An Integrated Active Hybrid Filter for ADSL

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I wish to acknowledge collaborations with:

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Outline

• Background
• System
• Circuits
• Process
• Measurements
• Summary
ADSL System

Central Office

Transmitter ➔ POTS Splitter ➔ Subscriber Loop ➔ Remote Terminal

Receiver

POTS Splitter

Remote Terminal

Transmitter

Receiver

PSTN

Frequency Division Multiplexed Operation

POTS

Up

26 kHz

1.1 MHz

Down
System Definitions

• This is a Frequency Division Multiplexed (FDM) system
• The Upstream band is defined as data from the Remote Terminal (RT) to the Central Office (CO) in frequency range 26kHz – 138kHz
• The Downstream band is defined as data from the CO to RT in the frequency range 160kHz – 1104kHz
• The hybrid design presented here is for the upstream case.
Third Order High-Pass Line Coupling
Transformer Line Coupling is Good

- Transformer coupling is nice for voltage gain, longitudinal balance and surge protection
- The bidirectional 3rd order high-pass isolates DSL from POTS and visa versa
- A 25kHz corner is optimal for maximum rejection of POTS without interfering with the Rx band
- Hybrid provides a signal path and transfer function from Tx to Rx such that the net Tx signal in the Rx signal path is eliminated (analog echo canceller)
- Hybrid is tuned to a specific loop impedance looking into the transformer
- To the extent the hybrid eliminates the echo, requirements on the data converters can be relaxed
Transformers are Good continued:

- Our system partition requires very good echo cancellation at low frequency, just where the impedance looking into the transformer is complicated.
- This makes for a complex hybrid transfer function and difficult circuit design.
- Line coupling components will differ for ADSL/POTS and ADSL/ISDN.
Passive Hybrid Topology

\[ V_{txp} \]

\[ V_{txm} \]

\[ R_T \]

\[ R_R \]

\[ R_{RR} \]

\[ Z_a \]

\[ Z_b \]

\[ Z_{LOOP} \]

\[ Z_{LOOP} \]

\[ R_A \]

\[ R_B \]

\[ C_B \]

\[ C_P \]

\[ C_S \]
A Bridge as Hybrid

• A Bridge circuit cancels the echo by construction
• Ideally the Rx amp only amplifies the receive signal
• The Bridge is tuned to the line coupling and loop impedance
• The Z-Loop model is not exact, but good enough to calculate $Z_a$ & $Z_b$
Hybrid Circuit Realization
Circuit Realization Comments

• The exact equation solution for the Bridge component values exits
• Complicated: requires 4 resistors, 3 inductors and 1 capacitor
• Large cost and board area
• Inductors must be non-saturating and Capacitors have the best dielectric to be distortion free
Lower cost and better board area because only 1 L, 3 C’s, 4 R’s
Alternative Passive Hybrid Topology

Diagram showing a passive hybrid topology with components labeled as follows:

- $V_{txp}$ and $V_{txm}$
- Hybrid sections with $Z_a$ and $Z_b$
- RX amp
- $R_T$, $R_R$, $C_S$, $C_P$, $R_A$, $R_B$, and $C_B$
- Loop impedance $Z_{LOOP}$

The diagram illustrates the interconnection of these components in a passive hybrid topology.
Non-Bridge Passive Solution

• Since there already exits a Rx amplifier, use it to subtract the echo and echo replica
• The Replica is just the “filtered” version of the transmitted signal.
• The transfer function is $H = \frac{Z_b}{Z_a + Z_b}$
• Need a passive filter that implements $H$
Alternative Realization

- Passive solution for H, but still requires 3 L’s, 2 R’s, 1 C
Active Hybrid Topology

\[ V_{txp} \] \[ V_{txm} \] 

[Diagram with various components and labels such as RX, hybrid, filter, Z_LOOP, \( R_T \), \( C_S \), \( C_P \), \( R_A \), \( R_B \), \( C_B \).]
Active Filter Solution

- If a passive filter works, then use an active filter to construct the echo replica.
- Design constraint: Distortion & Noise must be less than the receiver noise floor.
- The Rx amp should be the limitation to the system noise design.
Typical Hybrid Filter Transfer Function\textsuperscript{1,2}

\[
\frac{(s + 7.9 \times 10^5)(s^2 + 3.6 \times 10^4 s + 5 \times 10^{10})}{(s + 4.1 \times 10^5)(s^2 + 1.4 \times 10^5 s + 4.9 \times 10^{10})}
\]

1. Ideal transformer
2. Passive termination
Transfer Function Details

• This case is for Annex A (ADSL over POTS)

• Note a f>500 kHz the network looks like a resistive divider

• Example is for an IDEAL transformer, but note that a real transformer with leakage inductance adds a fourth real pole

• Need a circuit that implements this H
$$\frac{VOUT}{VIN} = \frac{(s-Z_1)(s-Z_1^*)(s-Z_2)}{(s-P_1)(s-P_1^*)(s-P_2)(s-P_3)}$$
Hybrid Filter Details

- The first stage is a differential biquad which implements 2 complex pole/zero pairs.
- The second stage has high frequency gain of one, therefore a passive RC network can be used to implement a real pole and zero.
- Then unity gain voltage followers are used to drive the Rx amp.
- A real pole \((1/R_4C_4)\) is added to model the leakage inductance of the transformer.
- Low noise design leads to BIG capacitors and SMALL resistors.
OpAmp Requirements

- Hybrid requires intermods >90dB so amp must have very low distortion
- Fully-Differential FCC amp chosen with resistive emitter degeneration of common-base amp; good high frequency signal path & simple compensation
- Topology has very good CMFB stability
- Low noise by using NPN inputs with right size & bias
- Hybrid Biquad section required pre-warped poles due to unity gain bandwidth of 125 MHz
- Odd order distortion products initially caused by low slew rate. Need to find a low power solution.
Differential Opamp for Hybrid

- $A_V = 76.5$ dB
- $F_U = 125$ MHz
- $PM = 57^\circ$
- $GM = 12$ dB
- $SR = 37$ V/µs
- $N_v = 4.2$ nV/√Hz
- $N_i = 0.35$ pA/√Hz
- Power = 36 mW
Single Ended Opamp for Hybrid

- $A_V = 72.5$ dB
- $F_U = 126$ MHz
- $PM = 56^\circ$
- $GM = 12.5$ dB
- $SR = 90$ V/µs
- $N_v = 4.7$ nV/√Hz
- $Ni = 0.26$ pA/√Hz
- Power = 8.8 mW
Slew Rate Boosting

• The hybrid is driven from the TX driver outputs (VA & VC) which act as AC ground
• Since voltage gain from input to biquad output is less than unity around 1 MHz, the compensation capacitor can be split into a voltage divider to ground and driven from the input. This pre-charges Cc and the tail current only handles the parasitic at comp node.
• Slew rate is improved ~10X without increasing tail current
Opamp with Boosted Slew Rate
SR = 360 V/µs
BiCOM-2 Technology Overview

- **Components:** 16V NPN (6 GHz) 16V Isolated VPNP (5 GHz) 5V CMOS (Logic) Laser-Trim Metal Fuses Poly R’s (150, 220 Ω/ Poly-N+ Cap’s (0.8, 1.65 fF/µm²)

- **Voltage:** Logic ⇒ 5V Analog ⇒ 16V

- **Gate Lengths:** Logic ⇒ 0.72 µm

- **Gate Oxides:** 5V CMOS ⇒ 135 Å

- **Isolation:** LOCOS, Trench, SOI

- **Routing Metallization:** TLM, 2.1 µm Pitch, Conv AlCu, SOG Planarization

- **Power Metallization:** 15 µm thick plated Cu

- **Complexity:** 34 Masks, SOI Sub, Deep Trench, N+BL, P+BL, N-Epi, SPSA NPN/PNP, NiCr Thin-Film.
Trimming the Hybrid Response

- Trim all R’s except $R_4$, to set low frequency pole locations
- Trim $C_4$ to set the zero locations
- Trim $R_4$ to set the high frequency real pole; $1/ R_4C_4$
Resistor with Laser Trim Fuses
Hybrid Magnitude Response

- Probed magnitude response from input to output with gain normalized to the RX amp input
- Echo at the output of RX channel referred to tip/ring divided by the TX signal at tip/ring
Hybrid Noise and Distortion Tip/Ring Referred

![Graph showing PSD (dBm/Hz) vs Frequency (kHz) with two lines: one for Noise floor and another for Distortion when transmitting.](Image)
• Connected to TI client modem over 26 AWG loop with no external noise sources or bridge taps
Full Die Photomicrograph
### Summary

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<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
<th>Units</th>
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<tr>
<td>Receiver Band Noise Floor</td>
<td>-130</td>
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<tr>
<td>Receiver Band Distortion</td>
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