ...

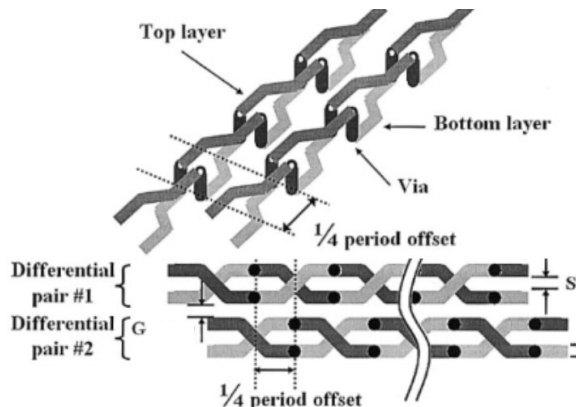


## Coupling of a differential line in planar technology

A transmission line couples with any references at direct proximity, as for example the complementary line



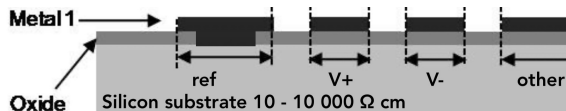
# Differential twisted pair in planar technology



IEEE TRANSACTIONS ON ADVANCED PACKAGING, VOL. 27, NO. 4, NOVEMBER 2004, D. G. Kam et al.

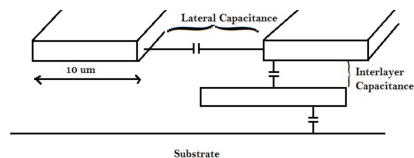
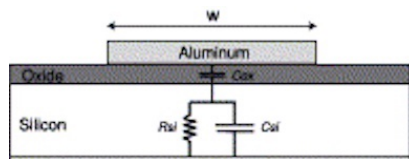
Twisted Differential Line Structure to Reduce Crosstalk and Radiated Emission

# Differential twisted pair in planar technology

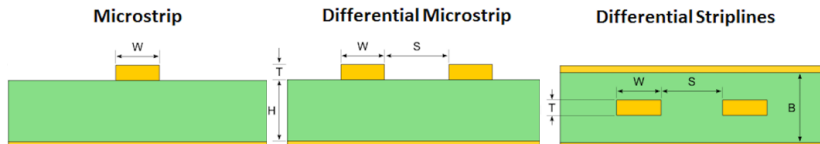


substrate resistance in the range 10 - 10 000  $\Omega$  cm

-> qq  $\Omega$  to a reference



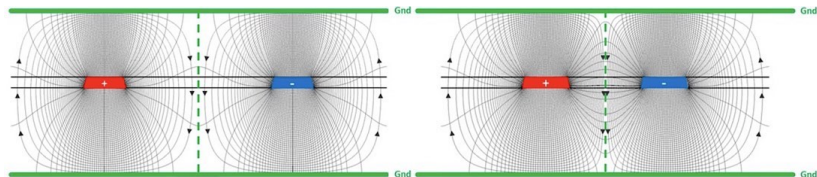
# Microstrip impedance : $Z_0$ single ended vs differential



$$Z_0 = \frac{87}{\sqrt{\epsilon_r + 1.41}} \ln \frac{5.98H}{0.8W + T}$$

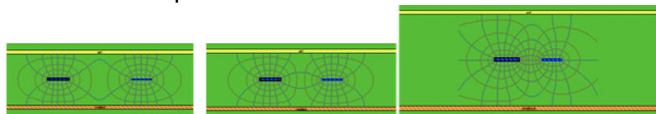
$$Z_{Diff} = 2Z_0(1 - 0.48\exp(-0.96S/H))$$

Differential pairs are never tightly coupled together. Electric and magnetic fields from the signal and return paths of one transmission line couple to another and to the substrate.



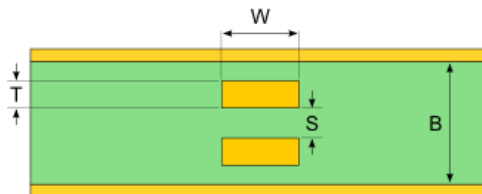
## Tight coupling

Tightly coupled (Spacing =  $w$ ), loosely coupled (Spacing =  $2w$ ) and uncoupled pairs (Spacing =  $3w$ ), drawn to scale for 100 Ohm differential impedance



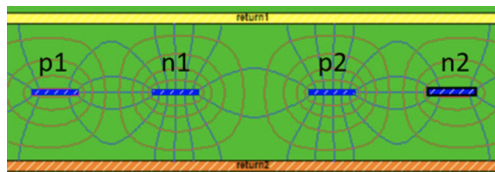
Tight or Loosely Coupled Differential Pairs to Reduce Cross Talk? Signal Integrity Journal

Broadstriplines can also reinforce differential coupling :



# Tight coupling and cross talk

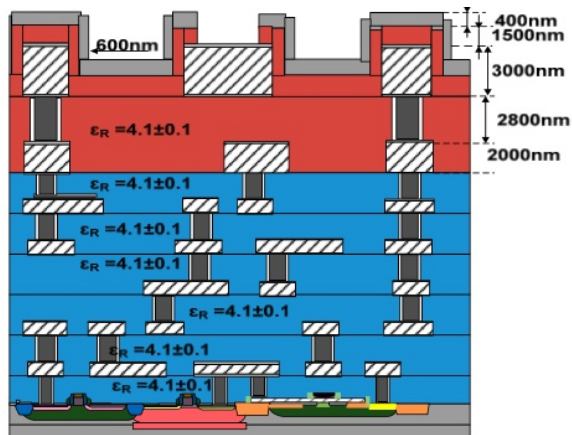
Trying to tightly couple a differential pair increases the risk of cross talk



differential pairs with fringe field lines between adjacent channels



# Dielectric constant and metal distances and thickness in a BiCMOS SiGe 130 nm technology



cross section showing thickness of the top two-layer metals layers and the relative permittivity ( $\epsilon_R$  FR4 4.7, SiO<sub>2</sub> 3.9, Silicon 12)



## Introduction

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### Differential amplifier

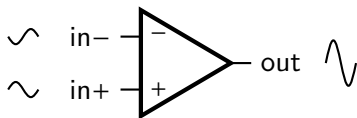
- Single to differential
- Fully differential amplifier
- Differential pair with "transistor load"
- Common Centroid Layout

### Noise and noise rejection

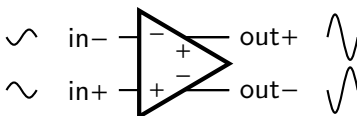


# What we call differential amplifier ?

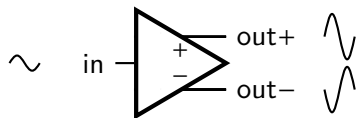
- ▶ Differential input  $\rightarrow$  single ended output



- ▶ but also ... Differential input  $\rightarrow$  differential output

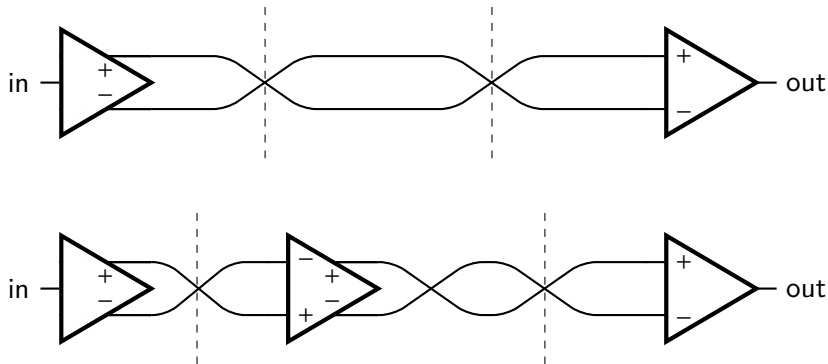


- ▶ or could be ... Single "ended" input  $\rightarrow$  differential output



## A "typical" differential transmission line

single to differential  $\Rightarrow$  differential signal  $\Rightarrow$  differential to single

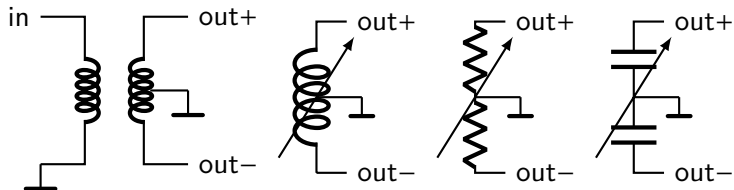


1. Single ended to differential (S2D)
2. Transmission line and differential to differential amplifier
3. Differential to single ended (D2S)

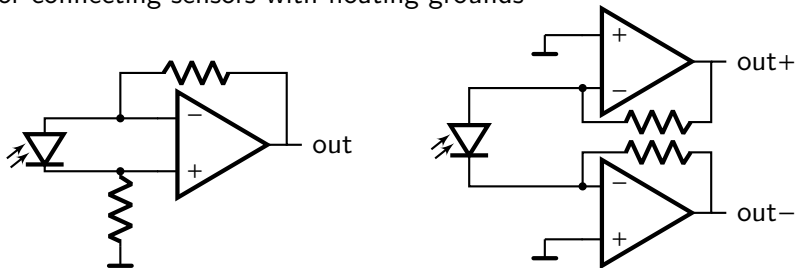


# Intrinsic differential signal: directly provide by the sensors

Center tap in transformer or in any devices (or with a dark one)

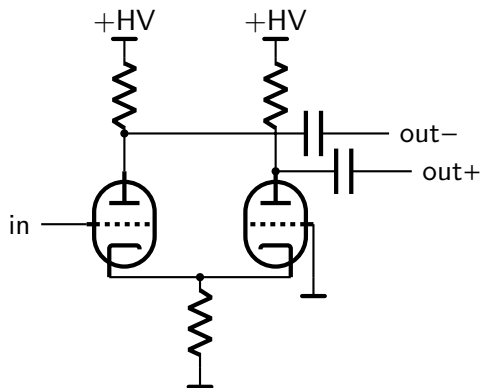
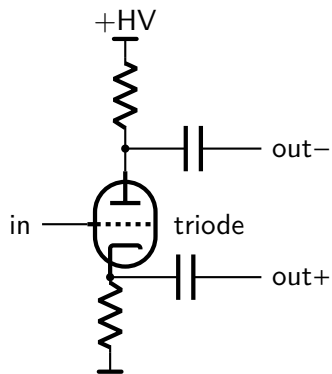


or connecting sensors with floating grounds



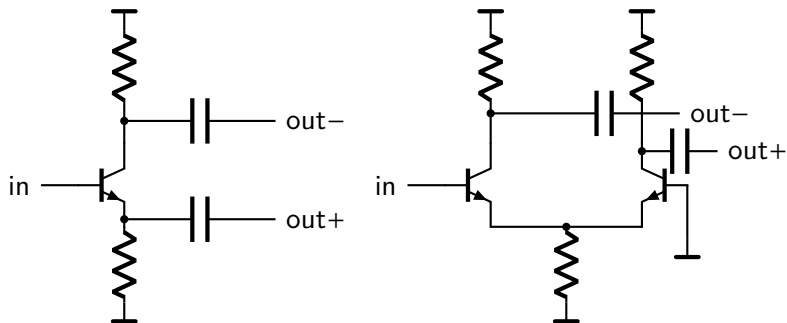
## Single to differential amplifier: phase splitter

Phase splitter stage of a push-pull vacuum tube amplifier, used during decades to drive "single type" push-pull + output transfo.



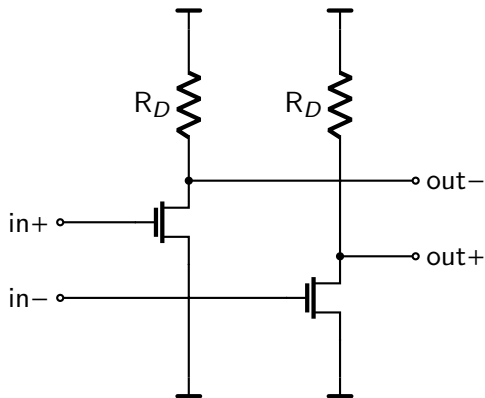
## Single to differential amplifier: phase splitter

Phase splitter with solid state devices. producing two balanced voltage outputs of equal amplitude but opposite polarity



used to produce differential signaling

## Differential amplifier could be 2 single ended amplifier



Double the dynamic, reject the Power supply Noise :- ) ... but not strongly the common mode :- (  $\Rightarrow G_{CM} \approx G_{Diff}$

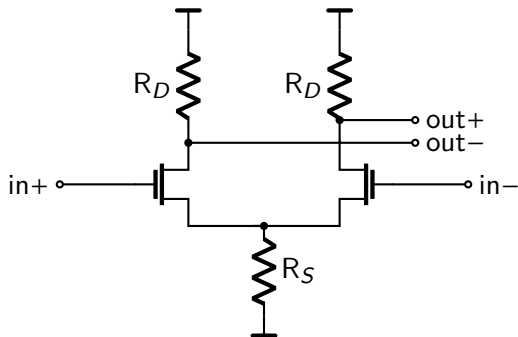
$$G_{Diff} = gmR_d, G_{CM} = gmR_d/2, CMRR=2$$

Not easy to determined  $gm$  ...  $gm = \sqrt{2\mu_n C_{ox} I_D W/L}$  ... but  $I_D$ ?





# Differential pair



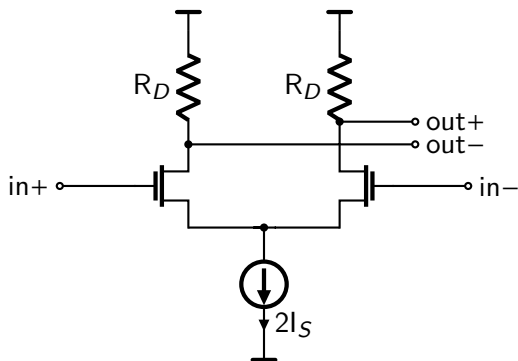
Double the dynamic, reject the Power supply Noise AND the common mode

$$G_{Diff} = gmR_D, G_{CM} = R_D/2R_S, CMRR=gm2R_S$$

Not easy to determined  $gm \rightarrow$  replace  $R_S$  by a current source  $2 I_D$

Output voltage and gain are linked and need high power supply for large gain

## Differential pair with current source



gm deduce from  $I_S$  :  $g_m = \sqrt{\mu_n C_{ox} I_S W/L}$  & larger CMRR

Fully symmetric differential pair senses differential. A differential change in the inputs  $V_+$  and  $V_-$  absorbed by  $V_{gs1}$  and  $V_{gs2}$  leaving middle voltage constant : virtual ground

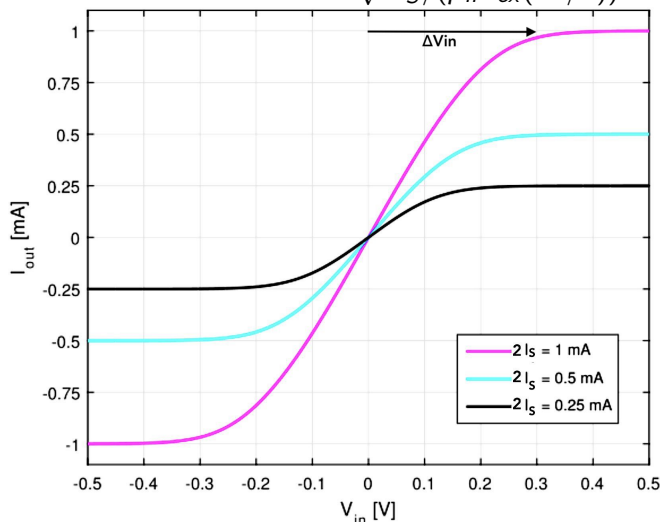
$V_D = V_{dd} - I_S \times R_D \rightarrow$  gain limitation and output common mode link We need a larger drain resistor to achieve

higher gain, but more drain resistance means a lower DC voltage at the output nodes

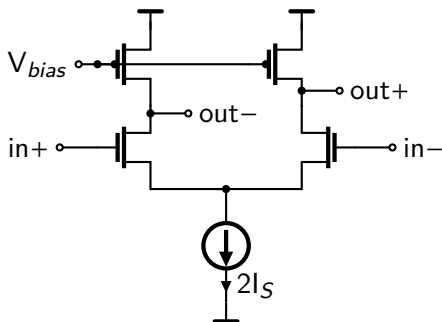


# Differential amplifier response

differential output current vs. the differential input voltage for various tail currents.  $\Delta V_{in} = \sqrt{2I_S / (\mu_n C_{ox} (W/L))}$



## Differential pair with current load

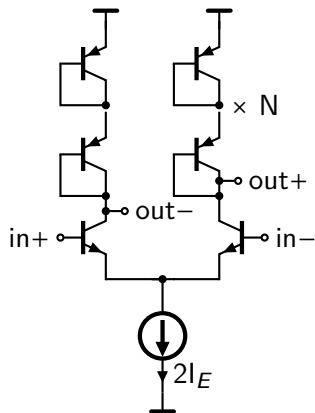
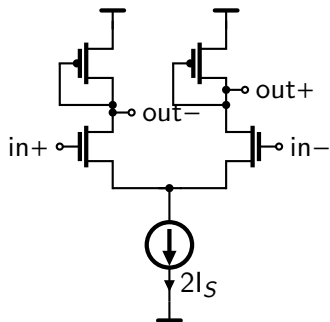


Decouple operating voltage and load impedance value.

Allows larger gain with moderate power supply voltage.

Current sources :  $G_{Diff} \approx g_{mN}/r_{oP}$  The input and output common mode voltage are "free" ... but have to be fixe by other "circuits"

## Differential pair with diode load



Diode Load :  $G_{Diff} \approx g_{mN}/g_{mP} \approx \sqrt{\mu_n W_N L_P / (\mu_p W_P L_N)}$

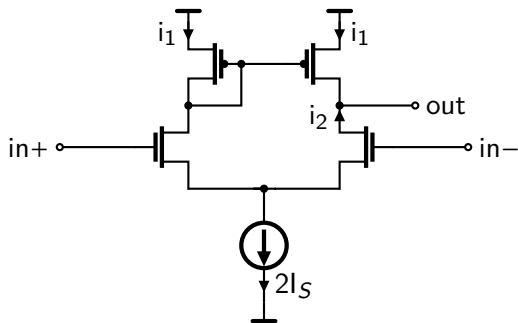
MOS : W/L to scale the gain (independent to bias and T)

Bipolar :  $G_{Diff} \approx g_{m_{npn}} \times 1/g_{m_{pnp}} \approx N$  number of diodes

( $g_m = qI_C/kT$  independent to size) → drift compensation & better linearity (in a given range)



# Single-ended differential pair with differential input: active load



coupling of the  $I_D$  of each NMOS through a mirror

$$i_1 = g_{mN} V_{in+} \quad i_2 = g_{mN} V_{in-} \quad V_{out} = (i_1 + i_2)(r_{0N} // r_{0P})$$

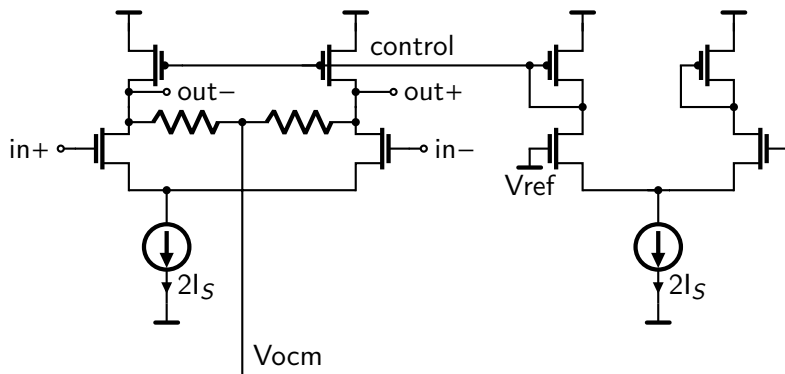
$$"G_{Diff}" \approx g_{mN} (r_{0N} // r_{0P})$$

Output common mode must be similar to the PMOS diode D voltage.

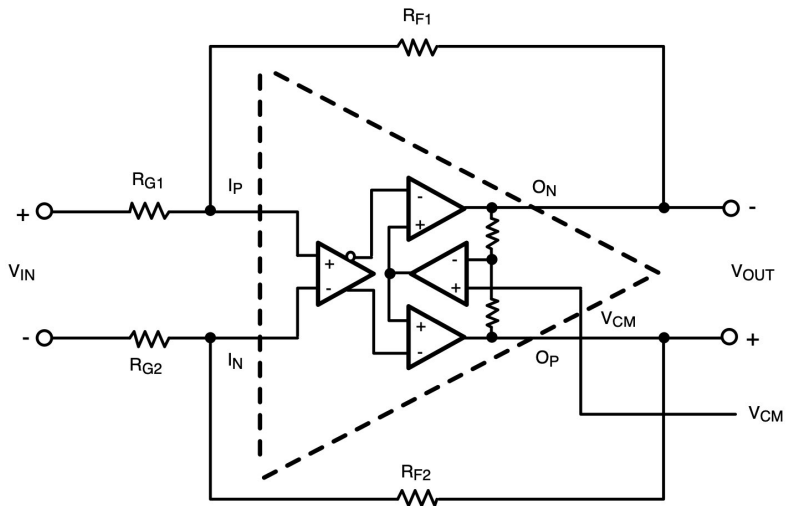


# Fully-Differential Amplifiers Common Mode Feedback

Output common mode voltage is measured and used to adjust the  $V_{DS}$  load  $\rightarrow V_{ocm} = V_{ref}$



# Fully-Differential Amplifiers Common Mode Feedback



AN-1719 Noise Figure Analysis Fully Differential Amplifier

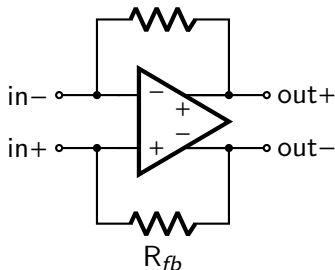




# Fully-Differential Amplifiers with feedback

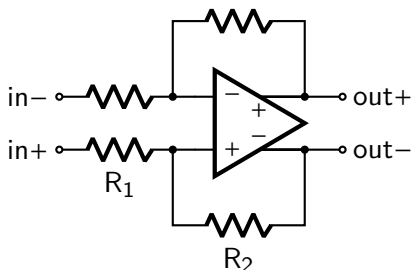
Miller effect:  $Z_{in} = 2R_{fb}/(1+G_{Diff})$

- ▶  $R_{fb}/G_{Diff} < 50 \Omega$  Trans-impedance amplifier
- ▶  $R_{fb}/G_{Diff} = 50 \Omega$  Active low noise impedance matching



## Fully-Differential Amplifiers with feedback

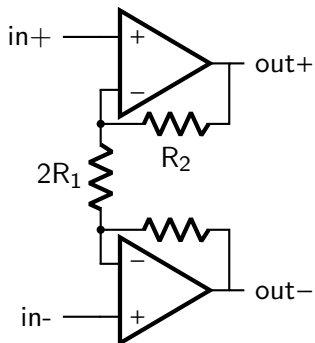
Intrinsic differential gain is often "proportional" to  $I$  and  $T$   
 -> To fix gain  $R_2/R_1$



if the intrinsic gain is large :  $G_{Diff} = R_2/R_1$   
 $Z_{in} \approx 2R_1$

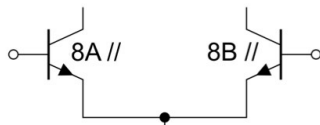
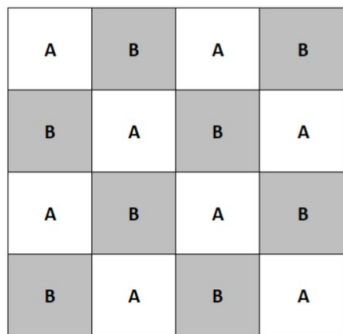
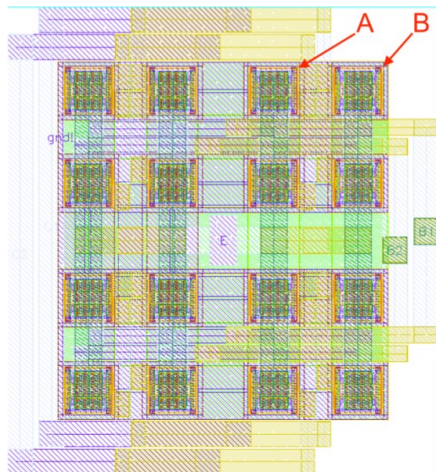


# Fully differential instrumentation-like amplifier



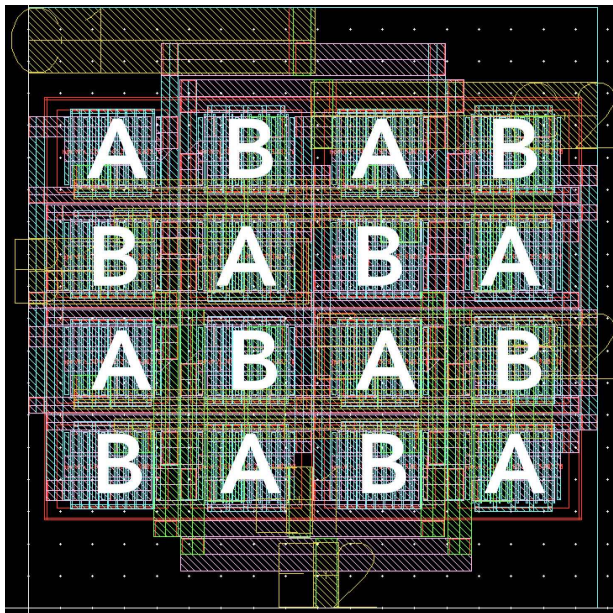
$G_{Diff} = R_2/R_1$  High differential input impedance

# Balancing = Common Centroid Method

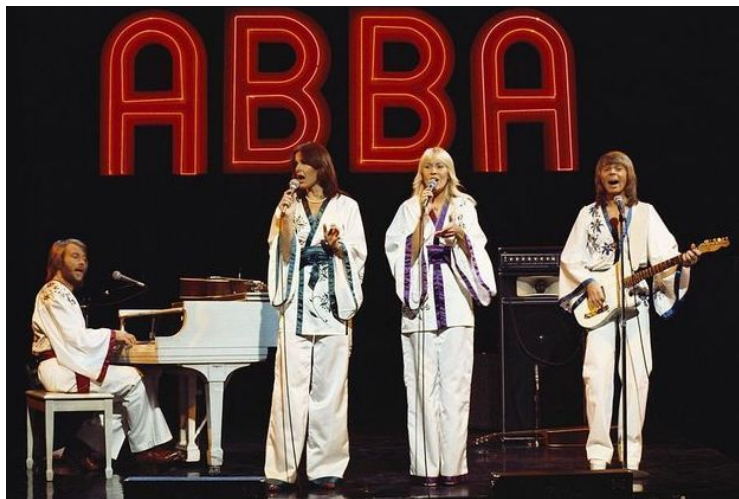


Si Chen PhD <https://tel.archives-ouvertes.fr/tel-02871901/>

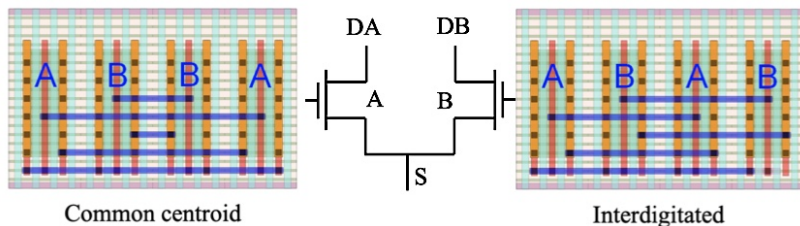




# For not square : ABBA preferred



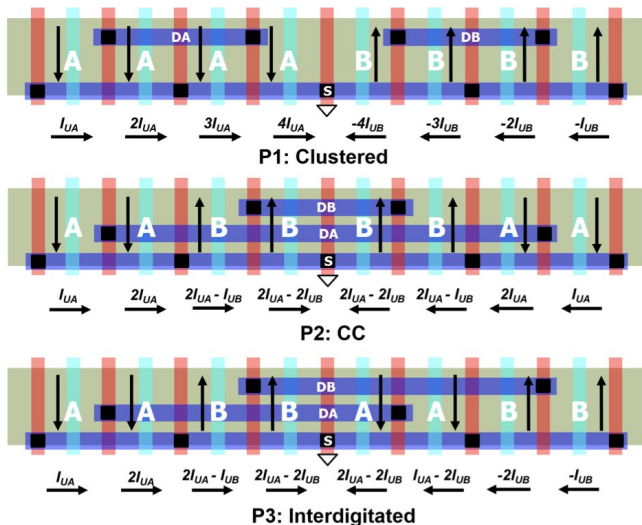
# For not square : ABBA preferred



Common-Centroid Layouts for Analog Circuits: Advantages and Limitations - A. K. Sharma et al.

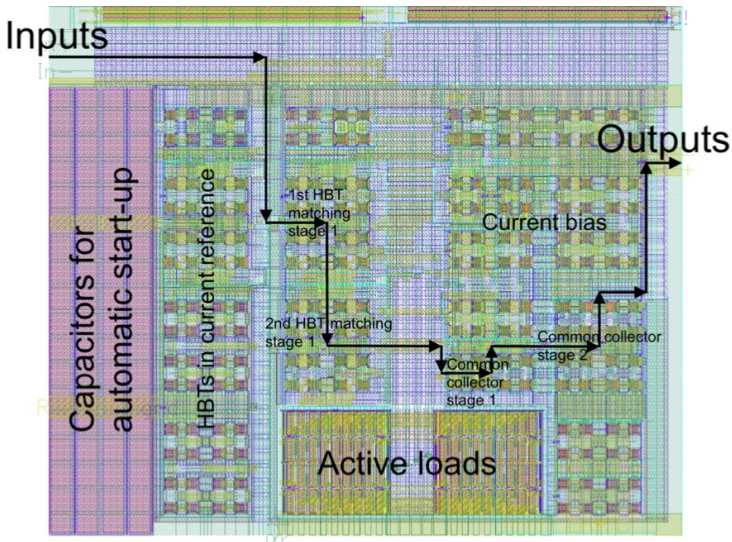


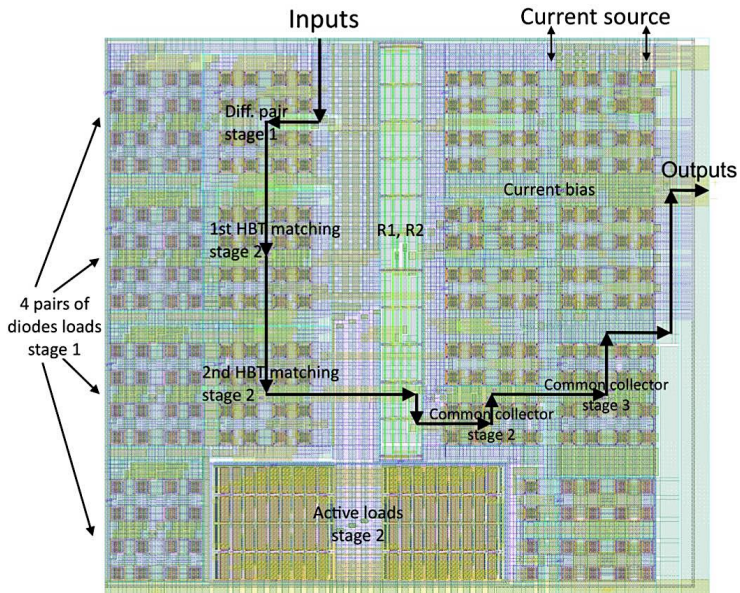
# Clustered, Common-centroid and InterDigitated layouts with routing connections





## Following the pair

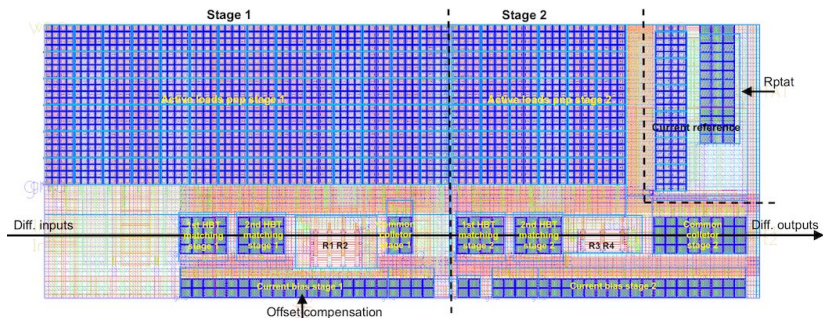




Si Chen PhD <https://tel.archives-ouvertes.fr/tel-02871901/>



# Crossing pairs in a straight line



Si Chen et al. Monolithic amplifier and current biasing for SQUID readout AwaXe v4 - 2022



## Introduction

### Differential transmissions

- Differential signals
- Differential lines
- Coupling

### Differential amplifier

- Single to differential
- Fully differential amplifier
- Differential pair with "transistor load"
- Common Centroid Layout

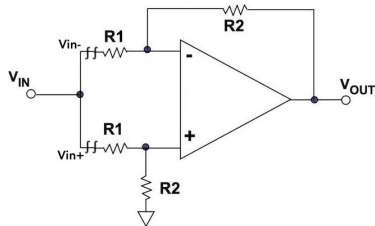
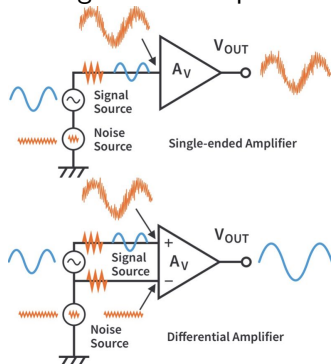
## Noise and noise rejection



# Common Mode Rejection Ratio Measurement - CMRR

Same signal applied to both inputs of differential device

Average of the outputs in case of differential output  $\neq$  differential signal



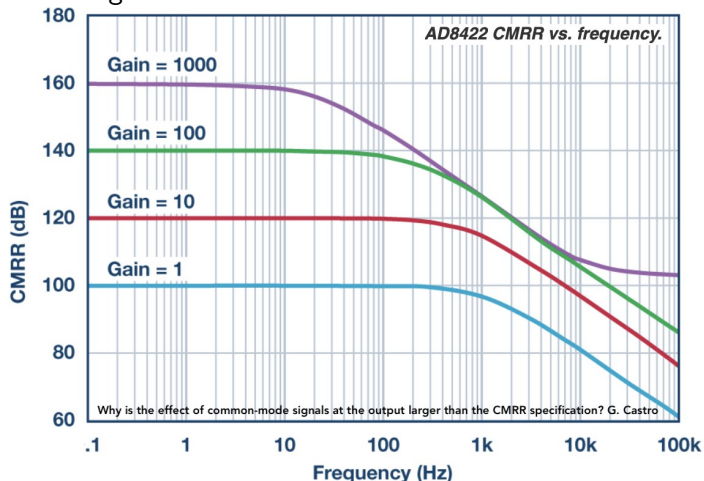
$$CMRR = \frac{\text{differential-mode gain}}{\text{common-mode gain}}$$

$$CMRR = \frac{G_{Diff}}{G_{CM}} = \frac{V_{out}/(V_{in+} - V_{in-})}{\Delta V_{out}/\Delta V_{in}} = \frac{R2/R1}{\Delta V_{out}/\Delta V_{in}} = \frac{R2/R1 \Delta V_{in}}{\Delta V_{out}}$$



# CMRR(f)

Common mode rejection decrease with frequency and depends the differential gain



## $\sqrt{2}$ noise more ?

Input noise is quadratically summed at the 2 inputs ... but signal is double !

SNR is increased by a factor of  $\sqrt{2}$  in differential for same amplitude signal at each end



# Common Mode Filters

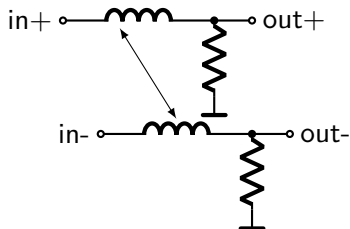
Differential topology

- ▶ with good symmetry and balancing
- ▶ with virtual ground and differential impedances

Allows Common Mode Rejection and Power Supply Rejection ...

Moreover, it exist filters allowing attenuation of the Common Mode, with no attenuation of the Differential signal

Common mode filter are inductive filter like LR low passe filter :



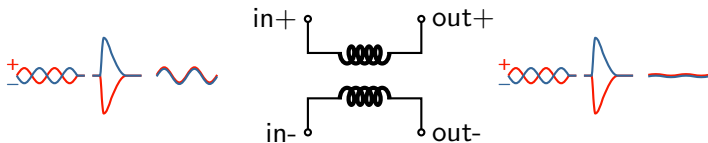
$$f_c = \frac{1}{2\pi L/R} \rightarrow \text{with } 50 \Omega, L \text{ must be } = \frac{50}{2\pi f_c} = 8 \mu\text{H} |_{f_c=1\text{MHz}}$$



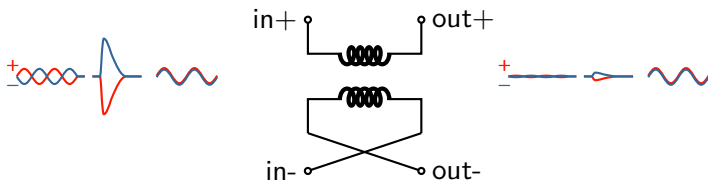


## Common Mode Filters Principle

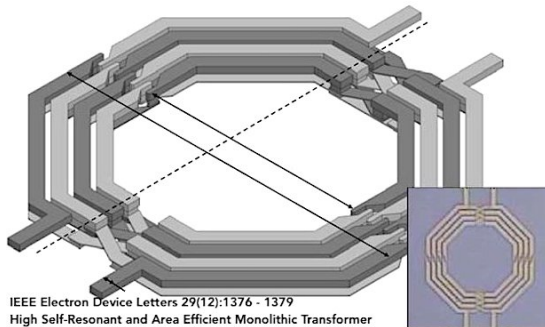
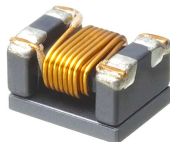
Can reduce the external noise and the CM noise induced by skew on a differential link



can also be use as a "differential filter" :



# Common Mode Filter Devices



IEEE Electron Device Letters 29(12):1376 - 1379  
High Self-Resonant and Area Efficient Monolithic Transformer



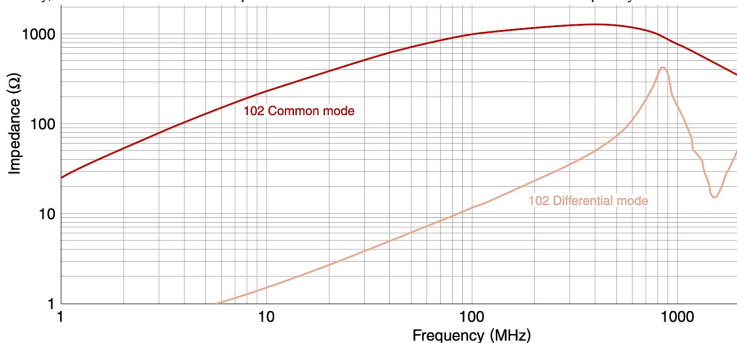
# Common Mode Filtering Impedance

Common mode impedance increase with  $f$  as  $L\omega$  (ACP3225)

Common mode impedance [at 100MHz]		DC resistance		Rated current*	Rated voltage	Insulation resistance
( $\Omega$ )	Tolerance	(m $\Omega$ )typ.	(m $\Omega$ )max.	(A)max.	(V)max.	(M $\Omega$ )min.
1000	$\pm 25\%$	50	100	1.5	60	10
500	$\pm 25\%$	40	100	2	60	10

Other with thin wire exhibit high resistance not compatible with 50 $\Omega$  matching : 3k $\Omega$  @ 500k $\Omega$  & DC resistance 2 k $\Omega$  (ST-101A )

Finally, the best is to have the impedance in CM and differential as function of frequency :



## Conclusion

- ▶ Common Mode Rejection
  - ▶ **Common Mode Noise Rejection**: use-full especially for transmission of signal over significant distances
  - ▶ Return current to ground is near zero reducing ground bounce issue
  - ▶ Ease the DC coupling between stages
- ▶ **Twice the amplitude** and improve signal to noise
  - ▶  $V_{pp}$  is twice the voltage amplitude of one end. Especially interesting with the decrease of ASIC technology power supply. Again, for transmission to an other stage ...
  - ▶ However the differential structure **twice the circuit area** and need **2 times more current**
  - ▶ The noise is also multiply by  $\sqrt{2}$  ... but the SNR is still improve
- ▶ Also: reduce glitches on supply if well balanced ...

The real interest depend the application: long transmission line with larger sensitivity to external noise sources and less well define references ... less interesting for low consumption compact readout

