EE539: Analog Integrated Circuit Design

Introduction

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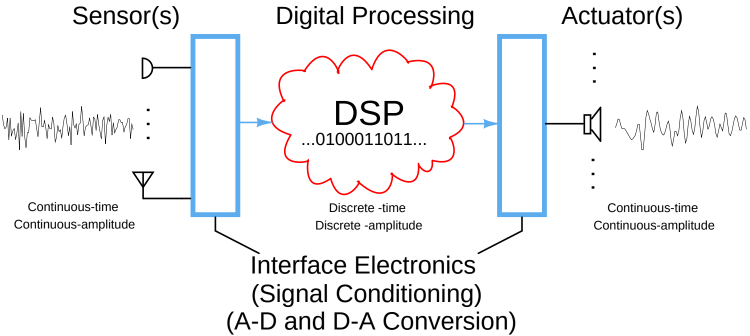
Outline

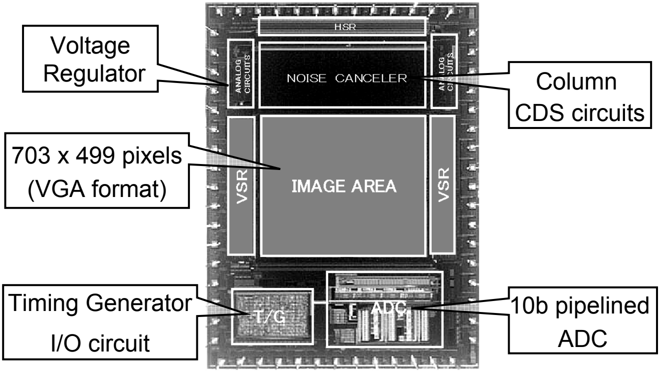

Sensor(s)
Digital Processing
Actuator(s)
DSP
...0100011011...
Continuous-time
Continuous-amplitude
Discrete -time
Discrete -amplitude
Continuous-time
Continuous-amplitude
Interface Electronics
(Signal Conditioning)
(A-D and D-A Conversion)

Analog circuits in modern systems on VLSI chips

- Analog to digital conversion
- Digital to analog conversion
- Amplification
- Signal processing circuits at high frequencies
- **Power management-voltage references, voltage regulators**
- **Oscillators**

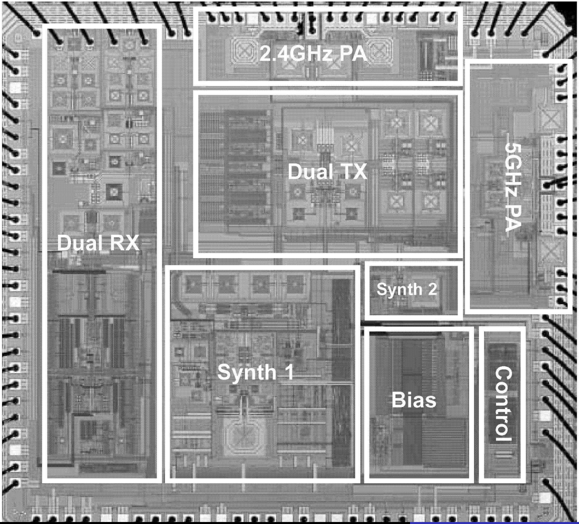
The last two are found even on many “digital” ICs

Chip Micrograph



Chip size: 4.74mm x 6.34mm

Die Micrograph



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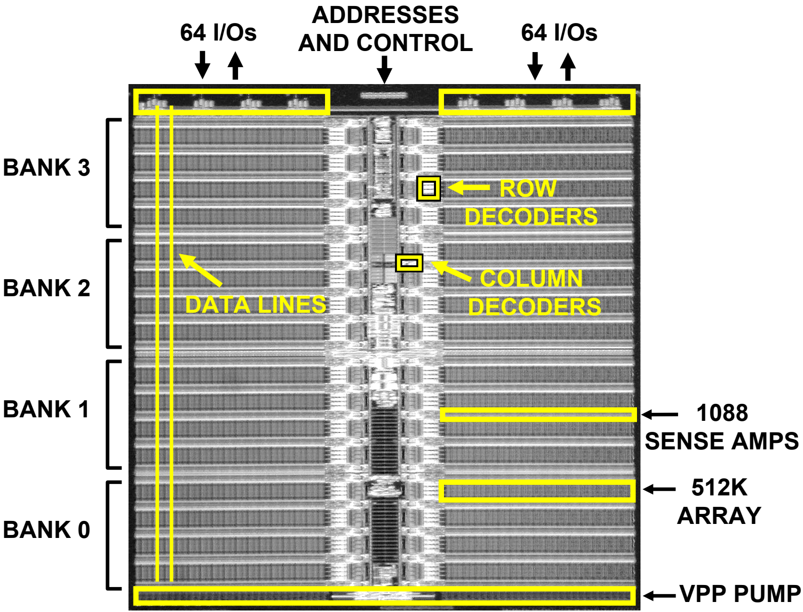

Analog IC design in India

- Many companies starting analog centers
- Multinationals-TI, National, ST, ADI etc.
- Indian start ups-Cosmic, Karmic, Sankalp etc.
- Big demand for skilled designers
- Interesting <u>and</u> profitable activity $\ddot\smile$

Course goals

Learn to design negative feedback amplifiers on CMOS ICs

- Negative feedback for controlling the output
- Amplifiers, voltage references, voltage regulators, biasing

Course prerequisites

- Circuit analysis
- Small and large signal analysis
- Laplace transforms, frequency response, Bode plots
- Differential equations
- Opamp circuits
- Basic transistor models and circuits

Course contents-Introduction/Review

- Circuit analysis, laplace transforms, differential equations
- Amplifiers using negative feedback
- Negative feedback circuits using opamps

Course contents-Amplifi ers on ICs

- Components available in CMOS integrated circuit (IC) processes
- Device models-dc small signal, dc large signal, ac small signal, mismatch, noise
- Basic single transistor amplifier stages
- Transistor biasing, compound amplifier stages
- Differential amplifiers
- Fully differential amplifiers and common mode feedback

Course contents-Design of opamps

- Single stage opamp
- Folded, telescopic cascode opamps
- Two stage opamp
- Fully differential opamps and common mode feedback
- Applications: Bandgap reference, constant g_m bias generation

Design versus Analysis

- Design: Create something that doesn't yet exist
- Analysis: Analyze something that exists

To be able to design

- Knowing analysis is necessary, not sufficient
- Multiple ways of looking at building blocks
- Trial and error approaches
- Intuitive thinking/understanding
- Curiosity
- Open mind
- Thoroughness

Intuition

- Intuitive thinking **is not** sloppy thinking!
- Relate problems to other problems already solved
- Use boundary conditions, dimension checks etc.
- Build your intuition
  - Solve many problems
  - Think about why the answer is what it is
  - Come up with the form of the solution <u>before</u> applying full blown analysis

- Nodal analysis-Kirchoff's Current Law (KCL) at each node
- Solve N simultaneous equations for an N node circuit
- Mesh analysis-Kirchoff's Voltage Law (KVL) around each loop
- Solve M simultaneous equations for a circuit with M independent loops

$$
\begin{aligned}
i_{11}(\overline{v}) + i_{12}(\overline{v}) + \ldots + i_{1N}(\overline{v}) &= i_1 \\
i_{21}(\overline{v}) + i_{22}(\overline{v}) + \ldots + i_{2N}(\overline{v}) &= i_2 \\
&\vdots \\
i_{N1}(\overline{v}) + i_{N2}(\overline{v}) + \ldots + i_{NN}(\overline{v}) &= i_N
\end{aligned}
$$

- i_{kl}: Current in the branch between nodes k and l
- i_{kk}: Current in the branch between node k and ground
- v_k: Voltage at node k; $\overline{v} = [v_1 v_2 \ldots v_N]^T$
- i_k: Current source into node k

i_{kl} **can be a nonlinear function of** $\overline{v}$

Nodal analysis—Linear circuits

$$
\begin{aligned}
g_{11}v_1 + g_{12}v_2 + \ldots + g_{1N}v_N &= i_1 \\
g_{21}v_1 + g_{22}v_2 + \ldots + g_{2N}v_N &= i_2 \\
&\vdots \\
g_{N1}v_1 + g_{N2}v_2 + \ldots + g_{NN}v_N &= i_N
\end{aligned}
$$

- g_{kl}: Conductance between nodes k and l
- g_{kk}: Conductance between node k and ground
- v_k: Voltage at node k
- i_k: Current source into node k

Nodal analysis—Independent voltage source

$$
\begin{aligned}
&\vdots \\
\sout{g_{k1}v_1 + g_{k2}v_2 + \ldots + g_{kN}v_N} &= \sout{i_k} \qquad \text{node } k \\
&\vdots \\
v_k &= V_o \qquad \text{node } k
\end{aligned}
$$

- Ideal voltage source V_o connected to node k

Nodal analysis—Controlled voltage source

$$\vdots$$

~~$g_{k1}v_1 + g_{k2}v_2 + \ldots + g_{kN}v_N = i_k$~~ node k

$$\vdots$$

$$v_k - kv_l = 0 \qquad \text{node } k$$

- Voltage controlled voltage source $v_k = kv_l$ driving node k

Nodal analysis—Controlled voltage source

$$
\begin{aligned}
g_{k1}v_1 + g_{k2}v_2 + \ldots + \cancel{g_{kl}v_l} + \ldots + g_{kN}v_N &= i_k && \text{node } k \\
g_{k1}v_1 + g_{k2}v_2 + \ldots + \frac{v_k}{R_m} + \ldots + g_{kN}v_N &= i_k && \text{node } k \\
g_{l1}v_1 + g_{l2}v_2 + \ldots + \cancel{g_{lk}v_k} + \ldots + g_{lN}v_N &= i_l && \text{node } l \\
g_{l1}v_1 + g_{l2}v_2 + \ldots - \frac{v_k}{R_m} + \ldots + g_{lN}v_N &= i_l && \text{node } l
\end{aligned}
$$

- Current controlled voltage source $v_k = R_m i_{kl}$ driving node k

Nodal analysis—Controlled current source

$$g_{k1}v_1 + g_{k2}v_2 + \ldots + g_{kl}v_l + \ldots + g_{kN}v_N = i_k + g_m v_l$$
$$g_{k1}v_1 + g_{k2}v_2 + \ldots + g_{kl}v_l - g_m v_l + \ldots + g_{kN}v_N = i_k$$

- Current controlled voltage source $i_0 = g_m v_l$ driving node k

Nodal analysis—Ideal opamp

$$\vdots$$

~~$g_{m1}v_1 + g_{m2}v_2 + \ldots + g_{mN}v_N = i_m$~~ node m

$$\vdots$$

$$v_k - v_l = 0 \qquad \text{node } m$$

- Ideal opamp with input terminals at nodes k, l and output at node m

Nodal analysis—solution

$$\begin{bmatrix} g_{11} g_{12} \cdots g_{1N} \\ g_{21} g_{22} \cdots g_{2N} \\ \vdots \\ g_{N1} g_{N2} \cdots g_{NN} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix} = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_N \end{bmatrix}$$

$$G\overline{v} = \overline{i}$$

$$v = G^{-1}\overline{i}$$

- g_{kl}: Conductance between nodes k and l
- g_{kk}: Conductance between node k and ground
- v_k: Voltage at node k
- i_k: Current source into node k
- Modified terms for voltage sources or controlled sources
- Matrix inversion yields the solution

Nodal analysis—solution

$$v_k = \frac{\begin{vmatrix} g_{11} g_{12} \cdots i_1 \cdots g_{1N} \\ g_{21} g_{22} \cdots i_2 \cdots g_{2N} \\ \vdots \\ g_{N1} g_{N2} \cdots i_N \cdots g_{NN} \end{vmatrix}}{\begin{vmatrix} g_{11} g_{12} \cdots g_{1k} \cdots g_{1N} \\ g_{21} g_{22} \cdots g_{2k} \cdots g_{2N} \\ \vdots \\ g_{N1} g_{N2} \cdots g_{Nk} \cdots g_{NN} \end{vmatrix}}$$

- Cramer's rule can be used for matrix inversion

$$\begin{bmatrix} Y_{11}(s) Y_{12}(s) \ldots Y_{1N}(s) \\ Y_{21}(s) Y_{22}(s) \ldots Y_{2N}(s) \\ \vdots \\ Y_{N1}(s) Y_{N2}(s) \ldots Y_{NN}(s) \end{bmatrix} \begin{bmatrix} V_1(s) \\ V_2(s) \\ \vdots \\ V_N(s) \end{bmatrix} = \begin{bmatrix} I_1(s) \\ I_2(s) \\ \vdots \\ I_N(s) \end{bmatrix}$$

$$\mathbb{Y}(s)\overline{V}(s) = \overline{I}(s)$$

$$\overline{V}(s) = \mathbb{Y}^{-1}\overline{I}(s)$$

- Conductances g_{kl} replaced by admittances $Y_{kl}(s)$
- Roots of the determinant of $\mathbb{Y}(s)$ are system poles

Laplace transform analysis for linear systems

Input	Output	
$X(s)$	$H(s)X(s)$	
e^{st}	$H(s)e^{st}$	
$X(j\omega)$	$H(j\omega)X(j\omega)$	
$e^{j\omega t}$	$H(j\omega)e^{j\omega t}$	
$\cos(\omega t)$	$\|H(j\omega)\| \cos\left(\omega t + \angle H(j\omega)\right)$	(Steady state solution)

- Linear time invariant system described by its transfer function $H(s)$
- $H(s)$ is the laplace transform of the impulse response
- $s = j\omega$ represents a sinusoidal frequency ω

Transfer function $H(s)$ (no poles at the origin)

$$
\begin{aligned}
H(s) &= A_{dc}\frac{1+b_1s+b_2s^2+\ldots+b_Ms^M}{1+b_1s+b_2s^2+\ldots+b_Ns^N} \\
&= A_{dc}\frac{\prod_{k=1}^{M}1+s/z_k}{\prod_{k=1}^{N}1+s/p_k}
\end{aligned}
$$

Single pole at the origin

$$
H(s) = \frac{\omega_u}{s}\frac{\prod_{k=1}^{M}1+s/z_k}{\prod_{k=2}^{N}1+s/p_k}
$$

- All poles p_k must be in the left half plane for stability

Frequency and time domain analyses

Frequency domain

- Algebraic equations-easier solutions
- Only for linear systems

Time domain

- Differential equations-more difficult to solve
- Can be used for nonlinear systems as well
- Piecewise linear systems occur quite frequently (e.g. saturation)

Bode plots

- Sinusoidal steady state response characterized by $|H(j\omega)|$, $\angle H(j\omega)$
- Bode plot: Plot of $20\log|H(j\omega)|$, $\angle H(j\omega)$ versus $\log\omega$ approximated by straight line segments
- Good approximation for real poles and zeros

Simulators

Very power tools, indispensable for complex calculations, but GIGO!

- Matlab: System level analysis (Frequency response, pole-zero, transfer functions)
- Spice: Circuit analysis
- Maxima: Symbolic analysis

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