E4332: VLSI Design Laboratory

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AM radio receiver

- AM radio signals: Audio signals on a carrier
- Intercept the signal
- Amplify the signal
- Demodulate the signal-recover the audio
- Amplify the audio to drive a speaker
AM signal basics: time domain

- Envelope (peak) of the carrier is the message
AM signal basics: frequency domain

- Sidebands around the carrier
AM signals

- Sidebands around the carrier
Broadcast AM signals

- Broadcast AM channels 10kHz from each other
Receiver bandwidth

- Receiver bandwidth must be constant
Receiver bandwidth

- \( f_{c_{bw}}/f_{bw} = 53 \) at the lowest end
- \( f_{c_{bw}}/f_{bw} = 161 \) at the highest end
- High Q (~ quality factor)
- Maintain constant bandwidth
Receiver sensitivity and selectivity

- **Sensitivity**: ability to detect small signals
  - AM radio sensitivity: $\sim 50\mu V$ signals with 30% modulation

- **Selectivity**: ability to reject adjacent signals
  - Dictated by the choice of architecture in our case
Tuned Radio Frequency (TRF) receiver

- Input tuned circuit is the only filter providing selectivity
- Coil on a ferrite rod
TRF receiver: input tuning

coil losses
load resistance
antenna coil

1:n transformer
antenna coil

1:n transformer
antenna coil

1:n transformer
antenna coil

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2nd order filter basics

- Resonant frequency (radians per second) $\omega_o = 1/\sqrt{LC_{\text{tune}}}$
- 3dB bandwidth $\omega_b$
- Quality factor $Q = \omega_0 / \omega_b$
- Series loss: $Q_s = 1/R_s \sqrt{L/C}$
  - Bandwidth = $R_s / L$
- Parallel loss: $Q_p = R_p \sqrt{C/L}$
  - Bandwidth = $1/CR_p$
TRF receiver: input tuning

- Resonant frequency \( \frac{1}{\sqrt{LC_{\text{tune}}}} \) varies from 530 to 1610kHz, approx 3x
- Fixed L, \( \Rightarrow C_{\text{tune}} \) varies by 9x
- Series loss \( R_s \) only
  - Bandwidth = \( \frac{R_s}{L} \)
  - No change with \( C_{\text{tune}} \)
- Parallel loss \( R_p \) only
  - Bandwidth = \( \frac{1}{C_{\text{tune}} R_s} \)
  - varies by 9x with change in \( C_{\text{tune}} \)
TRF receiver: input tuning

- Some bandwidth variation with tuning
  - Bandwidth < 10kHz at low end
  - Bandwidth > 10kHz at high end
- 2\textsuperscript{nd} order filter. Limited out of band attenuation
  ⇒ Poor selectivity in a TRF receiver
- Suggestion: Use a very large on chip $R_p$ to maintain as high a Q as possible
TRF receiver: Input amplifier

- High impedance input necessary
  - Source follower buffer
  - Differential amplifier
TRF receiver: Input amplifier

- Use large resistors for input biasing
TRF receiver: Input amplifier
TRF receiver: Detector

- No diodes in CMOS process
- Input amplitude > diode drop
- Use of an amplifier in feedback to improve sensitivity
AM radio: specifications

Signal levels:

- **Input from** 50µV to 5mV
- RF amplifier with AGC
- Output of RF amplifier with AGC from 50mV to 200mV
  - Max. gain = 50mV/50µV = 1000 (60dB)
  - Min. gain = 200mV/5mV = 40 (32dB)
  - Total gain variability = 1:25 (28dB)
- Detector must work with 50mV-200mV inputs
- Audio output max. ~ $1V_{pk}$ into 8Ω speaker
AM radio: specifications

Misc.:
• Supply voltage: 4.2-4.5V
  – Operation with 3x 1.5V batteries
  – Try to design for 4.2V
AM radio: input signal generation

\[(1 + m \cos(\omega_m t)) \cos(\omega_c t)\]

\[A(1 + m \cos(\omega_m t)) \cos(\omega_c t)\]

- Use A from 50\(\mu\)V to 5mV
- Parameterized subcircuit (using pPar(“m”), pPar(“A”) etc.) to make an AM source in Cadence
Amplifier basics

\[ V_{cm} + v_i/2 \]

\[ V_{cm} - v_i/2 \]

\[ V_{gs1} \]

\[ V_{gs2} \]

transistors: \( g_m, g_{ds}, g_{mbs} \) at \( I_0 \)
Amplifier basics

- Gain = \( g_m (R_L + 1/g_{ds}) \sim g_m R_L \)
- \( G_m = \sqrt{\mu C_{ox} / 2 \cdot W/L \cdot I_0} = I_0 / V_{GS} - V_T \)
- Gain = \( g_m R_L = I_0 R_L / V_{GS} - V_T \)
  - To change gain, \( I_0 R_L \) (the dc voltage drop across \( R_L \)) or \( V_{GS} - V_T \) (related to transistor current density) has to be changed
- Linearity improves with increasing \( V_{GS} - V_T \)
  - Amplifier: larger \( V_{GS} - V_T \)
  - Switch: smaller \( V_{GS} - V_T \)
RF amplifier I
RF amplifier I

- AC coupled to remove offsets
- Single ended input/output-simple
- Gain = $g_m R_L / 2$ (Analyze this!)
- Ac coupling resistors: pMOS transistors
- Ac coupling corner frequency: ~ 1dB attenuation at lower end of AM band
- Capacitor values: 5pF or less
  - Linear capacitor density ~ 0.9fF/µm²
- Resistor values: upto 10kΩ
  - Resistivity ~ 800Ω/sq.
RF amplifier II
RF amplifier II

- AC coupled to remove offsets
- Single ended input/output-simple
- Gain = $g_m R_L$ (Analyze this!)
- Ac coupling resistors: pMOS transistors
- Ac coupling corner frequency: ~ 1dB attenuation at lower end of AM band
- Capacitor values: 5pF or less
  - Linear capacitor density ~ 0.9fF/μm²
- Resistor values: upto 10kΩ
  - Resistivity ~ 800Ω/sq.
RF amplifier III

Diagram: Circuit diagram of an RF amplifier with single ended input and differential output.
RF amplifier III

- AC coupled to remove offsets
- Differential stages
  - 2x ac coupling capacitors
- Gain = \( g_m R_L \) (Analyze this!)
- Ac coupling resistors: pMOS transistors
- Ac coupling corner frequency: ~ 1dB attenuation at lower end of AM band
- Capacitor values: 5pF or less
  - Linear capacitor density \( \sim 0.9fF/\mu m^2 \)
- Resistor values: upto 10k\( \Omega \)
  - Resistivity \( \sim 800\Omega/sq. \)
Detector I

\[ V_{dd} \]

\[ \text{differential output} \]

\[ \text{upper pairs} \]
\[ \text{(switches)} \]

\[ \text{lower pair} \]
\[ \text{(amplifiers)} \]

\[ v_{in}\]

\[ + \]
\[ - \]

level shifter for the lower diff. pair
multiplier

\[ \text{gnd} \]
Detector I

- Implement $v_i(t) \cdot \text{sgn}(v_i(t))$ and filter the result
  - Full wave rectification and filtering
- Filtering capacitor C
  - retain audio, remove RF
  - External, if too large
- Upper pair should act as a switch: $\text{sgn}(v_i(t))$
- Lower pair should act as a linear amplifier
  (over the entire range of input signals)
Detector II

(a) full wave rectifier

(b) amplifier
Detector II

- Full wave rectifier with differential inputs
- Half wave rectifier with single ended inputs
- Followed by amplifier and filter
- Filtering capacitor C
  - retain audio, remove RF
  - External, if too large
Peak detector

\[ T_{audio, \ max} \gg RC \gg T_{RF, \ min} \]

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Detector III

capacitor charge (through $M_n$)

capacitor discharge ($I_{bias}$)
Detector III

- Single stage “op amp”
Detector III

- Peak detector
- Discharge time constant slower than charging time constant
  - Negligible discharge between RF cycles
  - Full discharge between audio cycles
Audio amplifier

- Feedback for linearity
- Output current $\sim 1V/8\Omega = 125mA$
Class A opamp

- Need to bias with $I_0 = 125\text{mA}$!
Class AB opamp

- $V_{b1}$ and $V_{b2}$ adjusted so that output branch current is $I_0$. 

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Class AB opamp

- Output pMOS gate pulled down to drive out a large current ( > bias)
Class AB opamp

- Output nMOS gate pulled up to pull in a large current (> bias)

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Class AB opamp: bias generation

cascode current source bias generator

class AB output bias generator

bias generator

class AB output stage
Class AB opamp: full schematic
Bias current generation

- One external resistor to fix bias currents
  - Bias line coupling can lead to problems in high gain multistage circuits
Bias current generation

- Separate mirroring branch for each stage
  + Reduced interstage coupling
  - Increased current in bias branches
Bias current generation

- RC filter to each biasing MOS transistor
  - Reduced interference and noise
  - No increase in bias currents
Passive components

**Resistor**
- $R_{\text{sheet}} = 800 \Omega/\text{sq.}$ (linear)
- $R = 800 (L/W)$

**nMOS**
- $V_d, V_s$: closer to gnd (nonlinear)
- $R = 1/\mu_n C_{\text{ox}} (V_{GS}-V_T)^*(L/W)$

**pMOS**
- $V_d, V_s$: closer to Vdd (nonlinear)
- $R = 1/\mu_p C_{\text{ox}} (V_{GS}-V_T)^*(L/W)$

**Poly1-Poly2 Capacitor**
- Passive, linear
- $C = 0.8 \text{fF} \times \text{WL}$

**Capacitors Connected to Ground**
- $C = 3 \text{fF} \times \text{WL}$

**Bias Voltage**
- $V_{\text{bias}} > V_T$
- $V_{dd} - V_{\text{bias}} > V_T$
Passive components: Resistors

• Passive resistor
  – Min. width = few kOhms

• MOS resistors
  – Need bias
  – Greater range of values
  – Voltage tunability
Passive components: capacitors

- Passive (poly1-poly2)
  - Few pF
  - Bottom plate to ground parasitic

- MOS capacitors
  - Higher capacitor density
  - Need to be biased in strong inversion