BANDWIDTH ENHANCEMENT OF THE CASCADED-CASCODE AMPLIFIER CONFIGURATION

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ABSTRACT
The demand for additional gain and bandwidth at high frequency normally presents the need to cascade amplifying circuits. However cascading technique always has a drawback of shrinking bandwidth. Cascade-cascode amplifier is hereby modified to have an enhanced bandwidth through the application of negative feedback. Both the simulation and analysis of the proposed configuration shows significant improvement on the bandwidth.

Keyword: Cascode amplifier, cascading, negative feedback.

1. INTRODUCTION
Wideband amplifiers are used in a variety of modern wireless communication systems. Wideband communication is fundamentally different from all other communication techniques because it employs extremely narrow radio frequency (RF) pulse to communicate between transmitter and receiver [5]. Utilizing short pulse as building blocks for communications directly generates a very wide bandwidth and offer several advantages such as large throughput, robustness to jamming, and coexistence with current radio services [8]. The signal at the receiving end normally arrives very weak due to channel problem; as such the front-end circuit of the receiver requires an appropriate amplifier having low noise, appreciable gain and bandwidth [6][10]. Circuits with very wide bandwidth are needed in modern communications for efficient high data rate transfer. The design of such circuit is one of the challenges faced in radio frequency receivers [4]. Many amplifier topologies have been proposed so as to satisfy the requirement for gain and bandwidth. Most of the single stage devices in the review could not satisfy the gain and bandwidth requirements [1][7][9]. Ibrahim et al. (2012) and Othman et al. (2013) adopted cascaded cascode and a single stage cascode with positive feedback respectively. The work of the last two authors suffered from bandwidth shrinkage due to cascading adopted by Ibrahim et al. (2012), and the inherent risk of instability due to positive feedback to get gain in the work of Othman et al. (2013). In this work, we proposed the application of negative feedback to a cascade cascode connection for front-end use. The circuit solved the instability problem associated with the work of Othman et al. (2013) as well as modifies the bandwidth shrinkage of the work of Ibrahim et al. (2012).

2. METHODOLOGY
The cascode configuration consists of common emitter and common base transistor, providing superior bandwidth and gain performance as compared with traditional common emitter amplifier. Some additional advantages, such as significantly higher output impedance, improved reverse isolation and drastically reduced miller feedback capacitance [2], make the cascode configuration a preferred technique for this work. Firstly cascode amplifier is design. Secondly, the design cascode amplifier is cascaded in two stages. However, cascading technique has drawback of shrinking bandwidth, as such negative feedback is applied to the cascade cascode in order to improve the frequency response of the amplifier and to minimize the detrimental effect of cascading.

2.1 CIRCUIT DESIGN
Cascaded-cascade amplifier with negative feedback (WNF) has been designed and simulated using NI Multisim 11. Fig. 1, 2, and 3, shows the complete schematic circuit of the cascode amplifier, cascade-cascode amplifier, and the proposed cascaded-cascode amplifier (WNF) respectively. The circuit design formula and equation were referred to [7]. The function generator and an oscilloscope were connected to the input and output of the amplifiers respectively. The amplitude of function generator was set to 10mV and frequency was varied from 10Hz to 10GHz, and an amplified output voltage was viewed and measured using the oscilloscope, and hence the voltage gain was determined.
2.2 DESIGN EQUATIONS
In the design, the same transistors were used in the common emitter and common base stage, hence $\beta_F_1 = \beta_F_2 = \beta > 1$, that is the base current of the transistors is negligible, and base current can be ignored in comparison to the currents through the biasing resistances. Therefore the DC biasing base voltages are given by

$$V_{BB1} = \frac{R_1}{R_1 + R_2 + R_3} V_{CC}$$  \hspace{1cm} (1)

$$V_{BB2} = \frac{R_1 + R_2}{R_1 + R_2 + R_3} V_{CC}$$  \hspace{1cm} (2)

The Collector and emitter currents is given by,

$$I_E_1 \approx I_C_1 = I_E_2 \approx I_C_2 = \frac{V_{BB1} - V_{BE}}{R_E}$$  \hspace{1cm} (3)

The collector emitter voltages are given by

$$V_{CE1} = V_{BB2} - V_{BE2} - (V_{BB1} - V_{BE1})$$ \hspace{1cm} (4)

$$V_{CE2} = V_{BB2} - R_C I_C_2 - (V_{BB2} - V_{BE2})$$ \hspace{1cm} (5)

**Figure 1**: Schematic diagram of cascode amplifier

**Figure 2**: Schematic diagram of cascaded-cascode amplifier
2.3 CIRCUIT ANALYSIS
The analysis result was obtained by replacing the transistors in the circuits above with the high frequency Hybrid-$\pi$ Model of the Bipolar Junction Transistor (BJT). Fig. 4 shows the high frequency BJT Hybrid-$\pi$ Model, by neglecting $r_s$ and $r_o$ we have the small signal equivalent circuit of the 3-configurations as shown in fig. 5, 6 and 7.
Where

\[ r_s = \text{Spreading resistance}, \quad gmV_{\pi} = gmV_{be} = I_c - \text{equivalent current generator} \]

\[ r_1 = r_\pi = \text{Dynamic emitter resistance}, \quad c_1 = c_\pi = \text{Dynamic emitter capacitance} \]

\[ c_{\mu} = \text{Collector base transition capacitance} \quad r_o = \text{output resistance} \]

Figure 4: High frequency BJT Hybrid-$\pi$ Model
Figure 5: Small signal equivalent circuit for cascode amplifier

Figure 6: Small signal equivalent circuit for cascaded-cascode amplifier

Figure 7: Small signal equivalent circuit for cascaded-cascode amplifier with negative feedback.
From the small signal equivalent circuit of the cascode amplifier we write the current equation at node \( V_1, V_2 \) and \( V_0 \), and we obtained equation (6), (7), and (8). From the nodal equations we get the expressions; equation (9), (10) and (11) for the voltage gains of the 3-amplifier configurations.

\[
\frac{V_1-V_2}{R_s} + \frac{V_1}{r_1} + \frac{V_1-V_2}{X_{c1}} = 0 \tag{6}
\]

\[
\frac{V_2-V_1}{X_{c1}} + g_m V_1 + \frac{V_2}{r_1} + \frac{V_2}{X_{c1}} - g_m V_2 = 0 \tag{7}
\]

\[
\frac{V_0}{V_c} + \frac{V_0}{X_{c1}} + g_m V_1 = 0 \tag{8}
\]

\[
A_p = \frac{-g_m \mu (SC_{c1} - g_m)}{[SC_{c1} (SC_{c1} - g_m)] - (G_s + g_f + SC_{c1} + SC_{c2}) (g_1 - g_m + SC_{c1} + SC_{c2})] [G_c + SC_{c1}]}
\tag{9}
\]

\[
A_p = \frac{-[g_m \mu (SC_{c1} - g_m)]^2}{[SC_{c1} (SC_{c1} - g_m)] - (G_s + g_f + SC_{c1} + SC_{c2}) (g_1 - g_m + SC_{c1} + SC_{c2})] [G_c + SC_{c1}]}
\tag{10}
\]

\[
A_p = \frac{-[g_m \mu (SC_{c1} - g_m)]^2}{[SC_{c1} (SC_{c1} - g_m)] - (G_s + g_f + SC_{c1} + SC_{c2}) (g_1 - g_m + SC_{c1} + SC_{c2})] [G_c + SC_{c1}]}
\tag{11}
\]

Where \( G_s = 1/R_s, G_c = 1/R_c, G_e = 1/R_e, G_f = 1/R_f \) and \( g_1 = 1/r_1 \).

3. RESULT
The simulated and the calculated results of the 3-amplifiers configuration are shown in TABLE I. The gain and the bandwidth for simulation was obtained from the plot of voltage gain against frequency, while the that of the analysis were obtained from equation (9) for cascode amplifier, equation (10) for the cascode-cascode amplifier and equation (11) for the cascode-cascode amplifier with negative feedback, the gain function for the 3-amplifier configuration are in equation (12), (13) and (14) respectively. And the the graphs for the simulation and analysis are shown in fig. 8, 9 and 10. The value of the components used in the design is shown below

\[
R_s = 500\Omega, R_c = 2.2K\Omega, R_E = 450\Omega, \quad R_1 = 22K\Omega, R_2 = 15K\Omega, R_3 = 7.5K\Omega, R_f = 10K\Omega, g_1 = 5.8 \times 10^{-4}, g_m = 6.5 \times 10^{-2}, \quad C_1 = 2.5pF, \quad C_\mu = 0.6pF, \quad C_1 = 7\mu\text{FC}_2 = 7\mu\text{FC}_E = 11\mu F, \quad R_f = 112l, \quad 1.68mA \text{Al}_{E_1} = 1.7mA \\
V_{CE_1} = V_{CE_2} = 4.9V, \quad V_{CC} = 9V
\]

\[
A_p (S) = \frac{-5(1.1 \times 10^{-2}) + 1.4 \times 10^{-12}}{S^3(1.3 \times 10^{-14}) + S^2(1 \times 10^{-9}) + S(1.1 \times 10^9) + 2.2 \times 10^{10}}
\tag{12}
\]

\[
A_p (S) = \frac{S^2(1.2 \times 10^{-6}) - S(3 \times 10^{10}) + 2 \times 10^{24}}{S^6(1.7 \times 10^{-38}) + S^5(2.6 \times 10^{-27}) + S^4(1.1 \times 10^{-19}) + S^3(6.9 \times 10^{-7}) + S^2(1.6 \times 10^3) + S(1.5 \times 10^{12}) + 4.8 \times 10^{15}}
\tag{13}
\]

\[
A_p (S) = \frac{S^2(1.2 \times 10^{-6}) - S(3 \times 10^{10}) + 2 \times 10^{24}}{S^6(1.7 \times 10^{-38}) + S^5(2.6 \times 10^{-27}) + S^4(1.3 \times 10^{-19}) + S^3(7 \times 10^{-7}) + S^2(1.6 \times 10^3) + S(1.6 \times 10^{12}) + 4.1 \times 10^{20}}
\tag{14}
\]

**TABLE I:** Comparison of gain and bandwidth of some amplifier configurations

<table>
<thead>
<tr>
<th>AMPLIFIER CONFIGURATION</th>
<th>CALCULATED RESULT</th>
<th>SIMULATED RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gain (dB)</td>
<td>Bandwidth (MHz)</td>
</tr>
<tr>
<td>CASCODE</td>
<td>36.1</td>
<td>123</td>
</tr>
<tr>
<td>CASCADED CASCODE</td>
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<td>52.8</td>
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<tr>
<td>CASCADED-CASCODE (WNF)</td>
<td>73.8</td>
<td>64.3</td>
</tr>
</tbody>
</table>

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Figure 8: Frequency response for cascode amplifier (a) Theoretical (b) Simulated
Figure 9: Frequency response of cascaded cascode amplifier (a) Theoretical (b) Simulated
4. DISCUSSION
We found that application of negative feedback on the cascaded cascode amplifier enhanced the bandwidth of the amplifier. It is observed from the simulated and calculated results that while cascading improved the gain of the amplifier it also has a detrimental effect of shrinking the bandwidth. The application of negative feedback reduces the accompanying problem of bandwidth shrinkage, suppress channel noise and stabilize gain; as such the amplifier has great potential for wideband application. Considering the fact that modern wireless communication demand high data rate and large coverage the circuit can be use in the front-end receiver for WiMAX, Wi-Fi, and RADAR applications.

5. CONCLUSION
The cascaded cascode amplifier with negative feedback is successfully designed and simulated. It is observed from the simulated and the calculated results, application of negative feedback enhance the bandwidth of the amplifier with appreciable gain. Higher gain would expand communication distance and wider bandwidth would enhance efficient data rate transfer.

Figure 10: Frequency response of cascaded cascode amplifier with negative feedback (a) Theoretical (b) Simulated
REFERENCES


