

Lecture 25: Different Coupling Techniques for cascading: Direct, RC, LC ...

Frequency Response of Transistor Amplifier

DI02011011: Electronics Circuit and Application (ECA)

Lecture Agenda & Learning Roadmap

- Core Roles and Functions of Inter-Stage Coupling Networks
- RC Coupling Technique: Topology, Biasing Isolation, and Audio Range Characteristics
- RC Coupling Limitations: Low-Frequency Attenuation and Inter-Stage Loading
- Direct Coupling Technique: Topologies, DC Response (0 Hz), and DC Level Shifting
- Transformer Coupling Technique: Principles, Electrical Isolation, and Impedance Matching
- Transformer Coupling Limitations: Frequency Non-Linearities, Bulk, and Parasitics
- LC (Tuned) Coupling Technique: High-Frequency RF Tank Circuits and Selectivity
- Detailed Comparative Matrix: Evaluating All Four Coupling Schemes
- Numerical Calculation Example 1: Transformer Impedance Matching for Output Driver
- Numerical Calculation Example 2: LC Tuned Coupling Bandwidth and Q-Factor Design
- Comprehensive Summary and Selection Flowchart

Role and Functions of Inter-Stage Coupling Networks

- Primary Function 1 - AC Signal Transfer: Pass AC output signal from stage k to input of stage $k + 1$ with minimal attenuation and phase distortion.
- Primary Function 2 - DC Bias Isolation: Prevent high DC collector voltage V_{Ck} of stage k from overriding or disturbing the DC base bias voltage $V_{B(k+1)}$ of stage $k + 1$.
- Primary Function 3 - Impedance Matching: Transform source/stage output impedance to match load/next-stage input impedance for maximum power transfer ($Z_{out} = Z_{in}^*$).
- Coupling Network Selection Factors: Operating frequency range (DC, Audio, RF), power transfer requirements, physical size, component cost, and monolithic IC compatibility.

RC Coupling Technique: Topology, Biasing Isolation, and Characteristics

- Circuit Topology: Coupling capacitor C_C placed in series between collector of Stage 1 and base of Stage 2. Collector resistor R_{C1} acts as AC load and DC bias path.
- DC Bias Isolation Principle: C_C acts as an ideal open circuit to DC ($X_C = \infty$ at $f = 0$), completely blocking DC voltage V_{C1} from affecting Stage 2 base bias V_{B2} .
- AC Signal Passband: At audio frequencies (20 Hz – 20 kHz), C_C impedance $X_C = \frac{1}{2\pi f C_C}$ is negligible, passing AC signals virtually unattenuated.
- Key Advantages: Excellent gain flatness across audio spectrum, low component cost, lightweight, compact discrete implementation.

RC Coupling Frequency Limitations and Inter-Stage Loading

- Low-Frequency Attenuation: At low frequencies ($f < f_L$), reactance $X_C = \frac{1}{2\pi f C_C}$ rises, forming a high-pass filter with Stage 2 input impedance R_{in2} and dropping gain at +20 dB/decade.
- High-Frequency Attenuation: At high frequencies ($f > f_H$), internal parasitic capacitances (C_π, C_μ) shunt signal current to ground, causing gain to roll off at -20 dB/decade.
- Inter-Stage Loading Reduction: Collector resistor R_{C1} dissipates DC power and loads Stage 1, reducing loaded voltage gain: $A_{v1} = -g_{m1}(R_{C1} \parallel R_{in2})$.
- Inability to Amplify DC Signals: Impossible to use in bio-medical instrumentation, DC sensors, or direct-coupled operational amplifiers where 0 Hz response is mandatory.

Direct Coupling Technique: Topologies and DC Level-Shifting

- Circuit Topology: Direct electrical connection (wire or resistor) from collector/emitter of Stage 1 directly to base of Stage 2 without capacitors or transformers.
- DC to High-Frequency Response: Operates from DC (0 Hz) up to high frequencies f_H . Essential for operational amplifiers (op-amps), analog ICs, bio-medical sensors, and DC power supplies.
- Cumulative DC Bias Shift Challenge: Collector voltage of Stage 1 becomes base voltage of Stage 2 ($V_{B2} = V_{C1}$). In multi-stage cascades, DC bias voltages climb progressively higher, risking transistor saturation.
- DC Level-Shifting Solutions: (1) Alternating NPN and PNP transistor stages. (2) Zener diode voltage shifters in series. (3) Active current-mirror level shifters in integrated circuits.

Transformer Coupling Technique: Principles and Impedance Matching

- Circuit Topology: Primary winding of an inter-stage transformer acts as collector load for Stage 1; secondary winding connects across base-emitter nodes of Stage 2.
- DC Isolation & Zero DC Load Resistance: Primary winding DC resistance is near zero ($R_{DC} \approx 0 \Omega$), eliminating DC voltage drop across collector load and maximizing V_{CE} headroom.
- Impedance Transformation Property: A transformer with turns ratio $n = \frac{N_p}{N_s} = \frac{N_1}{N_2}$ reflects secondary load impedance Z_L to primary side as $Z_p = n^2 Z_L = \left(\frac{N_1}{N_2}\right)^2 Z_L$.
- Maximum Power Transfer Application: Transforms low load impedance (e.g. 8Ω loudspeaker) to match high transistor output impedance (e.g. $2 \text{ k}\Omega$), maximizing power transfer efficiency.

Transformer Coupling Frequency Limitations and Practical Drawbacks

- Low-Frequency Degradation: Primary magnetizing inductance L_m causes low-frequency attenuation as $X_{Lm} = 2\pi fL_m$ drops, creating core saturation and frequency distortion below 50 Hz.
- High-Frequency Degradation: Transformer leakage inductance L_l and inter-winding parasitic capacitance C_w cause high-frequency attenuation and self-resonance peaks.
- Poor Frequency Response Uniformity: Non-flat frequency response curve makes transformer coupling unsuitable for high-fidelity (Hi-Fi) audio amplification.
- Physical Constraints: Transformers are bulky, heavy, expensive, introduce magnetic hum pickup, and CANNOT be integrated onto monolithic silicon IC chips.

LC (Tuned) Coupling Technique: High-Frequency RF Bandpass Cascades

- Circuit Topology: A parallel LC resonant tank circuit (L in parallel with C) serves as the collector load for Stage 1, coupled to Stage 2 via a small coupling capacitor.
- Resonant Frequency (f_0): Implements a narrow bandpass filter centered at $f_0 = \frac{1}{2\pi\sqrt{LC}}$. Tank impedance peaks sharply to $R_p = Q\omega_0 L$ at resonance.
- Quality Factor (Q) & Selectivity: Tank $Q = \frac{R_p}{\omega_0 L} = \omega_0 R_p C$. High Q provides steep selectivity, suppressing adjacent channel interference in radio receivers.
- Passband Bandwidth (BW): 3-dB bandpass bandwidth $BW = \frac{f_0}{Q}$. Ideal for RF receivers, IF amplifiers (455 kHz, 10.7 MHz), and wireless transmitters.

Comprehensive Comparative Analysis of Coupling Techniques

- Direct Coupling: Frequency Range = 0 Hz (DC) to > 100 MHz; DC Isolation = None; Impedance Matching = Poor; IC Integrability = Excellent (Preferred in ICs); Cost = Very Low.
- RC Coupling: Frequency Range = 20 Hz – 20 kHz (Audio); DC Isolation = Excellent (via C_C); Impedance Matching = Poor; IC Integrability = Poor ($C_C > 10$ pF too large); Cost = Low.
- Transformer Coupling: Frequency Range = Narrow audio/RF; DC Isolation = Excellent (magnetic); Impedance Matching = EXCELLENT (n^2 ratio); IC Integrability = Impossible; Cost = High.
- LC (Tuned) Coupling: Frequency Range = High RF (100 kHz – GHz); DC Isolation = Good (via C); Impedance Matching = Moderate; IC Integrability = Moderate (RF-IC spirals); Cost = Moderate.

Design Calculation Example 1: Transformer Matching for Output Driver

- Problem Statement: A BJT power stage has an output internal resistance $R_{out} = 1.8 \text{ k}\Omega$. It must drive a low-impedance loudspeaker $R_L = 8 \text{ }\Omega$. (1) Calculate required transformer turns ratio $n = N_p/N_s$ for maximum power transfer. (2) Compare power delivered to load with transformer vs direct RC connection.
- Step 1 - Turns Ratio Calculation: For maximum power transfer, primary reflected impedance $R_p = R_{out} = 1800 \text{ }\Omega$. Using $R_p = n^2 R_L \implies n = \sqrt{\frac{R_p}{R_L}} = \sqrt{\frac{1800}{8}} = \sqrt{225} = 15 : 1$.
- Step 2 - Power Comparison: AC signal voltage source $V_{oc} = 12 \text{ V}_{rms}$.
- With Transformer Matching: Load power $P_L = \frac{(V_{oc}/2)^2}{R_p} = \frac{6^2}{1800} = \frac{36}{1800} = 20 \text{ mW}$.
- Without Transformer (Direct Connection): $I_L = \frac{12}{1800+8} = 6.637 \text{ mA}_{rms}$. Load power $P_{L,direct} = I_L^2 R_L = (6.637 \text{ mA})^2 \times 8 \text{ }\Omega = 0.352 \text{ mW}$. Transformer matching increases output power by over 56 times ($56.8\times$)!

Design Calculation Example 2: LC Tuned Coupling Bandwidth and Q-Factor Design

- Problem Statement: An IF amplifier in an AM radio receiver operates at a center frequency $f_0 = 455$ kHz using LC tuned coupling with inductance $L = 1$ mH. The parallel tank resistance is $R_p = 50$ k Ω . Calculate: (1) Required tuning capacitance C . (2) Tank Quality Factor Q . (3) 3-dB passband bandwidth BW .
- Step 1 - Calculate Tuning Capacitance C : Using
$$f_0 = \frac{1}{2\pi\sqrt{LC}} \implies C = \frac{1}{4\pi^2 f_0^2 L} = \frac{1}{4\pi^2 (455 \times 10^3)^2 \times 10^{-3}} = 122.2 \text{ pF}.$$
- Step 2 - Calculate Tank Reactance X_L : $X_L = 2\pi f_0 L = 2\pi \times 455 \times 10^3 \times 10^{-3} = 2858.8 \Omega$.
- Step 3 - Calculate Quality Factor Q : $Q = \frac{R_p}{X_L} = \frac{50,000 \Omega}{2858.8 \Omega} = 17.49$.
- Step 4 - Calculate 3-dB Bandwidth BW : $BW = \frac{f_0}{Q} = \frac{455 \text{ kHz}}{17.49} = 26.01 \text{ kHz}$ (ideal for selecting 10 kHz AM audio channels while suppressing adjacent stations).

Summary & Selection Criteria for Multi-Stage Coupling Networks

- Direct Coupling: Extends response down to DC (0 Hz). Mandatory for IC fabrication; requires level shifters to manage DC bias buildup.
- RC Coupling: Standard for discrete audio amplifiers (20 Hz – 20 kHz). Blocks DC bias using C_C ; inexpensive but causes inter-stage loading.
- Transformer Coupling: Provides maximum power transfer via turns ratio $n = \sqrt{R_p/R_s}$ and electrical isolation, but is bulky and non-linear.
- LC Tuned Coupling: Provides narrow-band high-frequency RF selectivity ($f_0 = \frac{1}{2\pi\sqrt{LC}}$, $BW = f_0/Q$). Ideal for wireless receiver IF stages.
- Selection Strategy: Match coupling topology to operational frequency range, integration constraints, and power efficiency requirements.