Lecture 34: Wideband Amplifiers - I

Applications:
- PCB chip-to-chip links
- Optical fibre communications
- Wideband wireline comm. (e.g. TV)
- Measurement instrument front-ends (e.g. Oscilloscopes)
- Wireless: UWB radio & multiband radios

ABW product

* C.S. amplifier driving identical stage

\[
\frac{V_{out}(s)}{V_{in}} = AV(s)
\]

\[
AV(s) = \frac{g_m R_{ds}}{1 + sC_L R_{ds}}
\]

DC gain \( A_0 = g_m R_{ds} \)

\[
W_{3dB} = W_0 = \frac{1}{C_L R_{ds}}
\]

Unity gain freq. \( W_u = A_0 W_0 = \frac{g_m}{C_L} \)
* Increasing power cannot take us far:

\[ g_m \]

* \( \frac{g_m}{C_L} \) = constant

* If \( W \uparrow \Rightarrow g_m \uparrow \)

* But so does \( C_L \)

\[ \Rightarrow \frac{g_m}{C_L} = \text{constant} \]

* Cascade a number of single-pole amps can accomplish this, but \( \Rightarrow \) more delay

\[ \Rightarrow \text{Gain - BW - Delay tradeoff is fundamental} \]
**BW Enhancement Techniques**

1) **Shunt Peaking**

- **Gain:**

  ![Gain Diagram]

  \[ g_{mL} \]

- **Frequency:**

  \[ \omega_0 = \frac{1}{\sqrt{L C}} \]

  * \( L \) introduces a zero

  (\( \omega \) rises with \( f \) even)

  \[ \Rightarrow \text{broader freq. range} \]

  than \( \omega_0 \) is possible

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* In the time domain: assume an input voltage step

  \[ \Rightarrow \text{inductive delay current flow in branch containing } R, L \]

  \[ \Rightarrow \text{more current available for charging } C \]

  \[ \Rightarrow \text{rise time is reduced} \]

  \[ \text{i.e. BW is increased} \]

\[ Z(s) = (sL + R) \frac{1}{sC} \]

\[ = \frac{R(s + \frac{1}{R})}{s^2 L C + s R C + 1} \]

\[ \{ \text{Av}(s) = 9m \mid \text{II}(j\omega) \} \]

\[ \Rightarrow \text{study } |Z(j\omega)| \]
\[ \Rightarrow 2 \text{ poles (complex conjugate is possible)} \]
\[ 1 \text{ zero } w(z) = -\frac{R}{L} \]

Define:
(i) original 3dB BW \( w_0 = \frac{1}{RC} \)
(ii) time constant corresponding to zero \( \tau = \frac{1}{R} \)
(iii) \( m = \frac{\text{original time constant}}{\text{new time constant}} = \frac{RC}{L/R} = \frac{1}{w_0 \tau} \)

\[ \Rightarrow z(s) = \frac{\delta z + 1}{s^2 + \delta z s + 1} \]

\[ \frac{|z(jw)|}{R} = \sqrt{\frac{(\frac{w^2 c^2}{1-w^2 c^2})^2 + (w c m)^2}{(1-w^2 c^2)^2 + (w c m)^2}} \]

\( w = w_{3dB}, \quad \frac{|z(jw)|}{R} = \frac{\sqrt{2}}{\sqrt{2}} \)

\[ \Rightarrow \frac{1 + \frac{w^2 c^2}{1-w^2 c^2}}{(1-w^2 c^2)^2 + (w c m)^2} = \frac{1}{2} \]

Let \( \alpha = w^2 c^2 \)

\[ \Rightarrow \frac{1 + \alpha}{(1 - \alpha x)^2 + \alpha x} = \frac{1}{2} \]

\[ \Rightarrow 2 + 2\alpha = \alpha x + 2mx + 1 + \alpha x \]
\[ m^2 x^2 + (m^2 - 2m - 2)x - 1 = 0 \]

\[ \Rightarrow x = \frac{(2m + 2 - m^2) \pm \sqrt{(2m + 2 - m^2)^2 + 4m^2}}{2m} \]

only +ve root because \( x = \omega^2 c^2 > 0 \)

\[ x = \frac{1}{m^2} \left\{ (m+1-m^2) \pm \sqrt{(m+1-m^2)^2 + m^2} \right\} \]

\[ x = (W_{3dB} \cdot \omega)^2 = \left( \frac{W_{3dB}}{W_0} \right)^2 \cdot (\omega_0 \cdot c)^2 \]

\[ = \left( \frac{W_{3dB}}{W_0} \right)^2 \cdot \frac{1}{m^2} \]

\[ \Rightarrow \frac{W_{3dB}}{W_0} = \sqrt{\left( \frac{m^2}{2} + m + 1 \right) + \sqrt{\left( \frac{m^2}{2} + m + 1 \right)^2 + m^2}} \]

* You can plot \( \frac{W_{3dB}}{W_0} \) as a function of \( m \)

* Also plot \( \frac{Z(j\omega)}{R} \) as a function of \( m \)

1) For max BW extension,

\[ m = \sqrt{2^2} = 1.41 \]

\[ \Rightarrow \frac{W_{3dB}}{W_0} = 1.85 \] at no increase in power!

\[ \frac{W_{3dB}}{W_0} = \text{BW extension factor (BWEF)} \]
Problem: almost 20% peaking in freq. response.

![Gain vs Frequency Graph](image)

- Set |z| = R @ \( w_0 \) to moderate peaking
  - Solving for \( m \) gives \( m = 2 \)

\[
W_{3dB} = W_0 \sqrt{1 + \sqrt{5}} \approx 1.8W_0
\]

- BW extension almost the same
- Peaking ~3% \( \{ \text{often-used optimum} \} \)
2) Maximally flat response (Butterworth)
   \[ |Z(j\omega)|^2 = \text{maximum # of derivatives where value is zero at DC} \]
   \[ m = 1 + \sqrt{2} = 2.41 \]
   \[ \Rightarrow \omega_{3\text{dB}} = 1.72 \omega_0. \]

3) Even with maximally flat response, phase distortion may occur. (IISD)
   \[ \Rightarrow \text{optimize for group-delay response} \]
   e.g. optical comm. applications, UWB

+ Ideal wide band amp \( \Rightarrow \) phase \( \propto \) linearly with freq. (i.e. same delay for all freq.) \( \Rightarrow \) \( \frac{d\phi}{d\omega} = \text{constant over freq.} \)
+ Non-linear phase response \( \Rightarrow \) unequal delay of freq. components
   \( \Rightarrow \) group-delay distortion
+ Maximally flat group delay:
   \[ T_D(\omega) = -\frac{d\phi}{d\omega} \]
   \( \Rightarrow \) maximize # of derivatives of \( T_D(\omega) \) where value is zero at DC.
after lots of algebra:
\[ m \approx 3.1 \]
\[ \Rightarrow w_1 \approx 1.12 \]

* conditions for maximally flat gain and delay do not coincide, so tradeoff is involved.

Design:
Given: DC gain, load cap C, \( \omega_2 \omega_3 \),
constraint on max BW/mag response,
phase response

\[ \omega_0 = \frac{\omega_2 \omega_3}{BWXF} = \frac{1}{RC} \Rightarrow (R) \]
\[ AV_{ac} = 9m \Rightarrow (g_m) \]
\[ m = \frac{RC}{L/2} \Rightarrow L = \frac{R^2C}{m} \Rightarrow (L) \]

* \( R \) is in series with \( L \)
\[ \Rightarrow \] low-Q \( L \) is ok, absorb series \( R_s \) into \( R \)

* Emphasize more on area \( \Rightarrow \) max \( L \) in minimum area
\[ \Rightarrow \] series stacked structures are popular
<table>
<thead>
<tr>
<th>Condition</th>
<th>( m = \frac{R^2C}{L} )</th>
<th>( BW \times F )</th>
<th>Normalised peak freq. response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max BW</td>
<td>1.41</td>
<td>1.85</td>
<td>1.19</td>
</tr>
<tr>
<td>(</td>
<td>Z</td>
<td>= R @ \omega_0 )</td>
<td>2</td>
</tr>
<tr>
<td>Minimally flat</td>
<td>2.41</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>Group delay</td>
<td>3.1</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>No shunt peaking</td>
<td>( \infty )</td>
<td>1</td>
<td></td>
</tr>
</tbody>
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**Series Peaking**

\[
\begin{align*}
V_{in} & \rightarrow R & L_2 & \rightarrow \frac{C}{m} \\
\end{align*}
\]

- \( m = 2 \Rightarrow \text{max BW} \Rightarrow BWXF = \sqrt{2} \)
- \( m = 3 \Rightarrow \text{minimally flat} \)
- \( m = 3 \Rightarrow \text{max flat group delay} \Rightarrow BWXF = 1.36 \)
- Shunt peaking BWXF > Series peaking BWXF
- Why not use both?
Shunt-series peaking

\[ T \quad R \]
\[ L_1 \quad L_2 \quad L_3 \]
\[ V_{out} \]
\[ V_{in} \]

* BW - delay

Tradeoff

* C_{db} & C_{l} are charged serially

in time

Shunt-double series peaking

\[ T \quad R \]
\[ L_1 \quad L_2 \quad L_3 \]
\[ V_{out} \]
\[ V_{in} \]

* L_1, L_2, L_3 can be replaced by a single Xfmr to save area

* Add bridging cap to create parallel resonance (this helps with BW too)

Bridged

T-Coil

\[ \overline{C_{b}} \quad \overline{L} \quad \overline{C_{l}} \]

\[ V_{in} \quad V_{out} \]
* You can show that

\[ L = \frac{R^2 C}{2(1+k)} \]

\[ C_B = C - \frac{(1-k)}{4(1+k)} \]

* \( k = \frac{1}{3} \) ⇒ Butterworth maj. response
* \( k = \frac{1}{2} \) ⇒ max. flat group delay
* Used in oscilloscopes for a long time
* \( W_{3dB \text{ (max)}} = 2\sqrt{2} \ W_0 \)

\( \approx 2.83 \ W_0 \)