An Integrated Active Hybrid Filter for ADSL

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I wish to acknowledge collaborations with:

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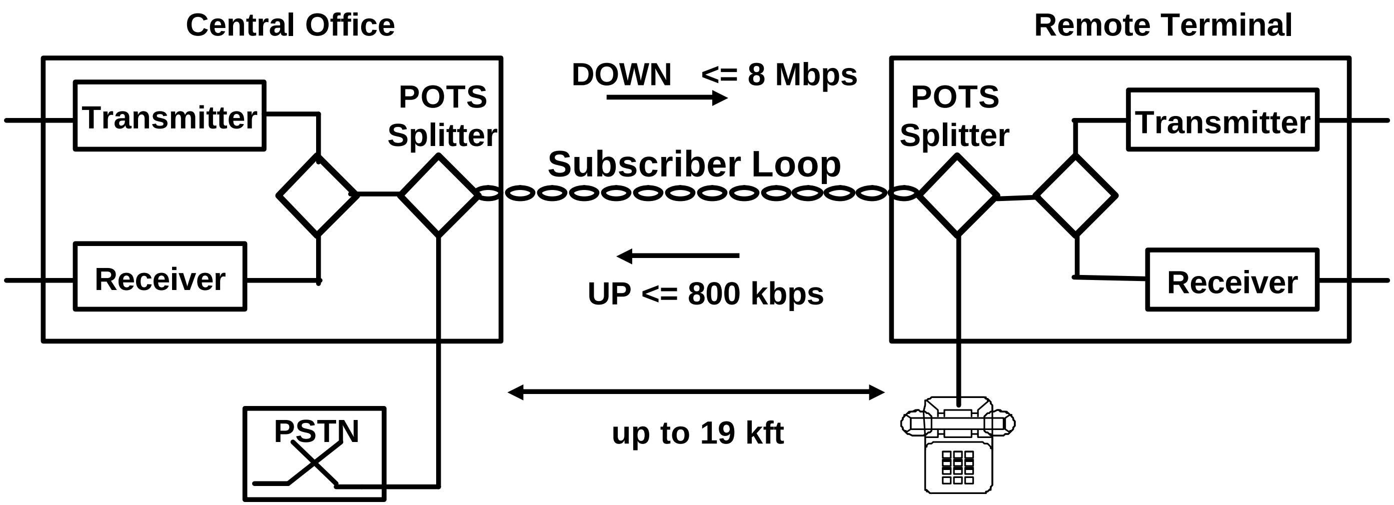
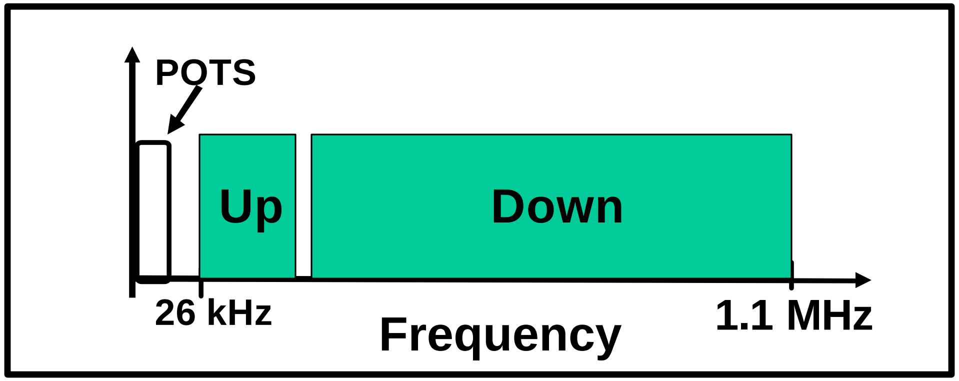
Outline

- Background
- System
- Circuits
- Process
- Measurements
- Summary

ADSL System



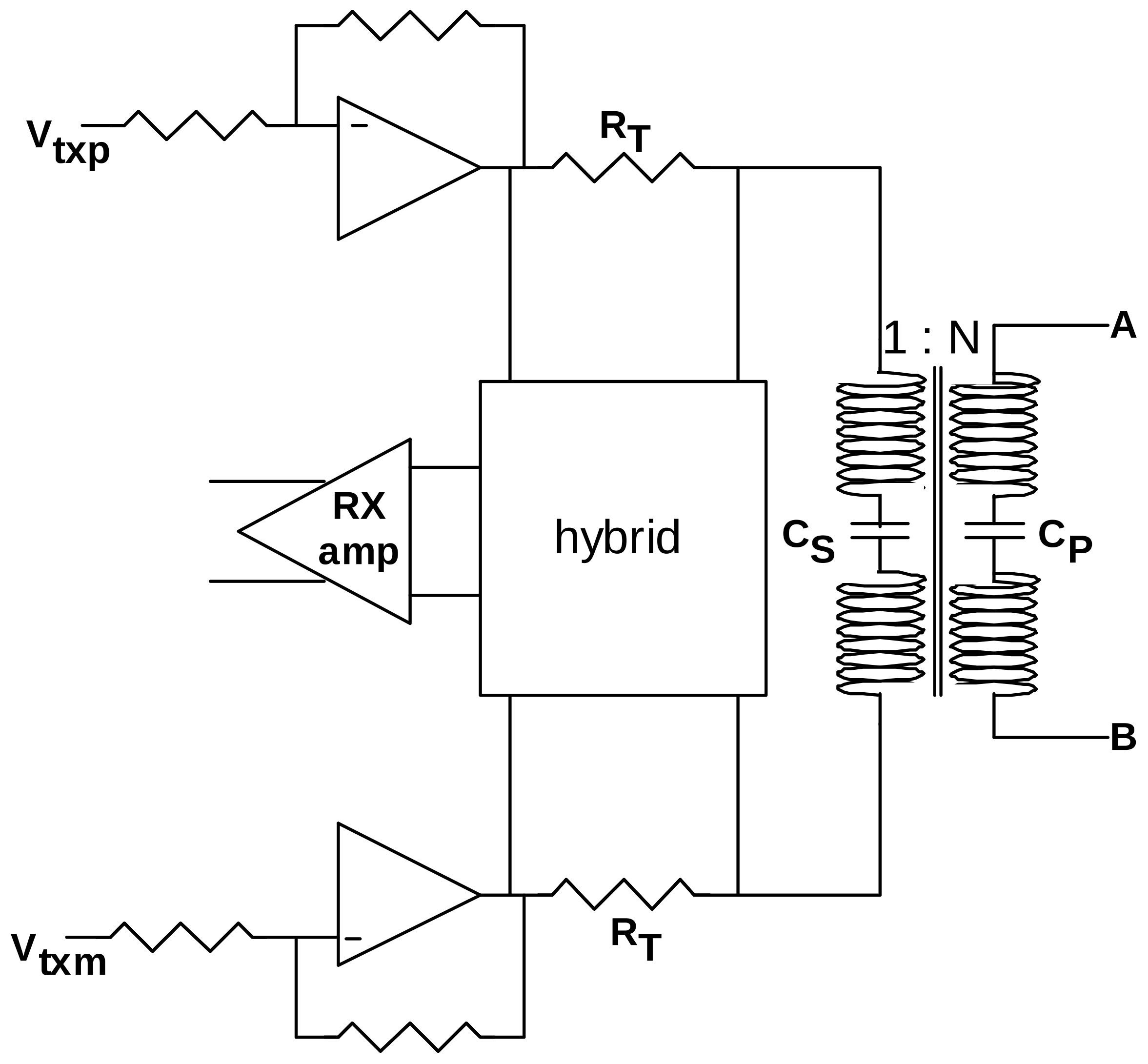
Frequency Division Multiplexed Operation



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



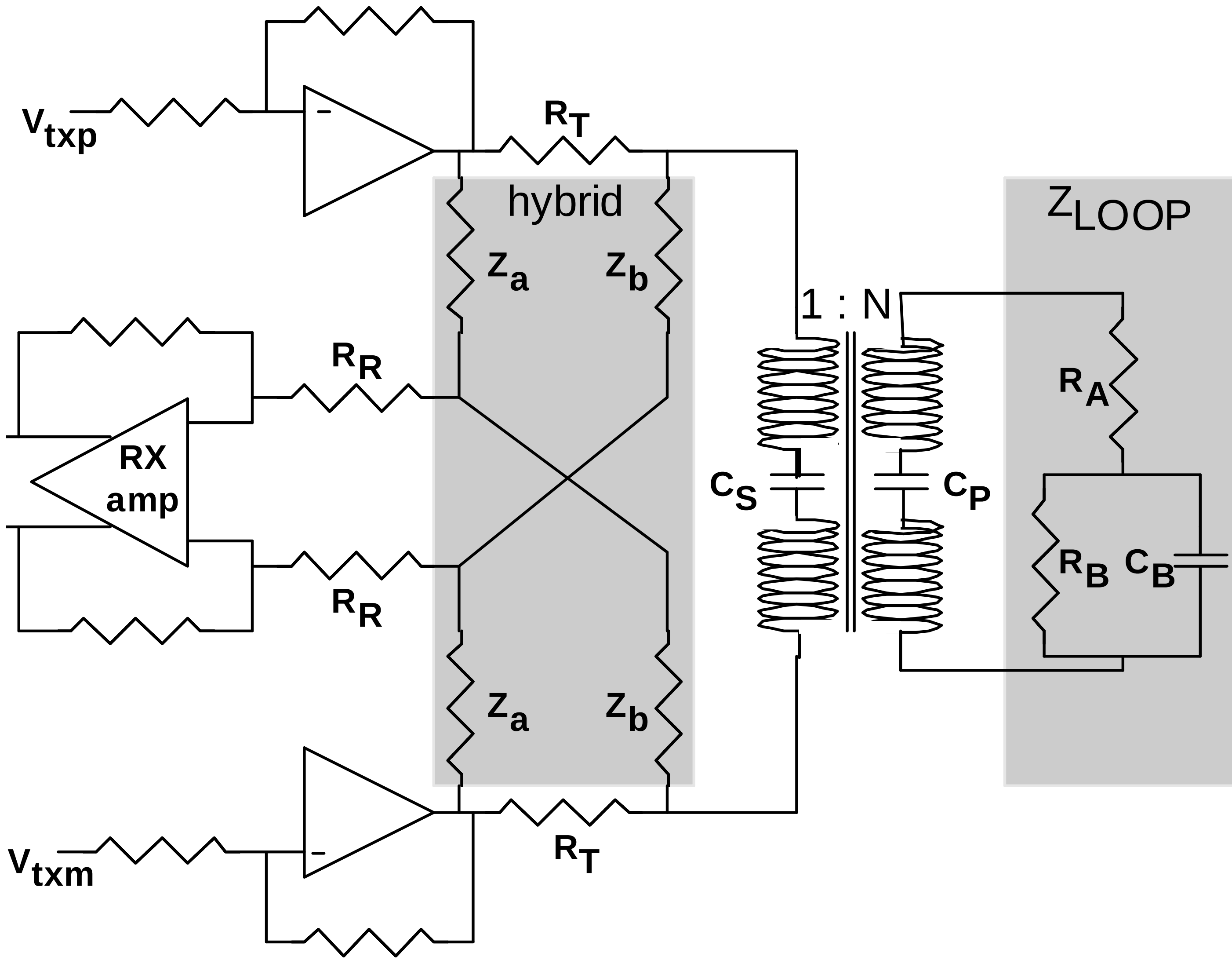
Transformer Line Coupling is Good

- 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

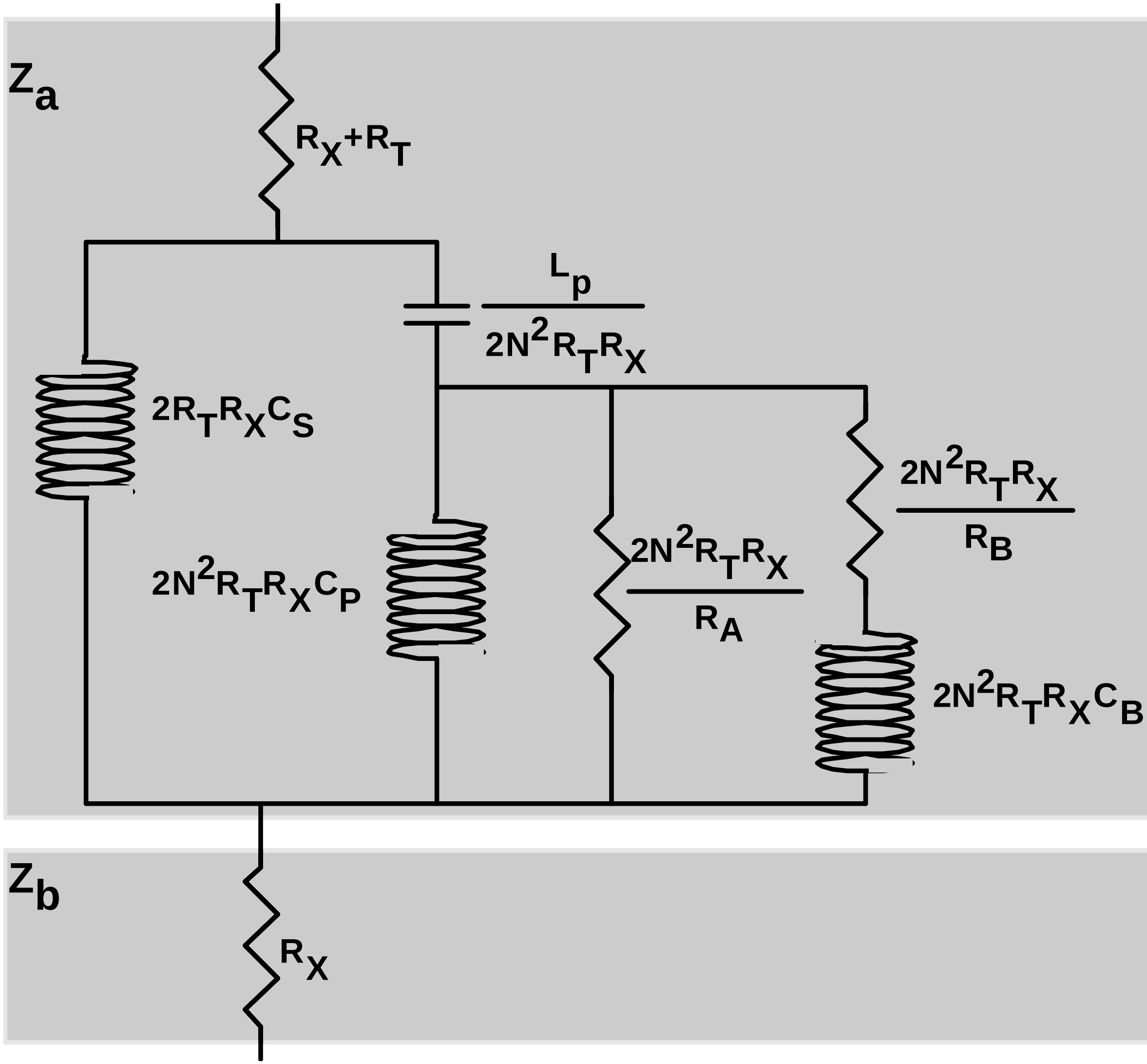
Passive Hybrid Topology



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

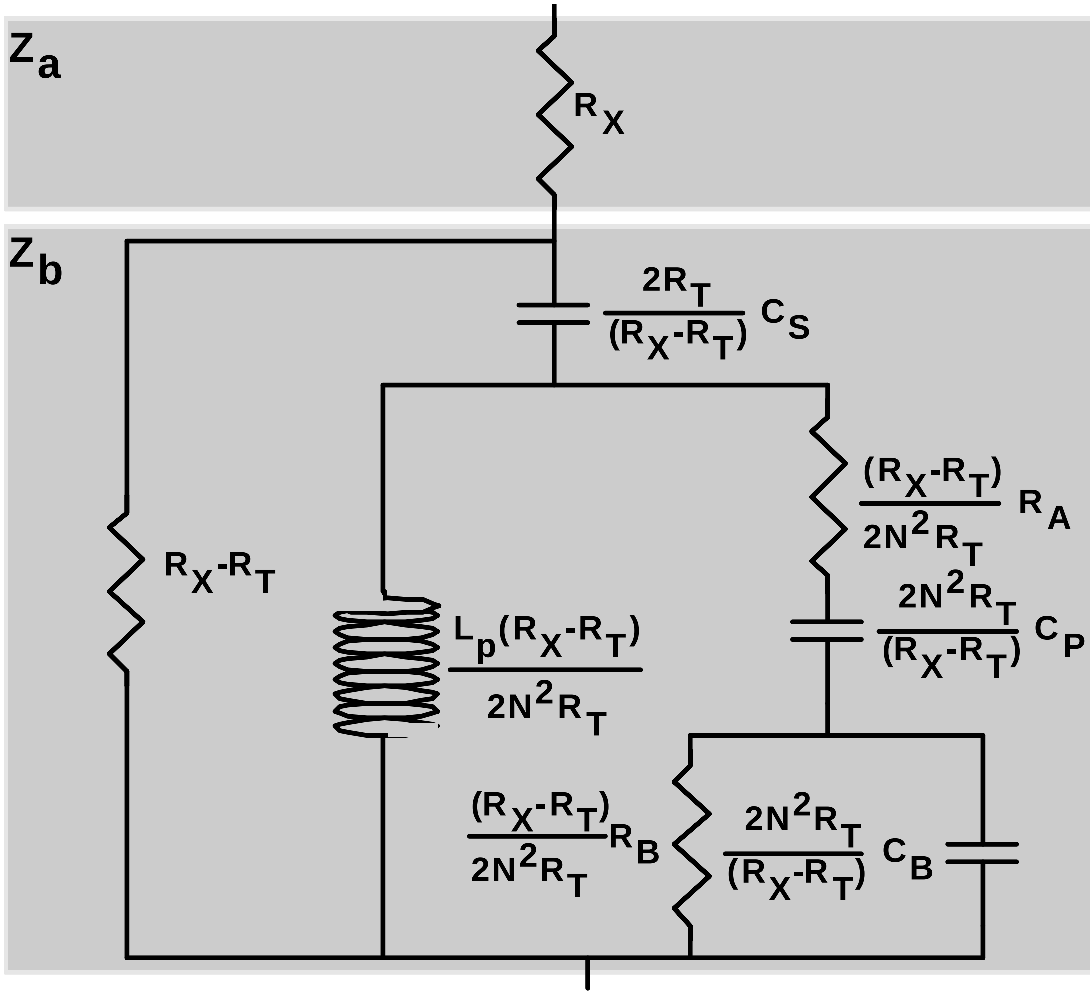
Hybrid Circuit Realization



Circuit Realization Comments

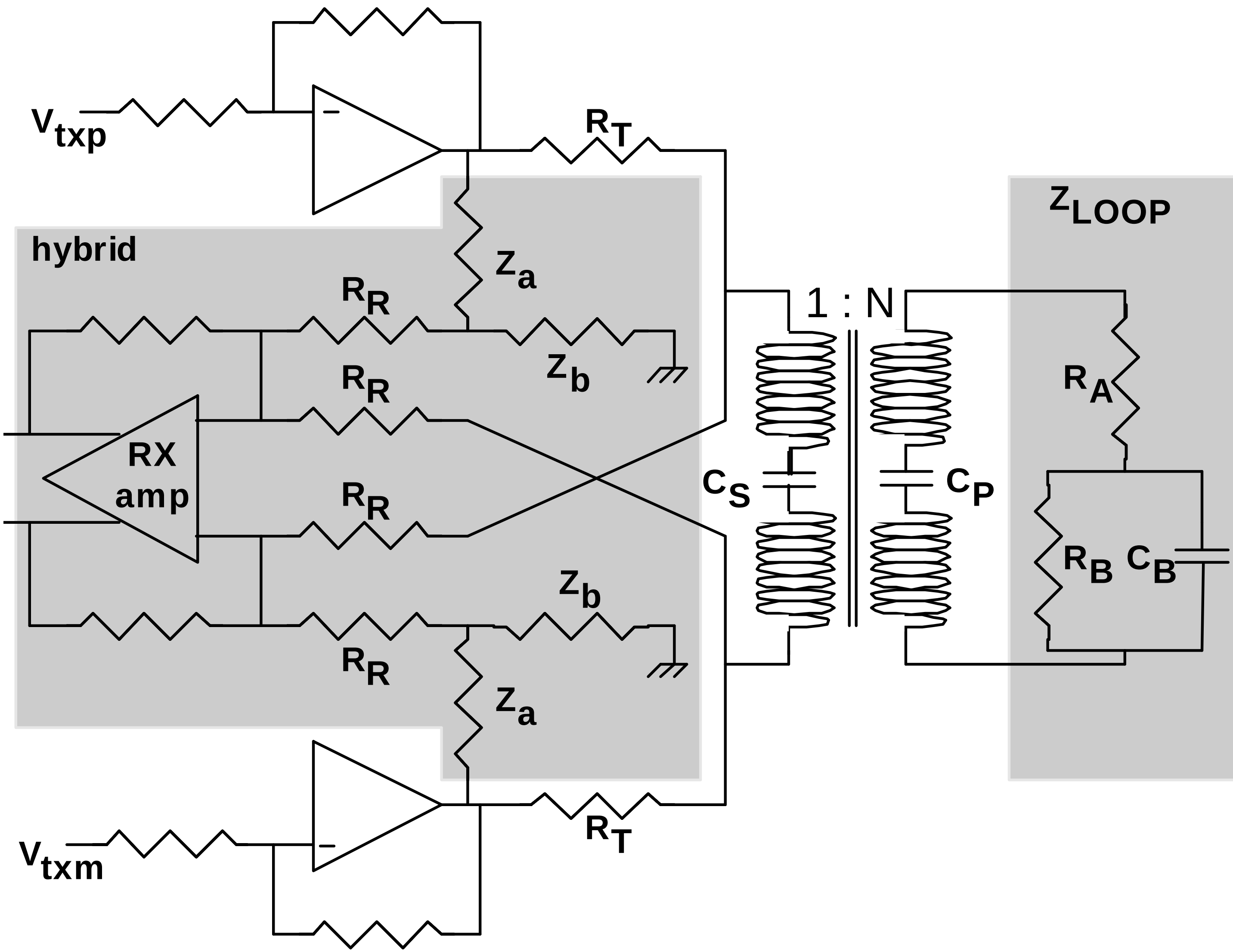
- The exact equation solution for the Bridge component values exits
- Complicated: requires 4 resistors, 3 inductors and 1 capacitors
- Large cost and board area
- Inductors must be non-saturating and Capacitors have the best dielectric to be distortion free

Alternative Circuit Realization



- Lower cost and better board area because only 1 L, 3 C’s, 4 R’s

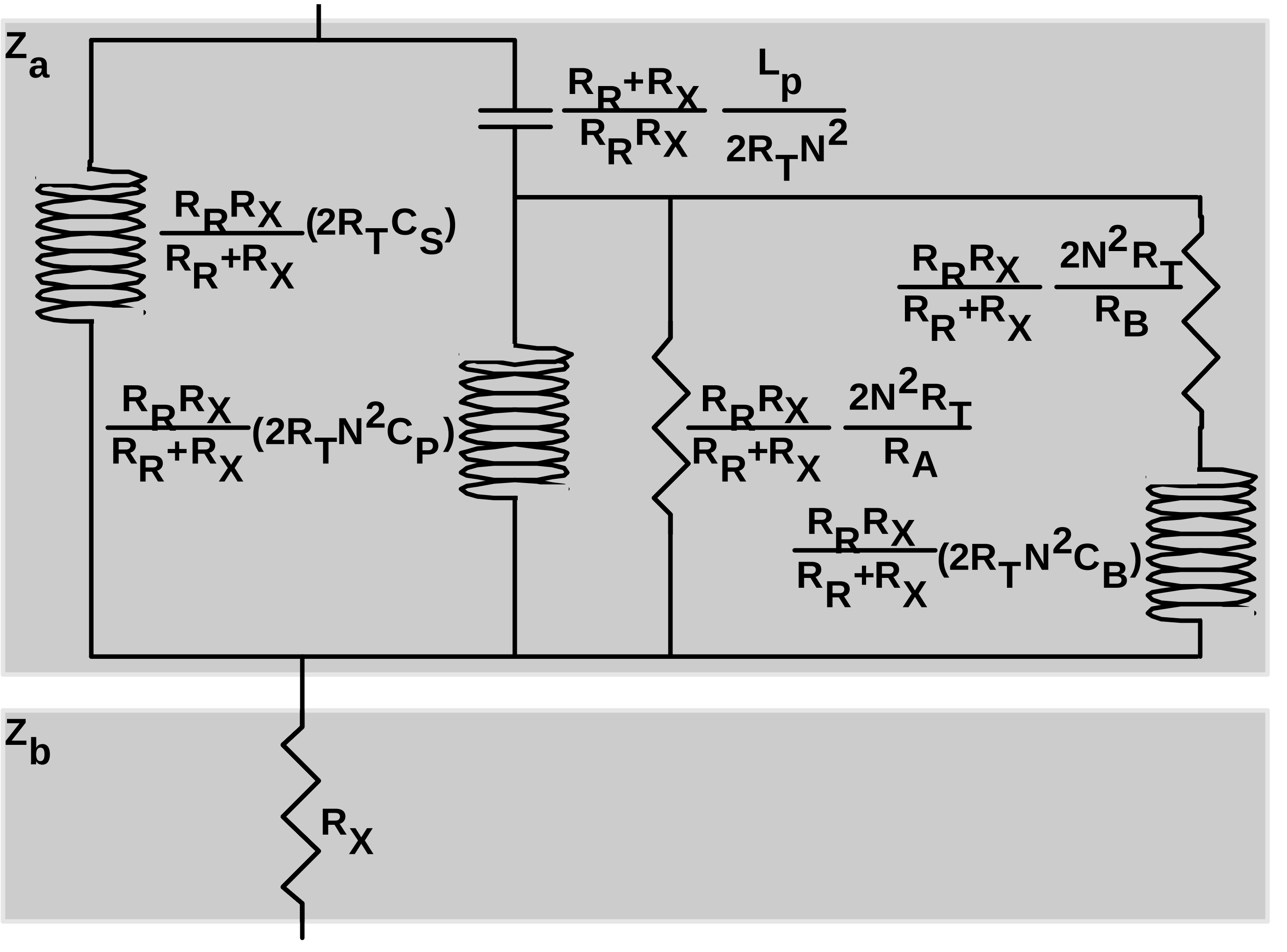
Alternative Passive Hybrid Topology



Non-Bridge Passive Solution

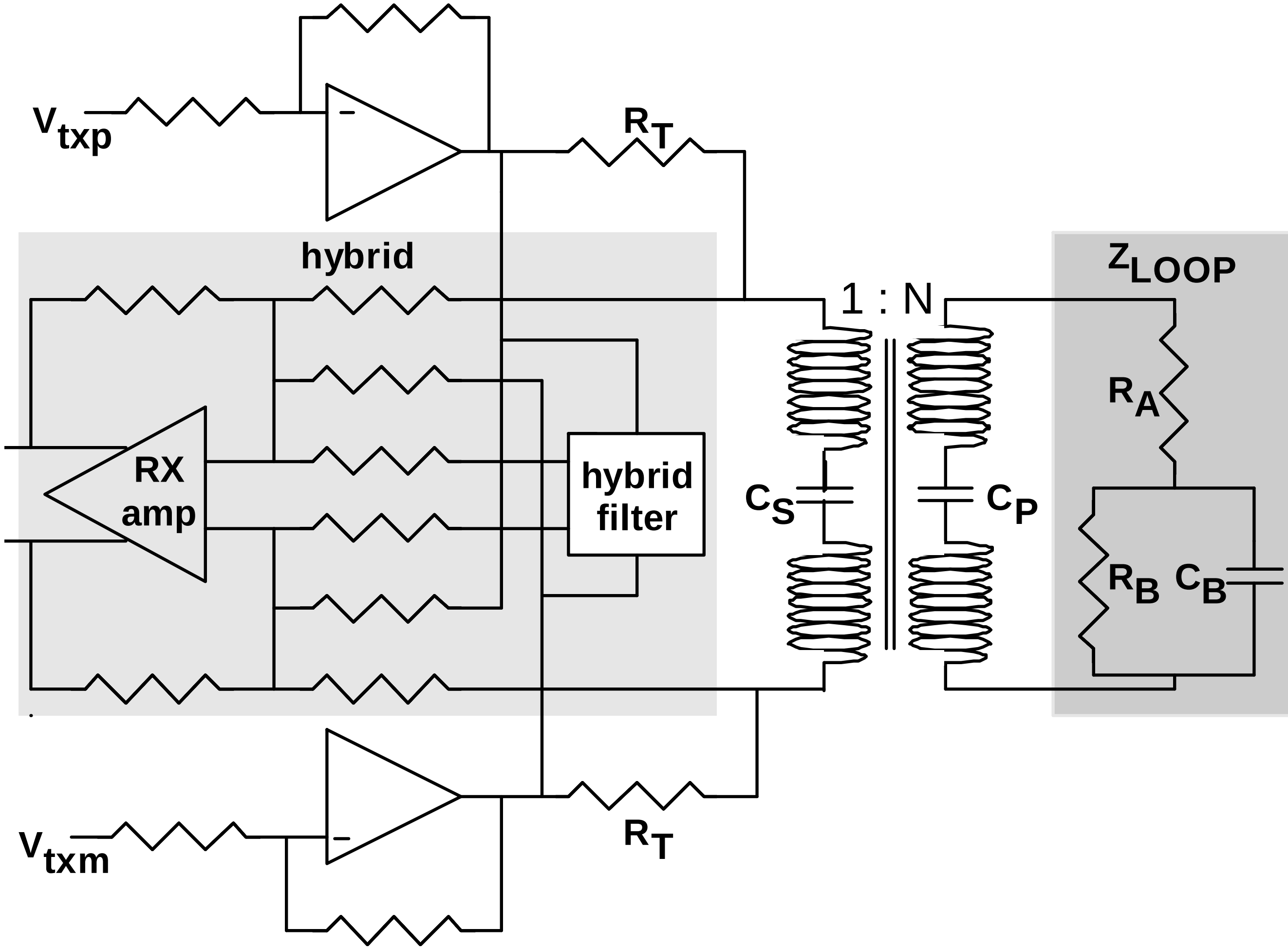
- Since there already exits a Rx amplifier, use it to subtract the echo and echo replica
- The Replica is just the “filtered” version of the transmitted signal.
- The transfer function is $H=Z_b/(Z_a + Z_b)$
- Need a passive filter that implements H

Alternative Realization



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

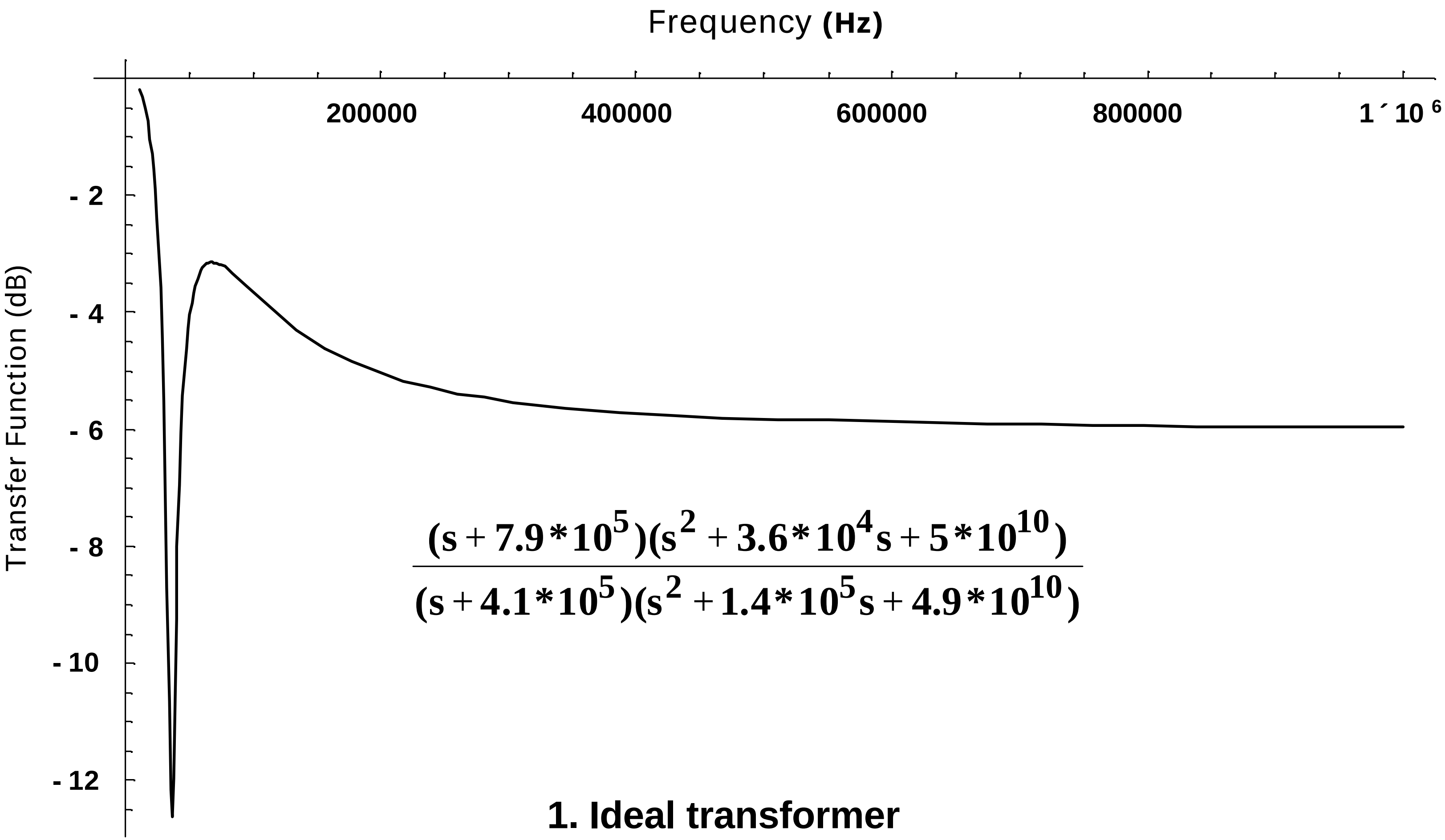
Active Hybrid Topology



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[1,2]



$$\frac{(s+7.9*10^5)(s^2+3.6*10^4 s+5*10^{10})}{(s+4.1*10^5)(s^2+1.4*10^5 s+4.9*10^{10})}$$

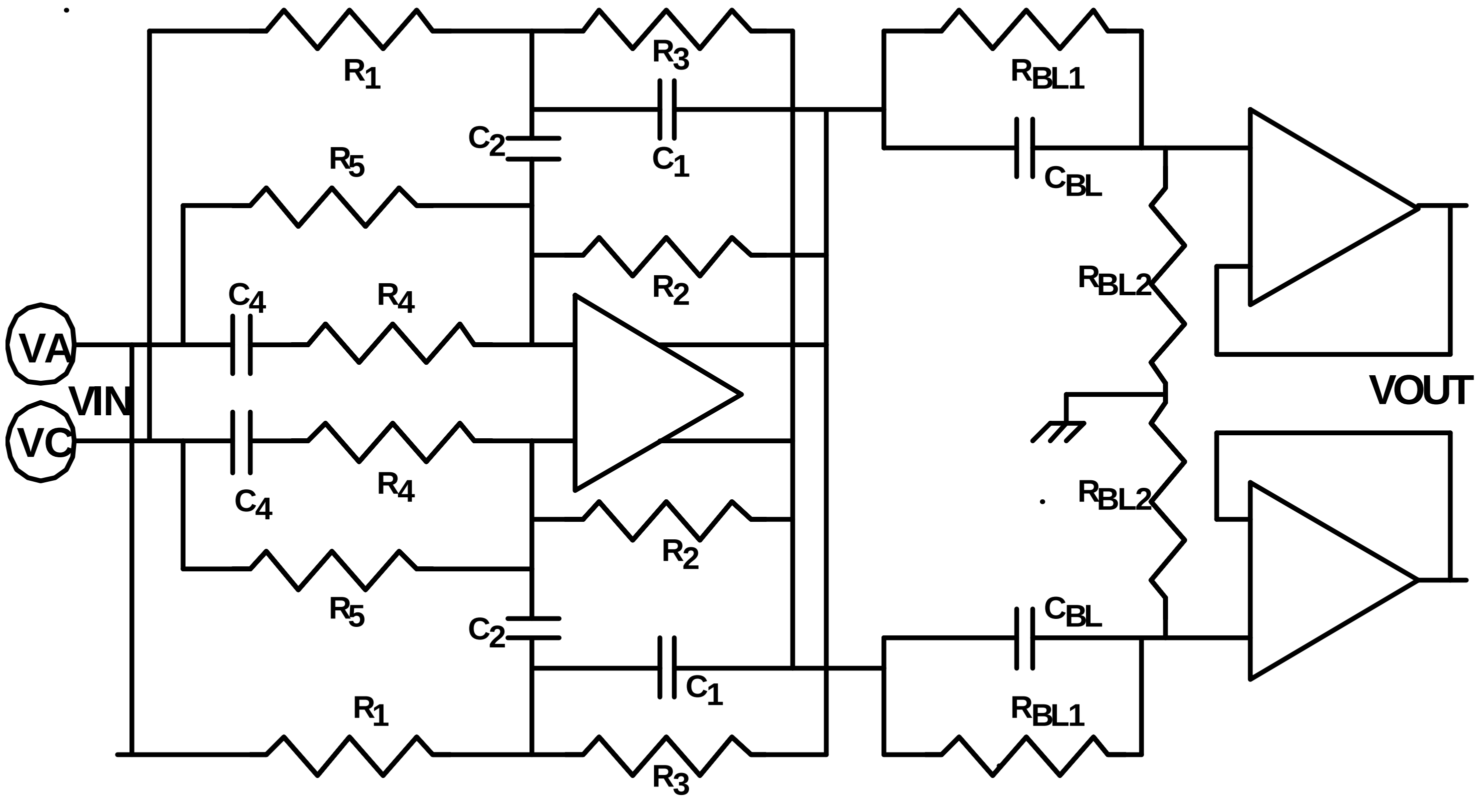
1. Ideal transformer

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

Active Hybrid Circuit Schematic



$$\frac{VOUT}{VIN} = \frac{(s - Z_1)(s - Z_1^*)(s - Z_2)}{(s - P_1)(s - P_1^*)(s - P_2)(s - P_3)}$$

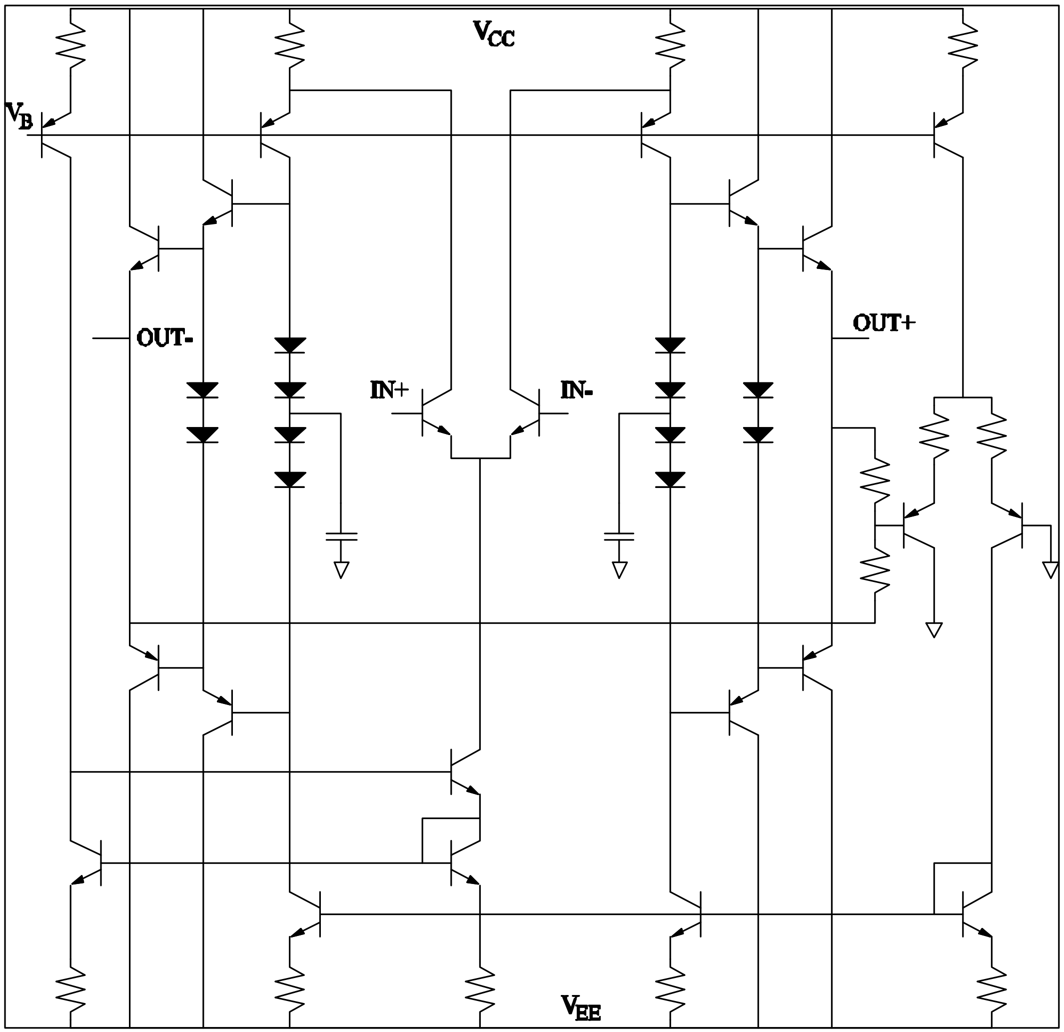
Hybrid Filter Details

- 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

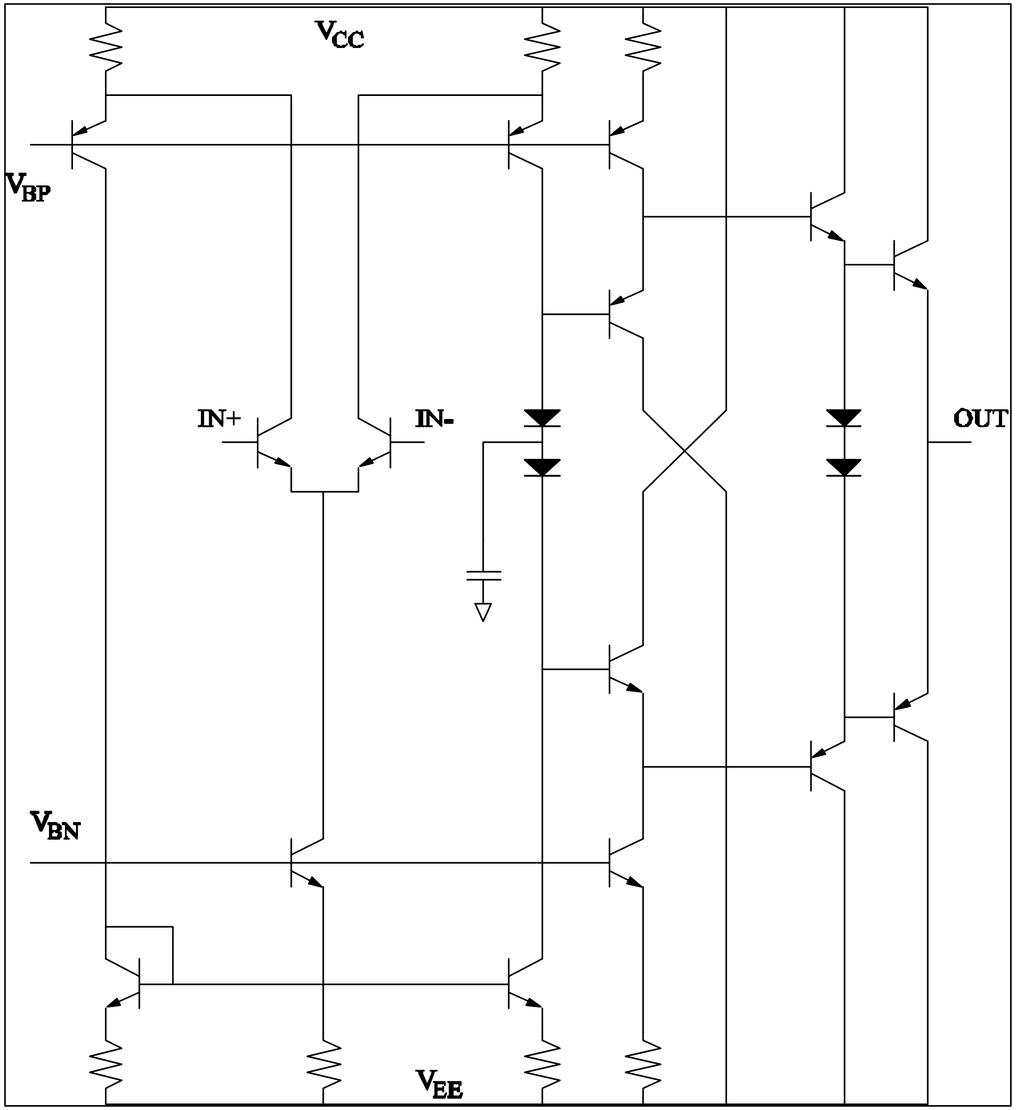
- Hybrid requires intermods >90dB so amp must have very low distortion
- Fully-Differential FCC amp chosen with resistive emitter degeneration of common-base amp; good high frequency signal path & simple compensation
- Topology has very good CMFB stability
- Low noise by using NPN inputs with right size & 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^o
- GM = 12 dB
- SR = 37 V/μs
- Nv = 4.2 nV/√Hz
- Ni = 0.35 pA/√Hz
- Power = 36 mW

Single Ended Opamp for Hybrid

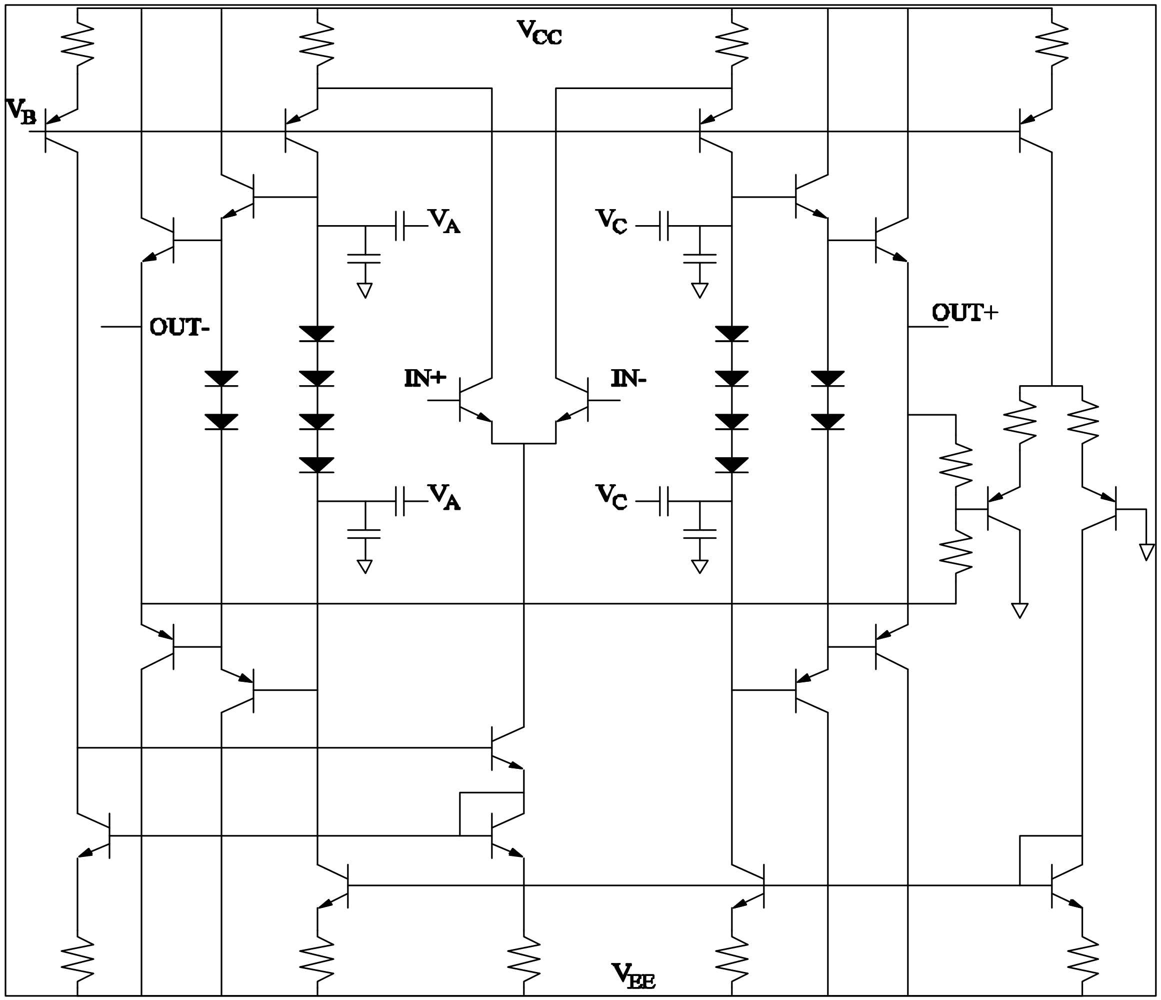


- A_V = 72.5 dB
- F_U = 126 MHz
- PM = 56º
- GM = 12.5 dB
- SR = 90 V/μs
- Nv = 4.7 nV/√Hz
- Ni = 0.26 pA/√Hz
- Power = 8.8 mW

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

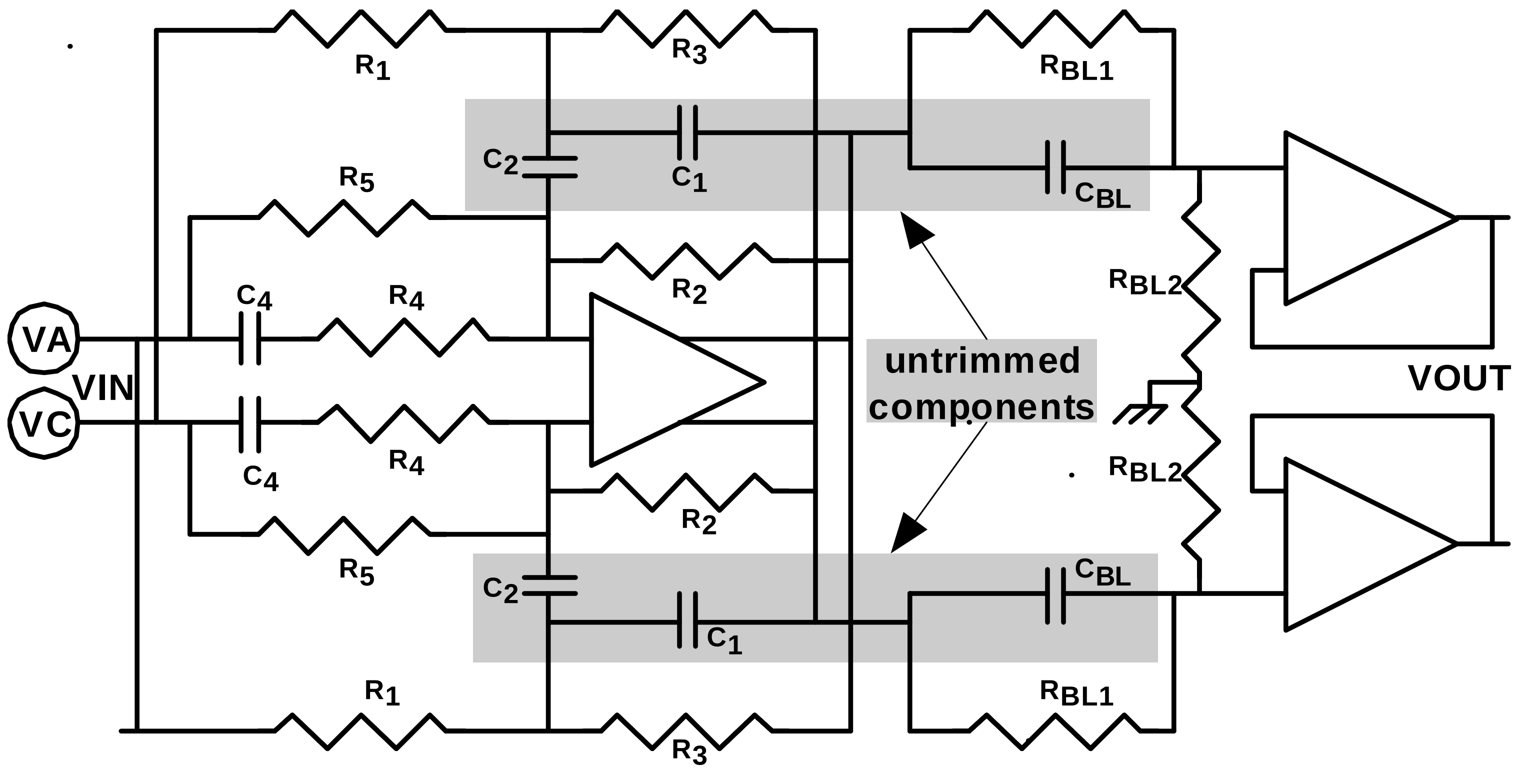
Opamp with Boosted Slew Rate
SR = 360 V/μs



BiCOM-2 Technology Overview

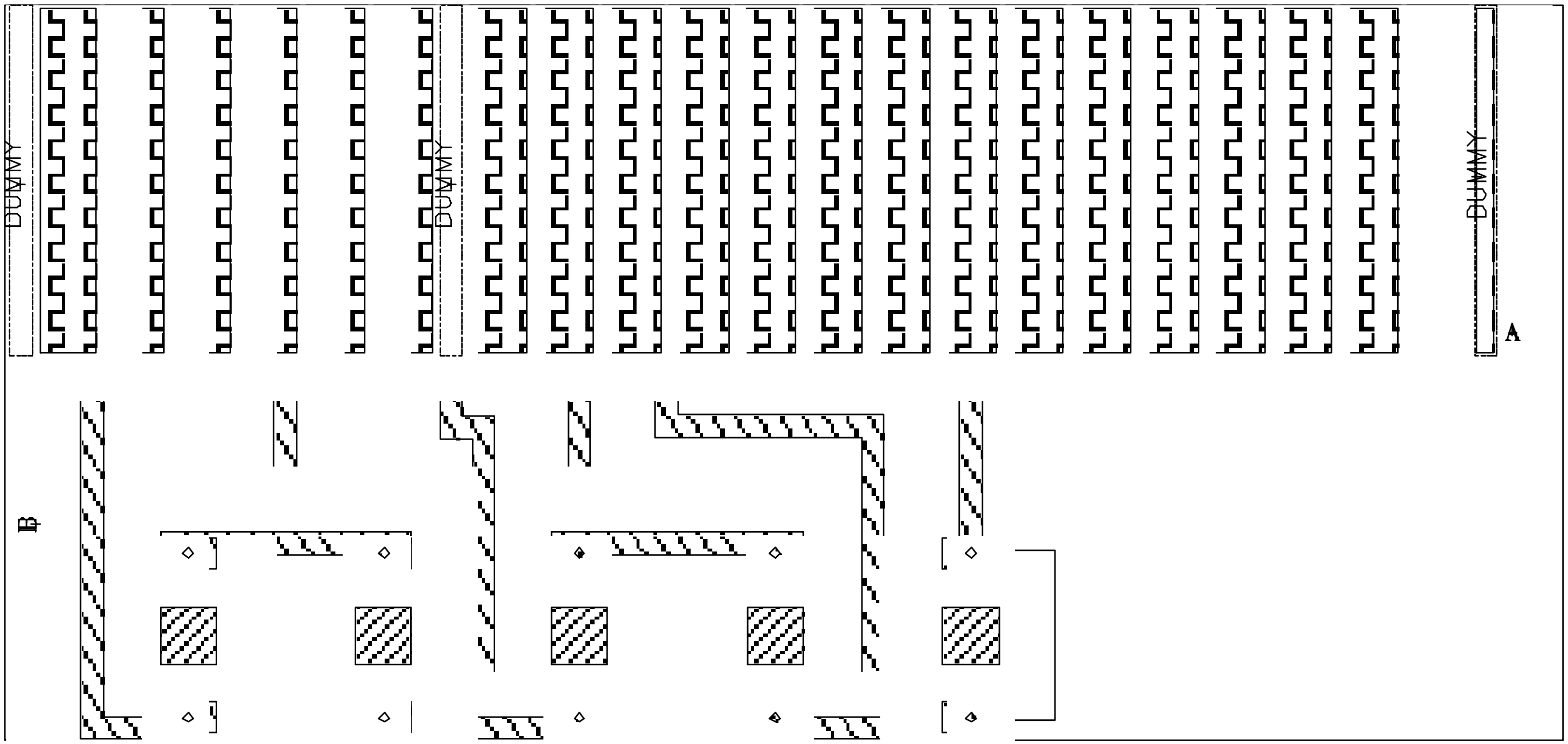
- **Components:** 16V NPN (6 GHz) 16V Isolated VPNP (5 GHz)
  5V CMOS (Logic) Laser- Trim Metal Fuses
  Poly R's (150, 220 Ω/) Laser-Trim Res (NiCr)
  Poly-N+ Cap's (0.8, 1.65 fF/μm^2)
- **Voltage:** Logic ⇒ 5V Analog ⇒ 16V
- **Gate Lengths:** Logic ⇒ 0.72 μm
- **Gate Oxides:** 5V CMOS ⇒ 135 Å
- **Isolation:** 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.

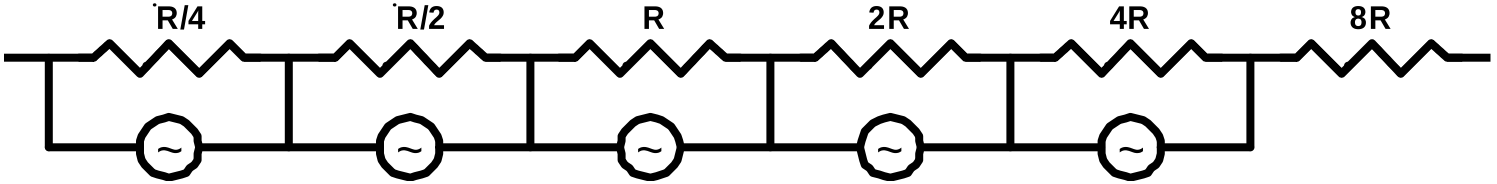
Trimming the Hybrid Response



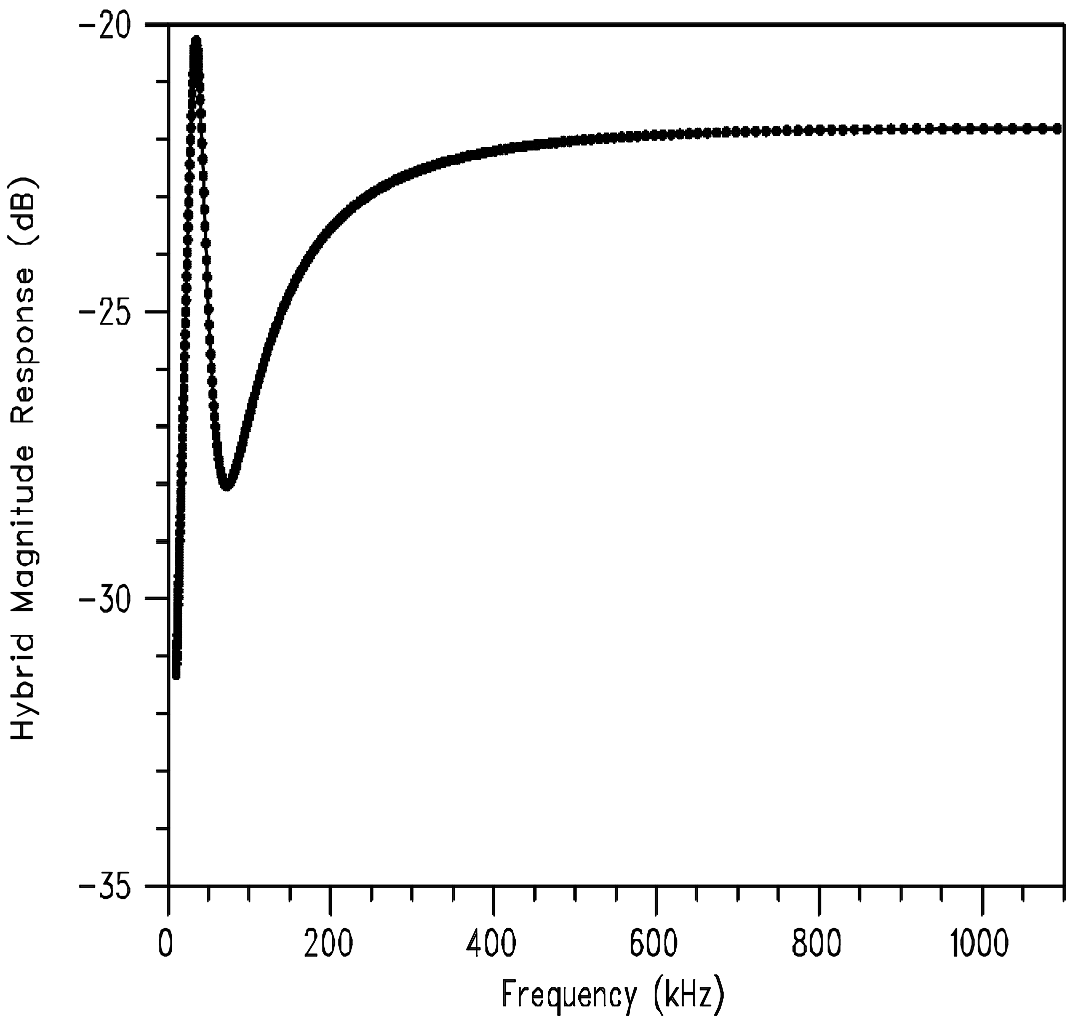
- Trim all R's except R_4, to set low frequency pole locations
- Trim C_4 to set the zero locations
- Trim R_4 to set the high frequency real pole; $1/R_4C_4$

Resistor with Laser Trim Fuses



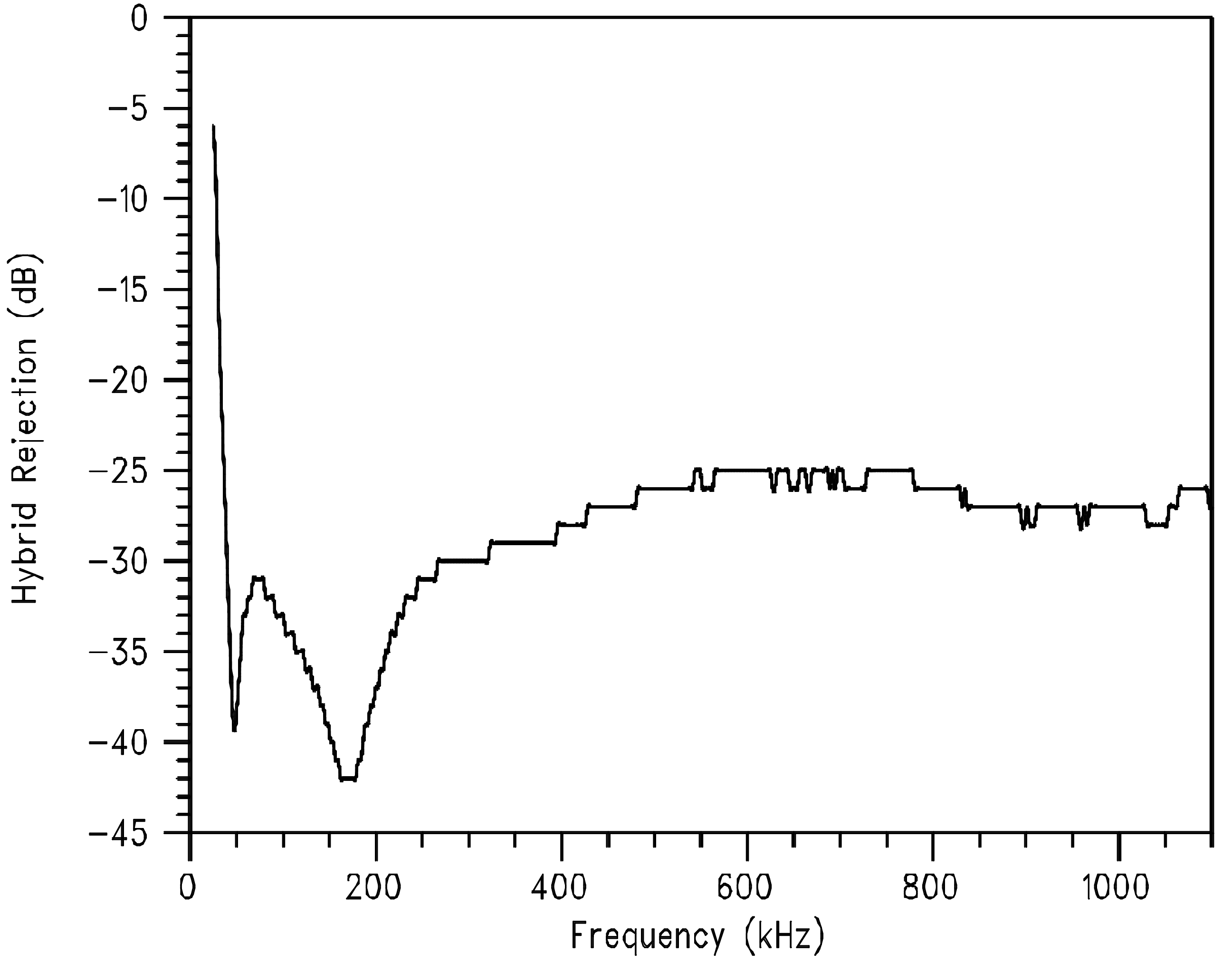


Hybrid Magnitude Response



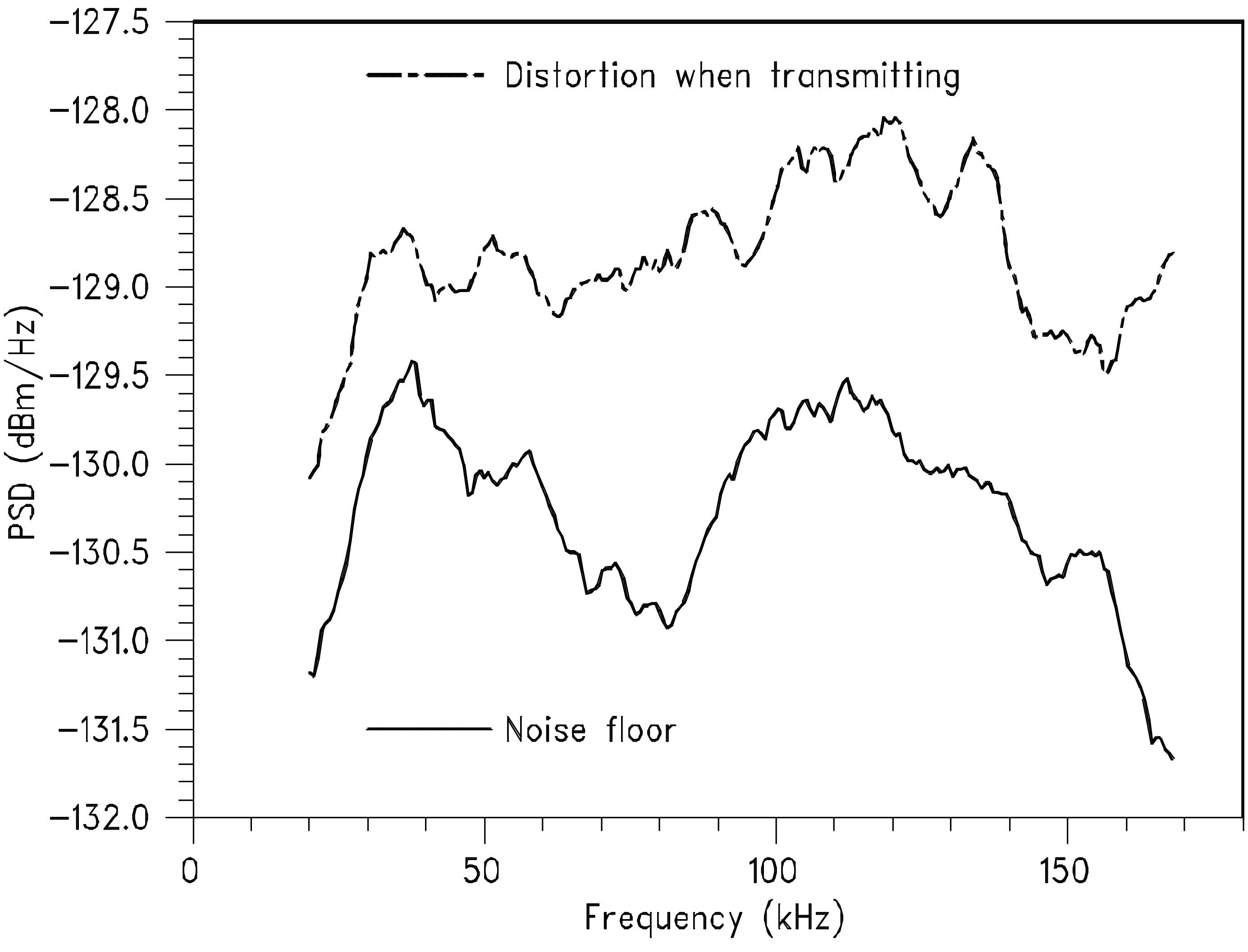
- Probed magnitude response from input to output with gain normalized to the RX amp input

Hybrid Rejection

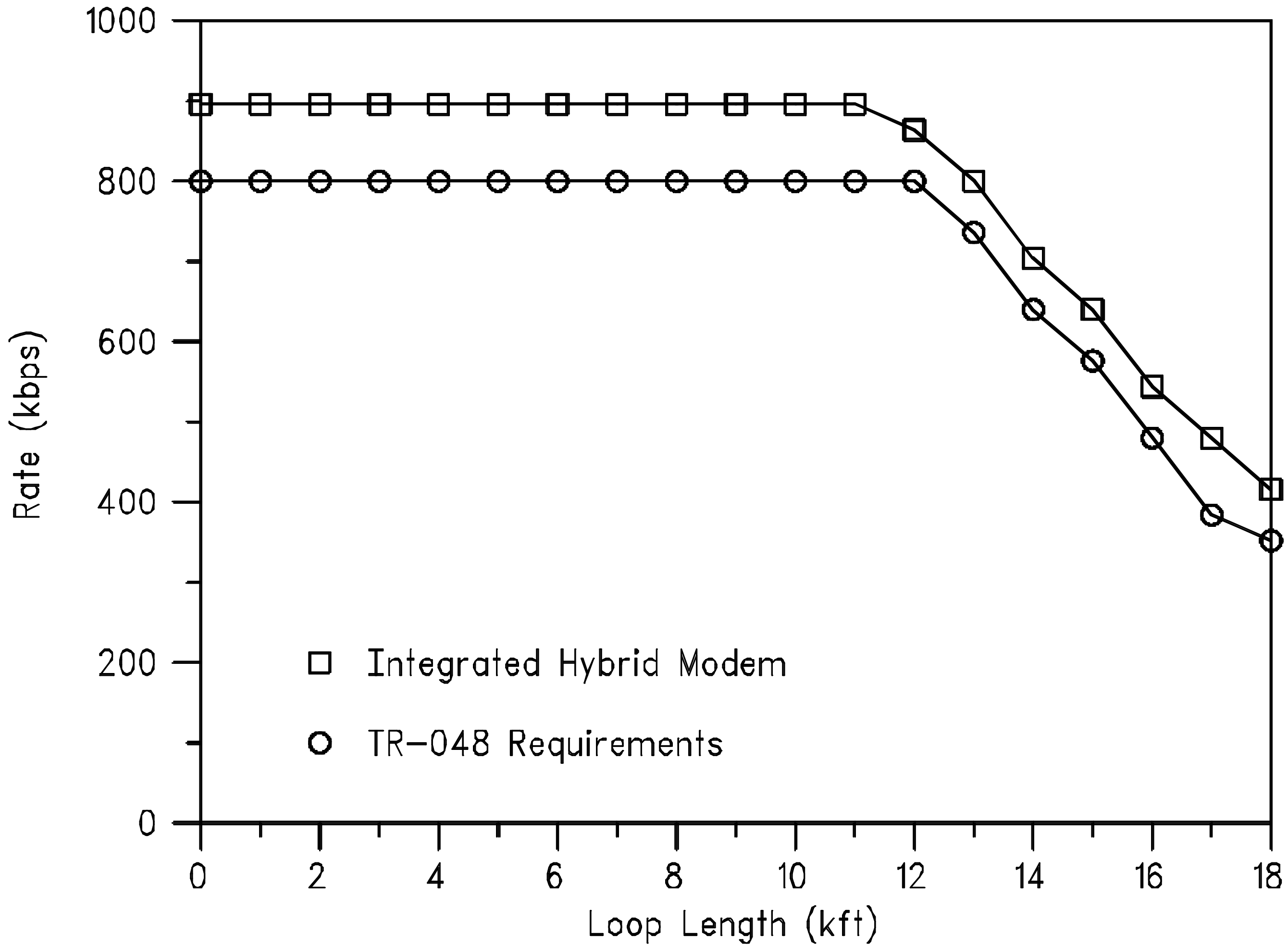


- Echo at the output of RX channel referred to tip/ring divided by the TX signal at tip/ring

Hybrid Noise and Distortion Tip/Ring Referred

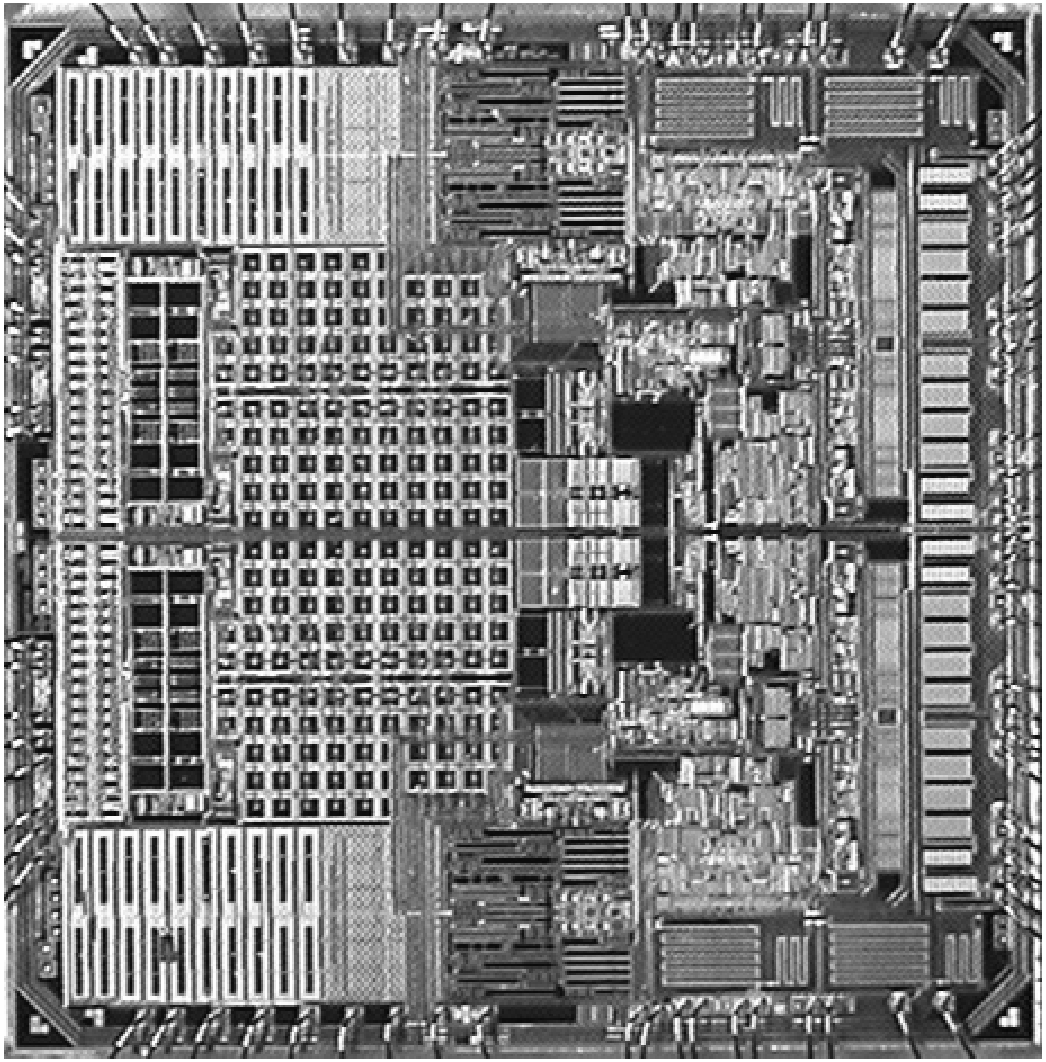


Upstream Noiseless Rate Reach



- Connected to TI client modem over 26 AWG loop with no external noise sources or bridge taps

Full Die Photomicrograph



Summary

Parameter	Measurement	Units
Receiver Band Noise Floor	- 130	dBm/Hz
Receiver Band Distortion	- 136	dBm/Hz
Total Noise + Distortion	- 128.5	dBm/Hz
Power Dissipation	< 63	mW
Trim Accuracy	± 3	%
Hybrid Area	4.24	mm^2