Announcements & Agenda

• Exam 3 is postponed to Dec. 11 during scheduled final time
• Project presentation will still need to be prepared and turned in by 5PM on Dec 11, but will not be presented

• Optical Receiver Overview
• Transimpedance Amplifiers
  • Common-Gate TIAs
  • Feedback TIAs
  • Common-Gate & Feedback TIA Combinations
Optical Receiver Technology

- Photodetectors convert optical power into current
  - p-i-n photodiodes
  - Integrated metal-semiconductor-metal photodetector

- Electrical amplifiers then convert the photocurrent into a voltage signal
  - Transimpedance amplifiers
  - Limiting amplifiers
  - Integrating optical receiver
Transimpeance Amplifier (TIA)

- Key design objectives
  - High transimpeance gain
  - Low input resistance for high bandwidth and efficient gain

Transimpeance $Z_T = \frac{v_{out}}{i_{in}}$ (Ω)

Also expressed in units of dBΩ by $20 \log(\lvert Z_T \rvert)$
Resistive Front-End

[Razavi]

\[ R_T = R_{in} = R_L \]

\[ BW_{\text{3dB}} = \omega_p = \frac{1}{R_{in}C_D} = \frac{1}{R_LC_D} \]

- Direct trade-offs between transimpedance, bandwidth, and noise performance

\[ \overline{V^2_{n,\text{out}}} = \int_0^\infty \overline{I^2_n} Z_T^2 df = \int_0^\infty \frac{4kT}{R_L} \left( \frac{R}{1 + j2\pi f RC} \right)^2 df = \frac{kT}{C_D} \]

\[ \overline{I^2_{n,\text{in}}} = \frac{\overline{V^2_{n,\text{out}}}}{R_L^2} = \frac{kT}{R_L^2C_D} \]

\[ I_{n,\text{in, rms}} = \sqrt{\frac{KT}{R_LC_D}} \]
Common-Gate TIA

- Input resistance (input bandwidth) and transimpedance are decoupled
Common-Gate TIA Frequency Response

Neglecting transistor $r_o$:
\[
\frac{v_{out}}{i_{in}} = \frac{R_D}{1 + s \left( \frac{C_{in}}{g_{m1} + g_{mb1}} \right) \left( 1 + s R_D C_{out} \right)}
\]

- Often the input pole may dominate due to large photodiode capacitance (100 – 500fF)
Common-Gate TIA Noise

Razavi

Both the bias current source and RD contribute to the input noise current.

RD can be increased to reduce noise, but voltage headroom can limit this.

Common-gate TIAs are generally not for low-noise applications.

However, they are relatively simple to design with high stability.
Regulated Cascode (RGC) TIA

- Input transistor gm is boosted by common-source amplifier gain, resulting in reduced input resistance
- Requires additional voltage headroom
- Increased input-referred noise from the common-source stage

\[ Z_{in}(0) \equiv \frac{1}{g_{m1}(1 + g_{mB}R_B)} \]
CMOS 20GHz TIA

- An additional common-gate stage in the feedback provides further gm-boosting and even lower input resistance.

- Shunt-peaking inductors provide bandwidth extension at zero power cost, but very large area cost.

\[ Z_i \approx \frac{1}{g_{m1} \left( 1 + |A_2 A_3| \right) + j \omega C_{i,\text{tot}}} \]

\[ A_2 = g_{m2} R_2 \quad A_3 = -g_{m3} R_3 \]
Feedback TIA w/ Ideal Amplifier

With Infinite Bandwidth Amplifier:

\[ Z_T(s) = -RT \left( \frac{1}{1 + s/\omega_p} \right) \]

\[ R_T = \frac{A}{A+1} R_F \]

\[ R_{\text{in}} = \frac{R_F}{A+1} \]

\[ \omega_p = \frac{1}{R_{\text{in}} C_T} = \frac{A+1}{R_F (C_D + C_I)} \]

- Input bandwidth is extended by the factor A+1
- Transimpedance is approximately R_F
- Can make R_F large without worrying about voltage headroom considerations
Feedback TIA w/ Finite Bandwidth Amplifier

• Finite bandwidth amplifier modifies the transimpedance transfer function to a second-order low-pass function

With Finite Bandwidth Amplifier:

\[ A(s) = \frac{A}{1 + \frac{s}{\omega_A}} = \frac{A}{1 + sT_A} \]

\[ Z_T(s) = -R_T \left( \frac{1}{1 + s/(\omega_o Q) + s^2/\omega_o^2} \right) \]

\[ R_T = \frac{A}{A+1} R_F \]

\[ \omega_o = \sqrt{\frac{A+1}{R_F C_T T_A}} \]

\[ Q = \frac{\sqrt{(A+1)R_F C_T T_A}}{R_F C_T + T_A} \]

\[ R_{in} = \frac{R_F}{A+1} \]
Non-zero amplifier time constant can actually increase TIA bandwidth!!

However, can result in peaking in frequency domain and overshoot/ringing in time domain

Often either a Butterworth \((Q=1/\sqrt{2})\) or Bessel response \((Q=1/\sqrt{3})\) is used

- Butterworth gives maximally flat frequency response
- Bessel gives maximally flat group-delay

[Diagram of second-order TIA frequency response]

[Ampere to伏特]
Feedback TIA Transimpedance Limit

If we assume a Butterworth response for maximally flat frequency response:

$$Q = \frac{1}{\sqrt{2}}$$
$$\omega_A = \frac{1}{T_A} = \frac{2A}{R_F C_T}$$

For a Butterworth response:

$$\omega_{3dB} = \omega_0 = \sqrt{\frac{(A+1)\omega_A}{R_F C_T}} = \sqrt{\frac{(A+1)2A}{R_F C_T}} \approx \sqrt{2} \text{ times larger than } T_A = 0 \text{ case of } \frac{A+1}{R_F C_T}$$

Plugging $$R_T = \frac{A}{A+1} R_F$$ into above expression yields the maximum possible $$R_T$$ for a given bandwidth

$$\sqrt{\frac{(A+1)\omega_A}{\left(A+1\right) R_T C_T}} \geq \omega_{3dB}$$

$$\text{Maximum } R_T \leq \frac{A \omega_A}{C_T \omega_{3dB}^2}$$

[Mohan J SSC 2000]

- Maximum $$R_T$$ proportional to amp gain-bandwidth product
- If amp GBW is limited by technology $$f_T$$, then in order to increase bandwidth, $$R_T$$ must decrease quadratically!
Feedback TIA

Assuming that the source follower has an ideal gain of 1

\[
A = g_{m1}R_D
\]

\[
R_f = \frac{g_{m1}R_D}{1 + g_{m1}R_D}R_F
\]

\[
R_{in} = \frac{R_F}{1 + g_{m1}R_D}
\]

\[
R_{out} = \frac{1}{g_{m2}(1 + g_{m1}R_D)}
\]
• CMOS inverter-based TIAs allow for reduced voltage headroom operation
• Multiple inverter stages in feedback provide higher gain at the cost of reduced stability
• Diode-connected transistor loads allow for high-frequency internal poles
Common-Gate & Feedback TIA

- Common-gate input stage isolates CD from input amplifier capacitance, allowing for a stable response with a variety of different photodetectors
- Transimpedance is still approximately $R_f A/(1+A)$
- Transformer-based negative feedback boosts gm with low power and noise overhead
- Input series peaking inductor isolates the photodetector capacitance from the TIA input capacitance
- High frequency techniques allow for 26GHz bandwidth with group delay variation less than 19ps

[Li BCTM 2011]
Next Time

• Broadband amplifiers
  • Limiting amplifiers
  • Transimpedance amplifiers

• CML gate design