A LDO Regulator with Weighted Current Feedback Technique for 0.47nF-10nF Capacitive Load

*Presented by*

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Outline

• Introduction of LDO Regulator
• Multi-gain Stages in Output Capacitorless (OCL-LDO) regulator
• Negative Current Feedback (NCF) Technique
• Weighted Current Feedback (WCF) Technique
• Circuit Implementation of WCF LDO regulator
• Results and Discussions
• Conclusion
Introduction of LDO regulator

- Widely used due to its simple structure, fast response and low noise characteristics.

- Output capacitorless LDO (OCL-LDO) regulator eliminates the large output capacitor and supports fully on-chip applications.

- For large scale digital circuits, the effective supply line parasitic capacitance is large. The regulator needs to drive a wide range of load capacitance ($C_L$) with fast transient response.
Multi-gain Stages in a LDO Regulator

1. \( N_2 \) is low impedance node and \( N_P \) is high impedance node.
2. \( p_3 \) and \( p_O \) are low, limiting the stability at light \( I_L \).
3. Speed at node \( N_P \) is small due to limited quiescent bias current in 3\(^{rd}\) stage.
1. $N_P$ is low impedance node and $N_2$ is high impedance node.
2. 3rd stage is adaptively biased leading to a high speed.
3. Large $R_2$ and large $C_P$ results in two low frequency parasitic poles.
4. Negative feedback technique to reduce $R_2$. 
1. Negative feedback current reduce $R_2$ thus reduce the loop gain of the regulator as well. The regulation accuracy is degraded.

2. The charging/discharging rate at node $N_2$ is also reduced.
Weighted Current Feedback Technique: Operation

1st stage
+g_{m1}

2nd stage
-g_{m2}

3rd stage
-g_{m3}

Power T.
M_{P} (-g_{mp})

Frequency
Compensation

Overshoot
Reduction

V_{REF}

N_1 (V_1)

N_2 (V_2)

N_P (V_P)

V_{DD}

WCF (g_{mf})

WCF Loop

Weighted Current Feedback (WCF)

V_{fbin}

V_{fbout}

R_L

C_L

N_{O} (V_{OUT})
1. At low $I_L$, both $M_{a1}$ and $M_{a2}$ are weakly biased. Feedback is small.
2. At moderate $I_L$, both $M_{a1}$ and $M_{a2}$ are in saturation region. Feedback is strong.
3. At high $I_L$, $M_{a2}$ is forced to work in linear region by $M_{a3}$ and $M_{a4}$. Feedback is reduced.
Weighted Current Feedback Technique: Why it works?

- At low $I_L$, $R_O$ is large, $C_LR_O$ forms the dominant pole. $\omega_{UGF}$ is small. Feedback can be small to achieve stability.
- At moderate $I_L$, loop gain is large. $R_2$ and $R_P$ are moderate. A strong feedback is required to reduce $R_2$ and the loop gain.
- At high $I_L$, $R_P$ is small. $R_2$ is also small due to a large bias current introduced by the WCF circuit. The feedback can be reduced.
WCF loaded Output Impedance & Feedback Factor

1. $R_{2f}$ (feedback loaded impedance at node $N_2$) is significantly reduced at moderate and high $I_L$.

2. The feedback ($\beta$ is the feedback factor) is strong at moderate $I_L$ and weak at both low and high $I_L$. 
## Parameters of WCF Regulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case I: Large $C_L R_O$</th>
<th>Case II: Moderate $C_L R_O$</th>
<th>Case III: Small $C_L R_O$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback</td>
<td>Low $I_L$</td>
<td>Moderate $I_L$</td>
<td>High $I_L$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$g_{m3}g_{mf}R_2R_P + 1$</td>
<td>$g_{m1}g_{m2}g_{m3}g_{mp}R_1R_2R_P R_O / \beta$</td>
<td>$-\beta / (C_c g_{m2}g_{m3}g_{mp} R_1 R_2 R_P R_O)$</td>
</tr>
<tr>
<td>$A_{DC}$</td>
<td>$g_{m1}g_{m2}g_{m3}g_{mp} R_1 R_2 R_P R_O / \beta$</td>
<td>$-1 / (2C_L R_O)$</td>
<td>$-1 / (C_L R_O)$</td>
</tr>
<tr>
<td>$z_1$</td>
<td>$-g_{mc} / C_c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_{-3dB}$</td>
<td>$-1 / (C_L R_O)$</td>
<td>$-1 / (2C_L R_O)$</td>
<td>$-\beta / (C_c g_{m2}g_{m3}g_{mp} R_1 R_2 R_P R_O)$</td>
</tr>
<tr>
<td>$</td>
<td>p_{2,3}</td>
<td>_f$</td>
<td>$\sqrt{\beta g_{mc} / [(\beta C_c + C_P g_{mc} R_P) C_m R_1]}$</td>
</tr>
<tr>
<td>$</td>
<td>p_{4,5}</td>
<td>_f$</td>
<td>$\sqrt{(\beta C_c + C_P g_{mc} R_P) / (C_c C_2 C_P R_2 R_P)}$</td>
</tr>
<tr>
<td>$Q_{p_{2,3}}</td>
<td>_f$</td>
<td>$\sqrt{(\beta C_c + C_P g_{mc} R_P) / (\beta C_m g_{mc} R_1)}$</td>
<td>$\sqrt{(\beta C_c + C_P g_{mc} R_P) / (\beta C_m g_{mc} R_1)}$</td>
</tr>
<tr>
<td>$Q_{p_{4,5}}</td>
<td>_f$</td>
<td>$\sqrt{\beta C_L g_{mc} / (C_m g_{m2} g_{m3} g_{mp} R_2 R_P)}$</td>
<td>$\sqrt{\beta C_L g_{mc} / (C_m g_{m2} g_{m3} g_{mp} R_2 R_P)}$</td>
</tr>
<tr>
<td>$\omega_{UGF}$</td>
<td>$g_{m1}g_{m2}g_{m3}g_{mp} R_1 R_2 R_P / (\beta C_L)$</td>
<td>$g_{m1} / (2C_c)$</td>
<td>$g_{m1} / C_c$</td>
</tr>
</tbody>
</table>

Due to the WCF technique, $|p_{4,5}|_f$ can be pushed to a higher frequency. The stability can be achieved.
Circuit of WCF Regulator

Loop Gain and Phase Responses

Stable for $C_L = 470 \text{ pF}$ and $10 \text{ nF}$.
Minimum PM = $45^\circ$, Minimum GM = $11 \text{ dB}$.
Microphotograph

Area = 0.0133 mm$^2$
Measured Transient Responses

(a) $C_L = 470\,\text{pF}$

(b) $C_L = 1\,\text{nF}$

(c) $C_L = 3.3\,\text{nF}$

(d) $C_L = 10\,\text{nF}$
## Performance Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>JSSC 2005 no. 4</th>
<th>TCAS-I 2007 no.9</th>
<th>JSSC 2010 no. 2</th>
<th>JSSC 2010 no. 9</th>
<th>TCAS-I 2012 no. 5</th>
<th>TCAS-II 2012 no. 1</th>
<th>TCAS-I 2012 no. 9</th>
<th>TCAS-I 2013 no. 4</th>
<th>TCAS-II 2013 no. 6</th>
<th>JSSC 2014 no. 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology (μm)</td>
<td>0.09</td>
<td>0.35</td>
<td>0.35</td>
<td>0.09</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.065</td>
<td>0.11</td>
<td>0.065</td>
</tr>
<tr>
<td>Chip Area (mm²)</td>
<td>0.098</td>
<td>0.12</td>
<td>0.155</td>
<td>0.019</td>
<td>0.0987</td>
<td>0.064</td>
<td>0.4</td>
<td>0.017</td>
<td>0.21</td>
<td>0.0133</td>
</tr>
<tr>
<td>(V_{IN}) (V)</td>
<td>1.2</td>
<td>3</td>
<td>0.95-1.4</td>
<td>0.75-1.2</td>
<td>1.2</td>
<td>2.5-4</td>
<td>1.2-1.5</td>
<td>1.2</td>
<td>1.8-3.8</td>
<td>0.75-1.2</td>
</tr>
<tr>
<td>(V_{OUT}) (V)</td>
<td>0.9</td>
<td>2.8</td>
<td>0.7-1.2</td>
<td>0.5-1</td>
<td>1</td>
<td>2.35</td>
<td>1</td>
<td>1</td>
<td>1.6-3.6</td>
<td>0.55</td>
</tr>
<tr>
<td>Dropout Voltage (mV)</td>
<td>300</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>150</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>(I_Q) (μA)</td>
<td>6000</td>
<td>65</td>
<td>43</td>
<td>8</td>
<td>28-380.1</td>
<td>7</td>
<td>45</td>
<td>0.9-82.4</td>
<td>41.5</td>
<td>15.9* - 487</td>
</tr>
<tr>
<td>(I_{OUT}) (max) (mA)</td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>Total On-Chip Cap. (pF)</td>
<td>600</td>
<td>21</td>
<td>6</td>
<td>7</td>
<td>10</td>
<td>7.5</td>
<td>41</td>
<td>4.5</td>
<td>43.2</td>
<td>4.1</td>
</tr>
<tr>
<td>Load Cap. Range (F)</td>
<td>600p</td>
<td>0-100p</td>
<td>0, 100p, 1n</td>
<td>0-50p</td>
<td>0-100p</td>
<td>0-100p</td>
<td>0-1n</td>
<td>0-100p</td>
<td>40p</td>
<td>470p-10n</td>
</tr>
<tr>
<td>Line Reg. (mV/V)</td>
<td>N/A</td>
<td>23</td>
<td>N/A</td>
<td>3.78</td>
<td>0.39</td>
<td>1</td>
<td>N/A</td>
<td>4.7</td>
<td>8.9</td>
<td>4</td>
</tr>
<tr>
<td>Load Reg. (mV/mA)</td>
<td>1.8</td>
<td>0.56</td>
<td>0.4</td>
<td>0.1</td>
<td>0.0782</td>
<td>0.08</td>
<td>N/A</td>
<td>0.3</td>
<td>0.108</td>
<td>0.18</td>
</tr>
<tr>
<td>PSR @1kHz (dB)</td>
<td>N/A</td>
<td>-57</td>
<td>N/A</td>
<td>-44</td>
<td>-49.8</td>
<td>N/A</td>
<td>N/A</td>
<td>-58(@10kHz)</td>
<td>N/A</td>
<td>-51</td>
</tr>
<tr>
<td>Settling Time (μs)</td>
<td>N/A</td>
<td>15</td>
<td>3</td>
<td>5</td>
<td>N/A</td>
<td>~0.15</td>
<td>~4</td>
<td>6</td>
<td>0.65</td>
<td>0.25</td>
</tr>
<tr>
<td>(I_{L(min)}) (mA)†</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0.05</td>
<td>1</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>(\Delta I_{OUT}) (mA)</td>
<td>100</td>
<td>50</td>
<td>99</td>
<td>97</td>
<td>100</td>
<td>99.95</td>
<td>49</td>
<td>100</td>
<td>199.5</td>
<td>50</td>
</tr>
<tr>
<td>(\Delta V_{OUT}) (mV)</td>
<td>90</td>
<td>90</td>
<td>70</td>
<td>114</td>
<td>105</td>
<td>243</td>
<td>70</td>
<td>68.8</td>
<td>385</td>
<td>113</td>
</tr>
<tr>
<td>Edge Time (μs)</td>
<td>0.0001</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>300</td>
<td>0.5</td>
<td>0.1</td>
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<tr>
<td>Edge Time Ratio K</td>
<td>1</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>5000</td>
<td>10000</td>
<td>3000</td>
<td>5000</td>
<td>10000</td>
</tr>
<tr>
<td>FOM</td>
<td>0.0054</td>
<td>1.17</td>
<td>0.304</td>
<td>0.0094</td>
<td>0.294</td>
<td>0.085</td>
<td>0.643</td>
<td>0.0019</td>
<td>0.4</td>
<td>0.036</td>
</tr>
</tbody>
</table>

* Quiescent current includes the current consumption of bias circuit. † The minimum \(I_L\) used to test the transient performance.
Conclusion

1. A weighted current feedback technique is proposed in OCL-LDO Regulator.

2. Due to the smart control of the output impedance of the inter gain stage, the regulator can achieve a good stability, fast speed and high accuracy.

3. The comparison results have shown the WCF LDO regulator achieves a comparable or better FOM with respect to other reported designs whilst achieving wide range of $C_L$ driving ability.
Acknowledgment

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Thank You!
Q & A