Design and Fabrication of High-Fidelity Vacuum Tube Audio-Frequency Power Amplifiers

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for
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Danger: Do not attempt to build anything shown here unless you are experienced and trained in working with high voltage

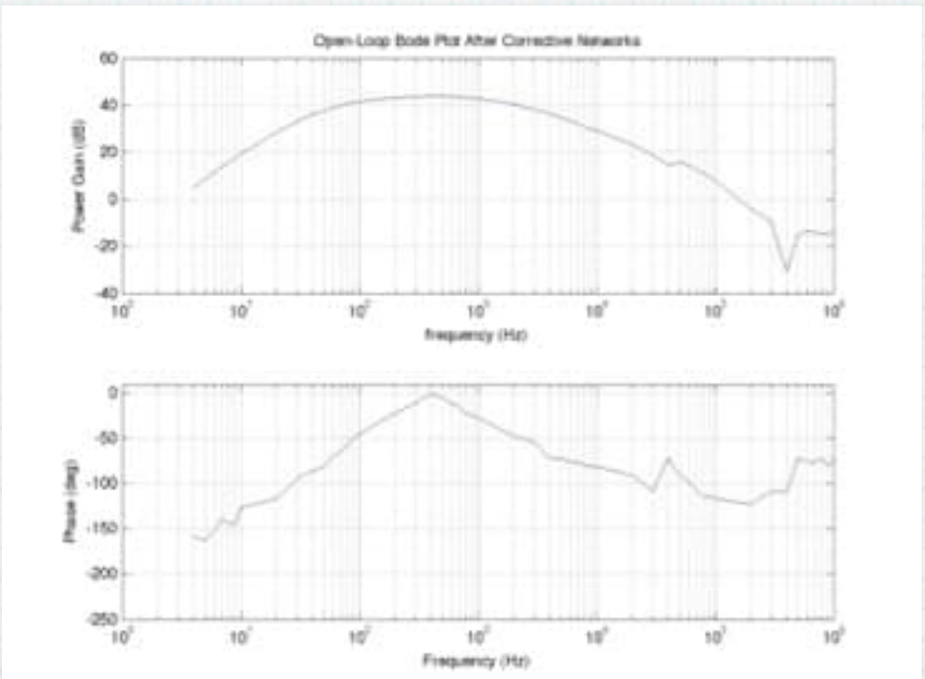
Vacuum Tube Audio

* Vacuum tube sound
  * musicians prefer it
* High peak power
* Vintage appearance

(vacuum tube home theater system)

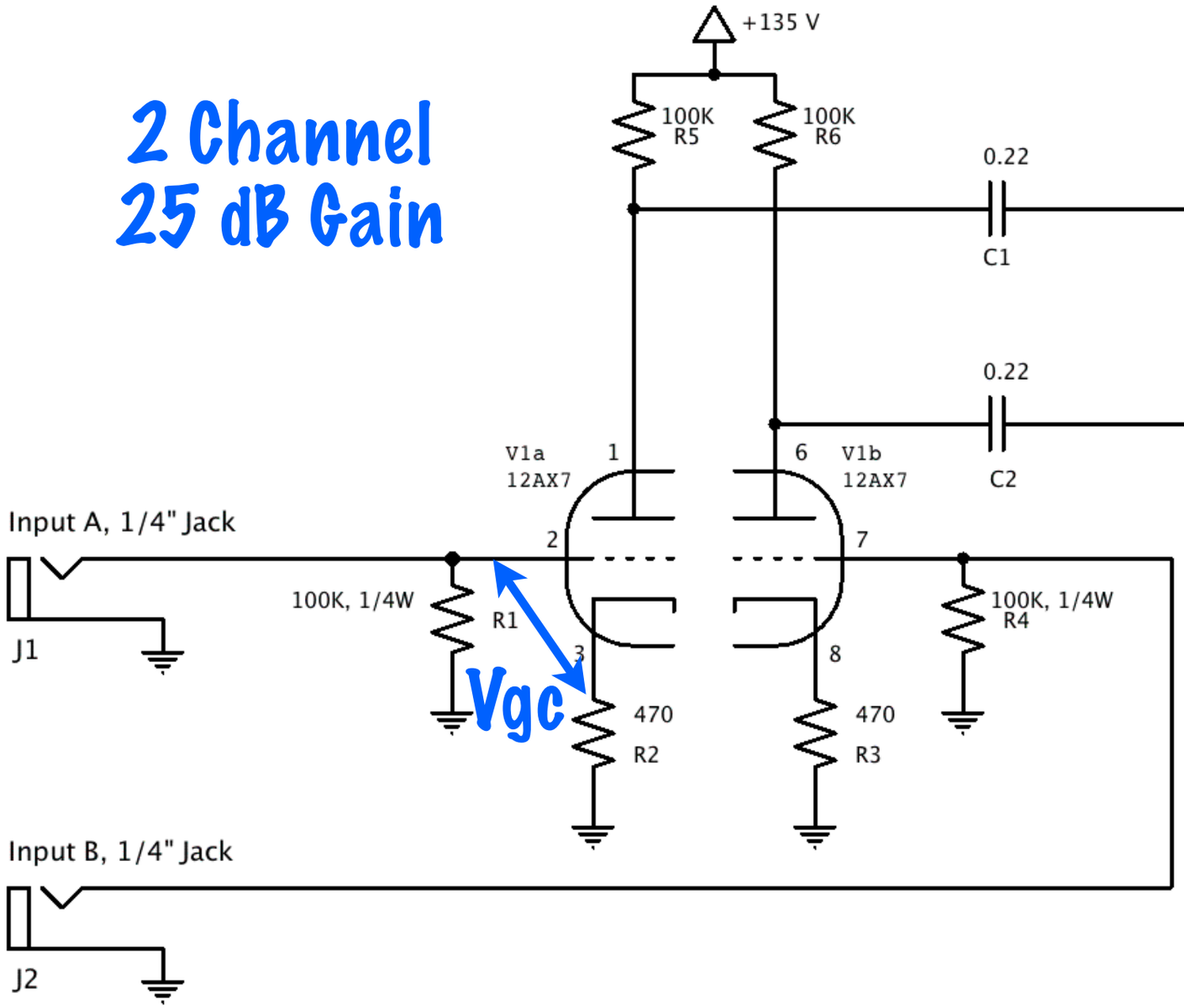
Outline

* Simple vacuum tube pre-amplifier
* Tube power amplifier philosophy
* Class AB power amplifier
* Summary



Build this Simple Pre-Amplifier

2 Channel
25 dB Gain



2-stage battery operated version to be in AEX magazine

* Triodes are similar to N-channel J-FETS, except they are always negative biased w.r.t. the cathode (Vgc < 0 V)
* biasing is easily achieved by using a cathode resistor

Tube Power Amplifier Design Philosophy

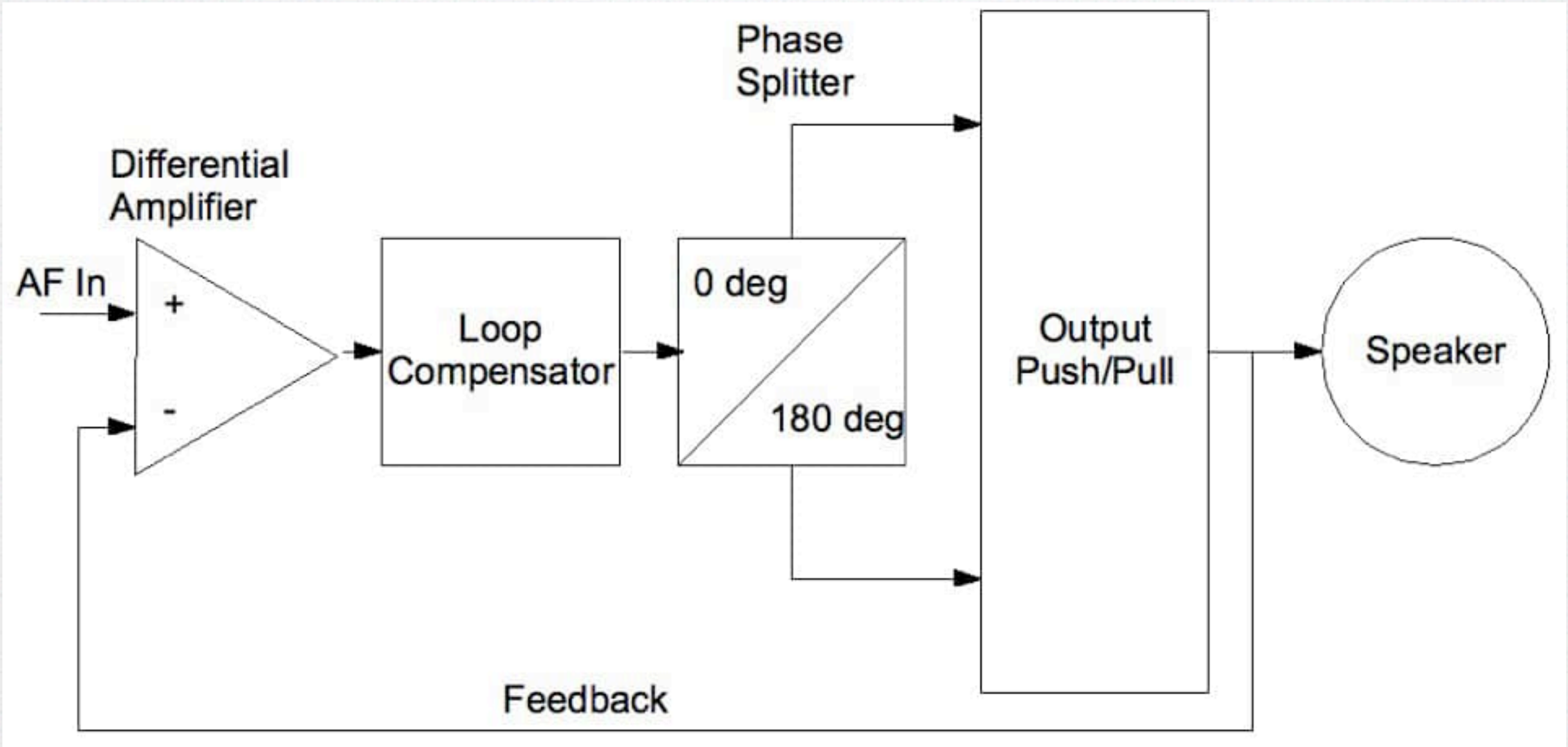
* Time domain audio signal:
  * low average power relative to peaks
  * low duty cycle of peaks (depending on type of music)
* Ideally suited for power amplification by vacuum tubes

Peak

RMS Average

(time domain of music image from Blue Cat Audio)

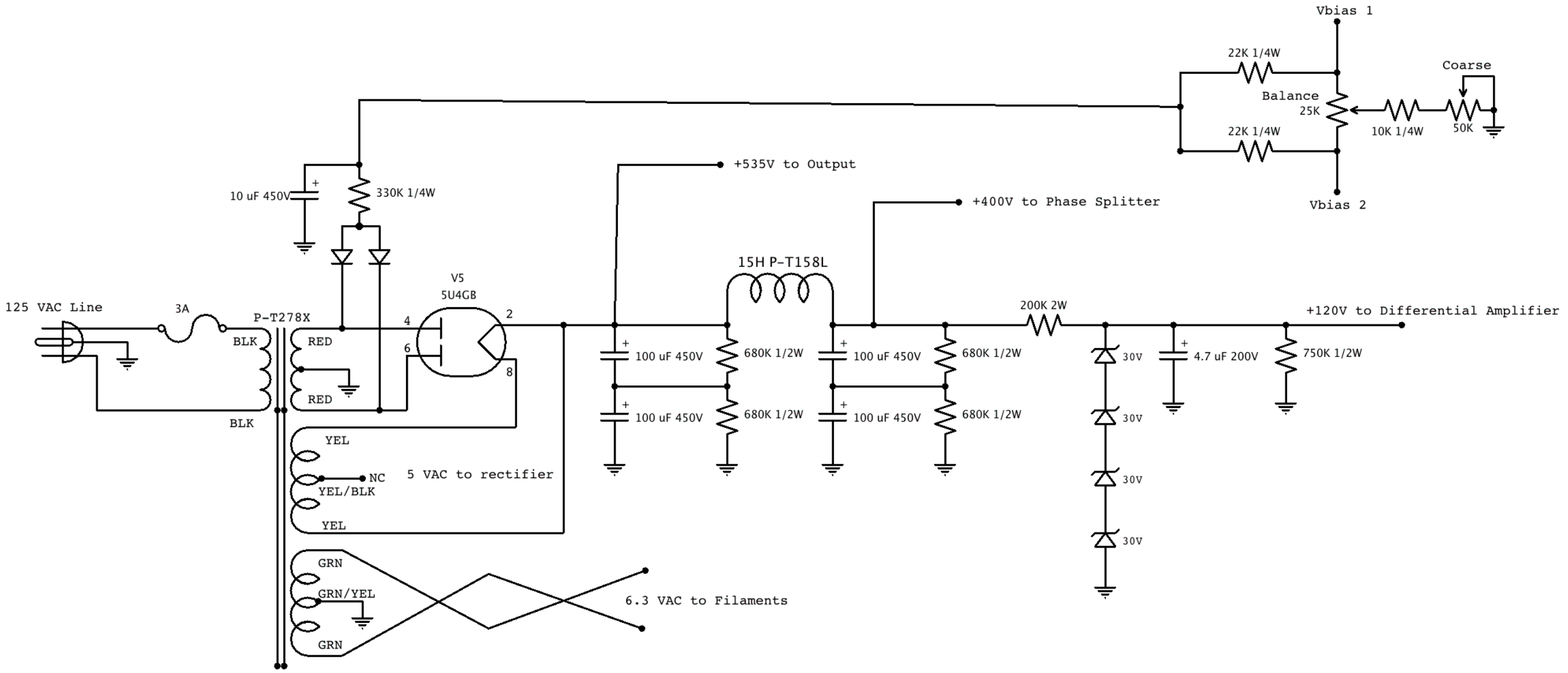
Block Diagram: Class AB Power Amplifier



Design Procedure

1. Construct power supply
2. Make output
3. Design phase splitter
4. Build differential amplifier
5. Measure open-loop frequency response
6. Design loop compensator
7. Re-measure open-loop and closed-loop response
8. Done!

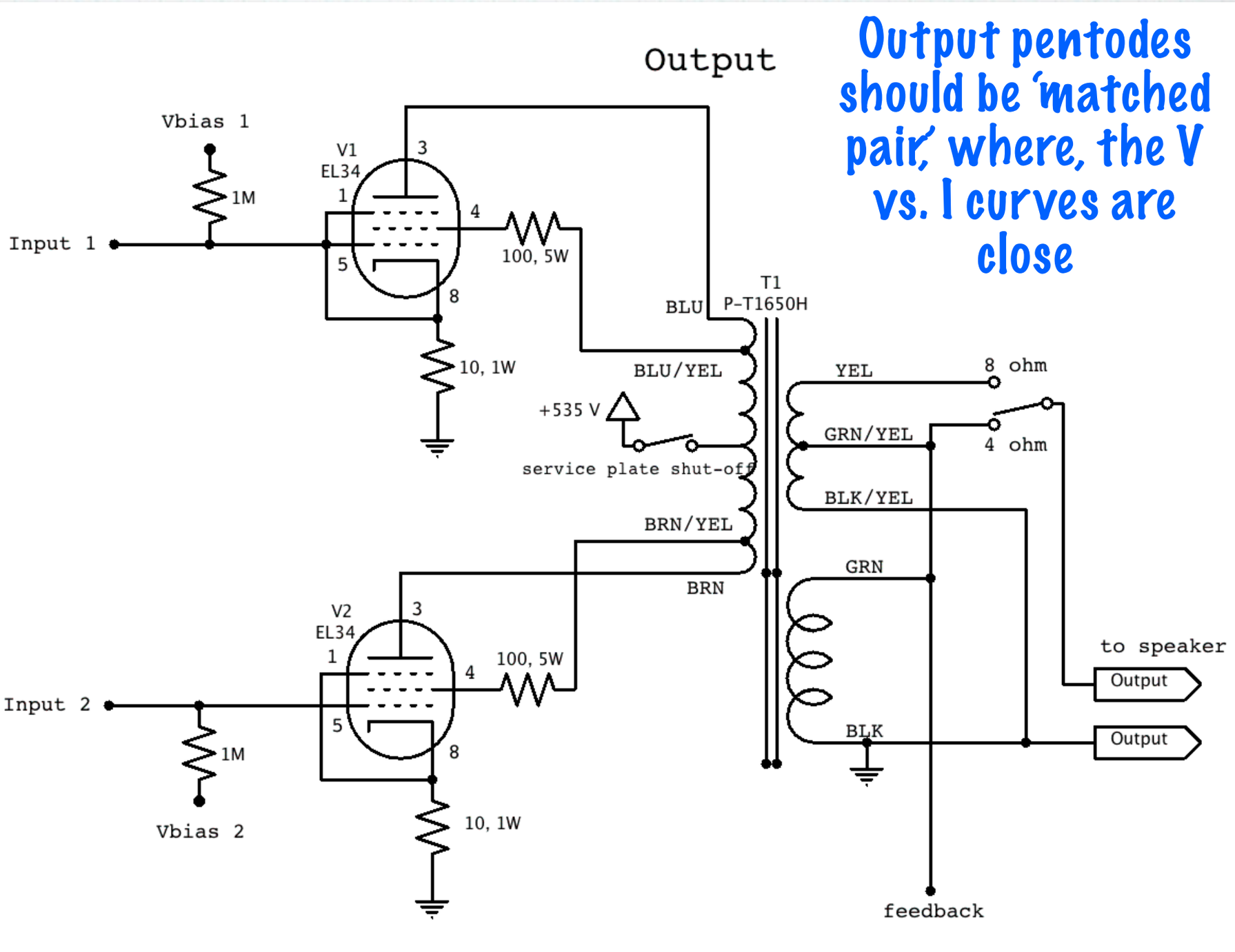
Construct the Power Supply



* Isolates each stage
* (or else oscillation will occur)
* Provides direct bias

Make the Push-Pull Output

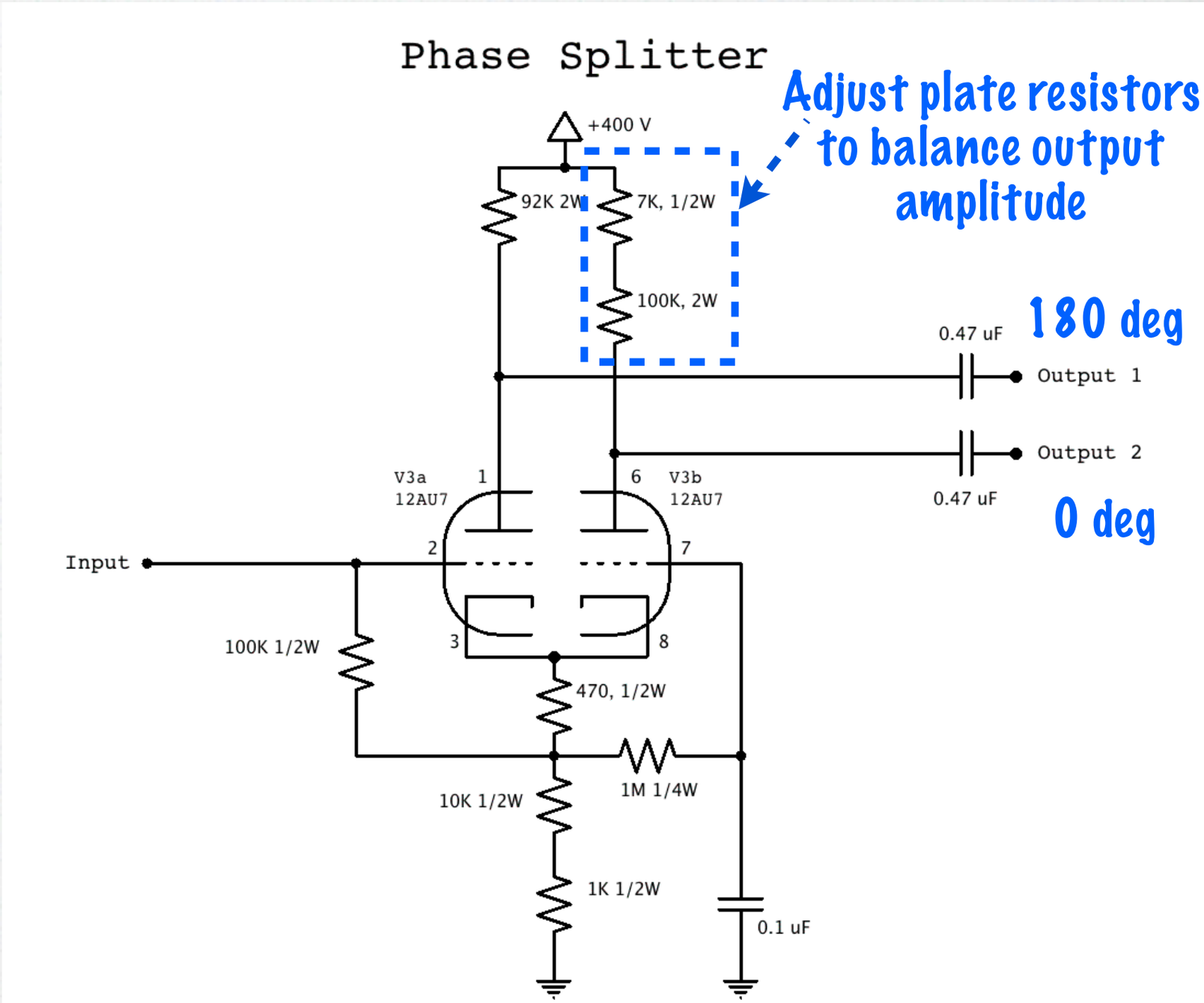
- Follow data sheets
- Direct bias utilized here, however, cathode bias is STRONGLY RECOMMENDED
- Quiescent current = 60 mA for class AB, 25 mA for class B



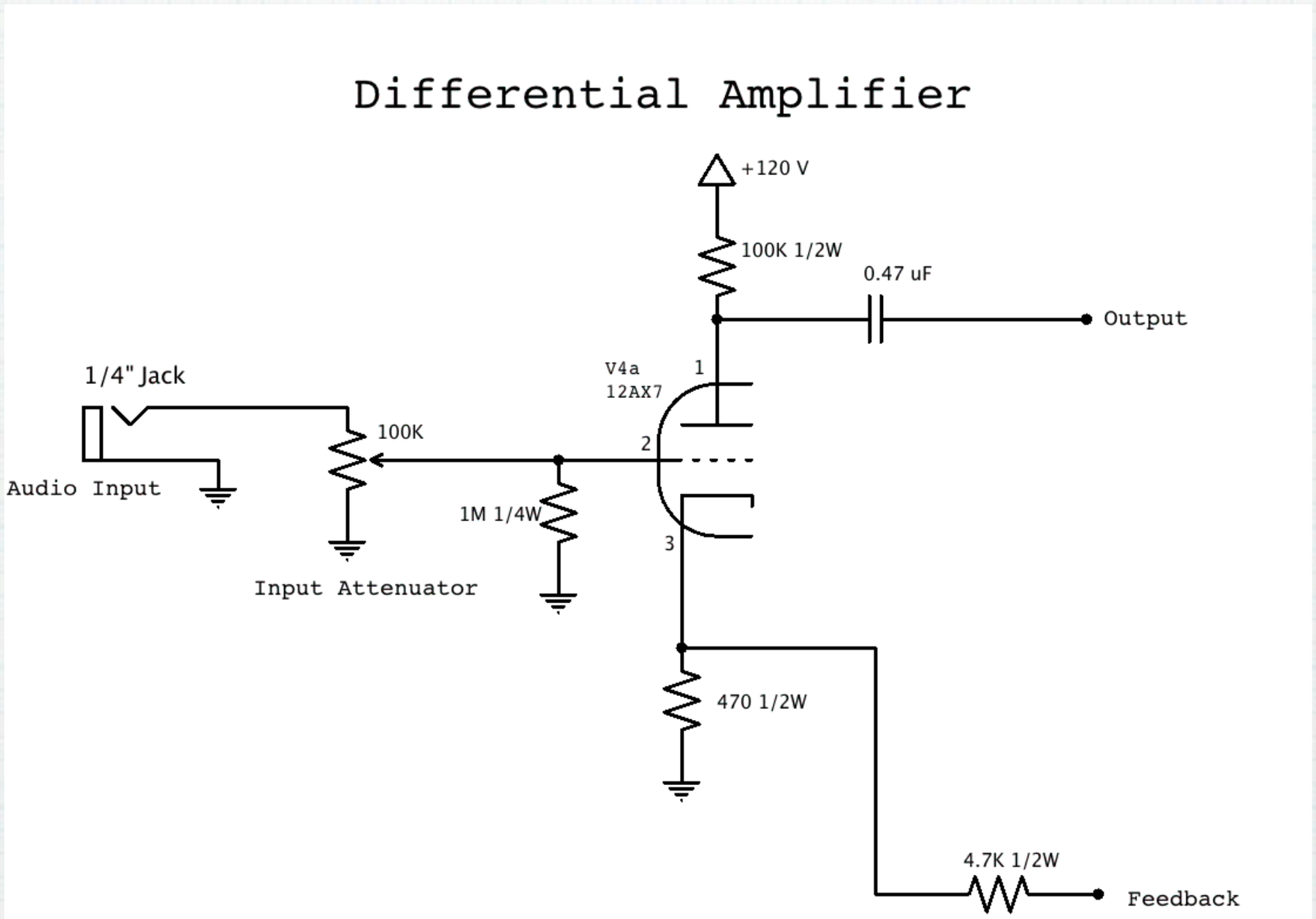
Output pentodes should be 'matched pair,' where, the V vs. I curves are close

Design a Phase Splitter

* Provides 0/180 deg split to drive push-pull output
* This version provides large output swing and forward loop gain
* Balance gain by adjusting plate resistors

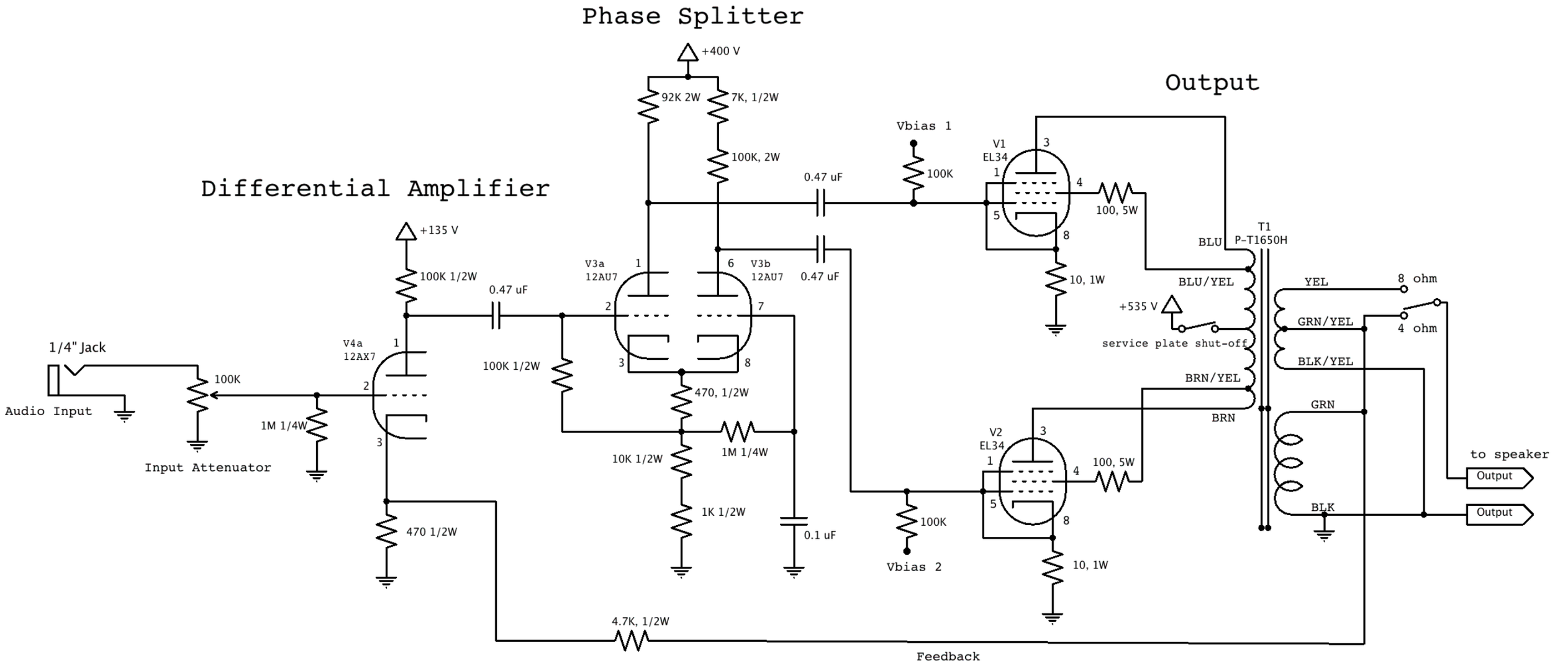


Build the Differential Amplifier



* Similar to the simple pre-amp
* Provides the majority of forward loop gain
* Closes feedback loop

Complete circuit (but not compensated yet!)



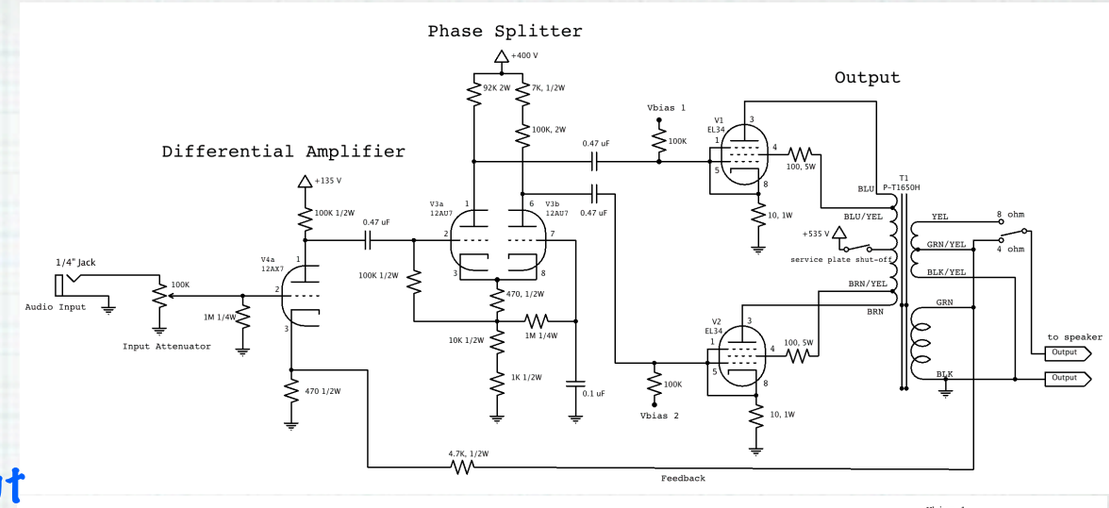
Warning: this will oscillate

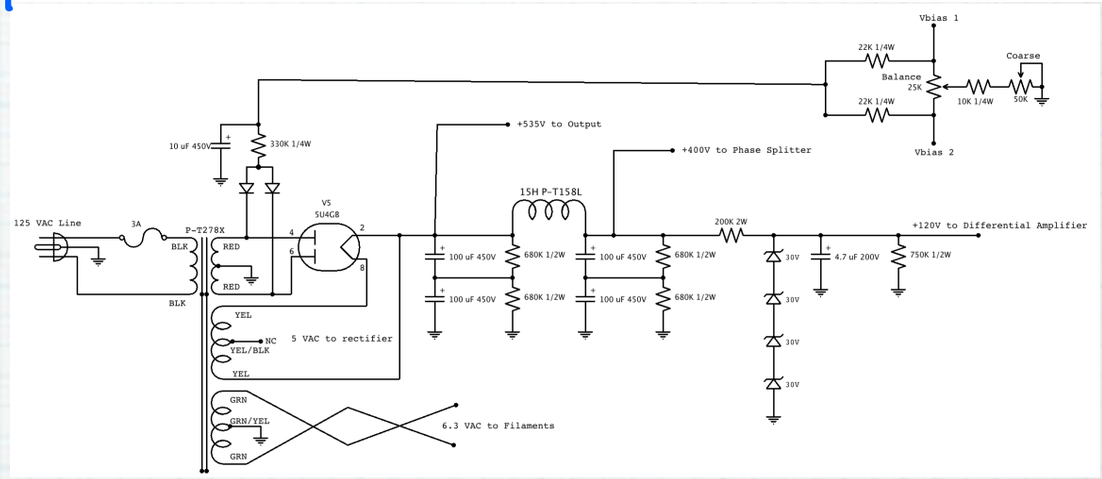
Output

Diff. Amp

Phase Splitter

Power Supply



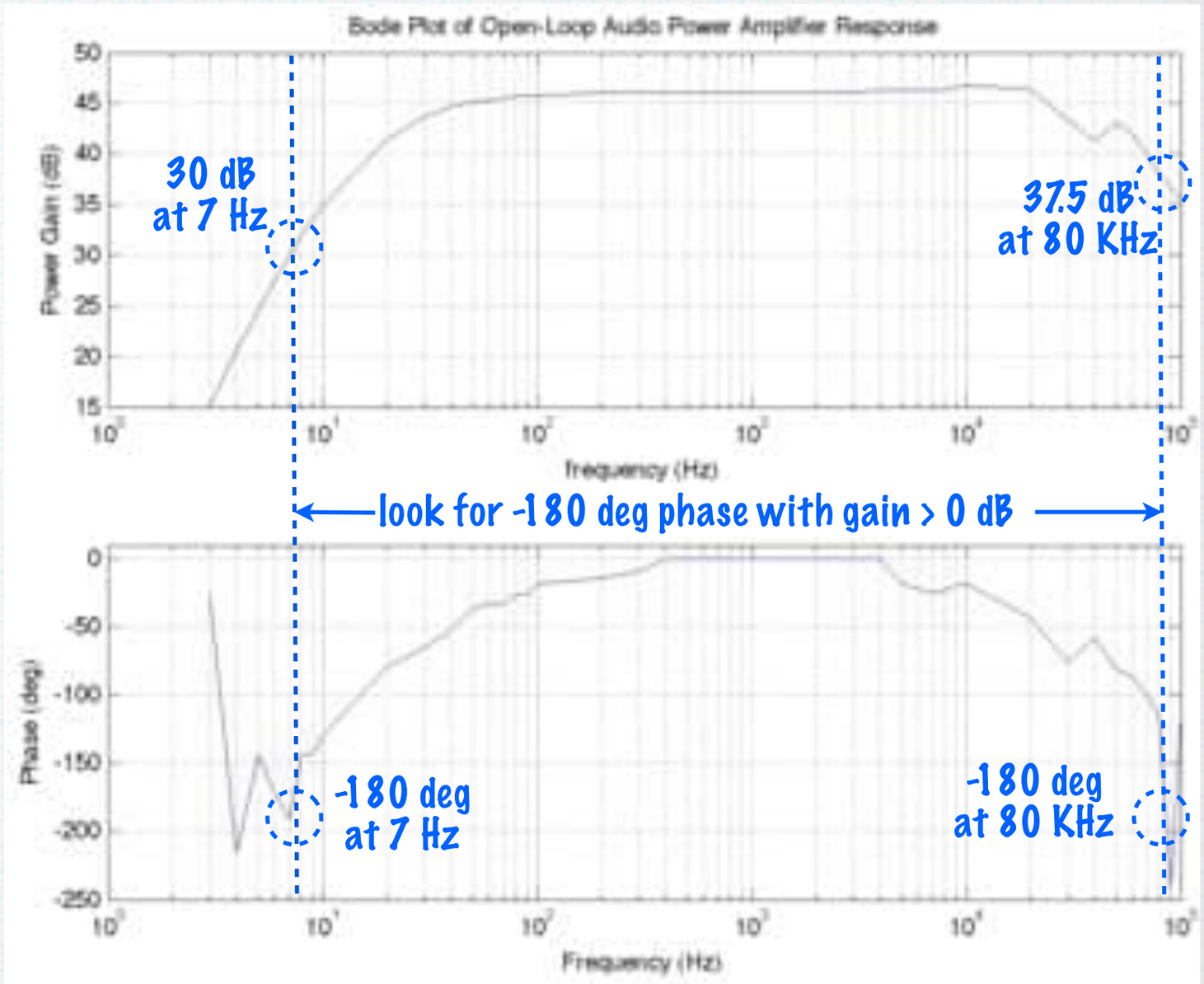


Bias

Phase Splitter

Diff. Amp

Measure the Open-Loop Transfer Function using a Bode Plot

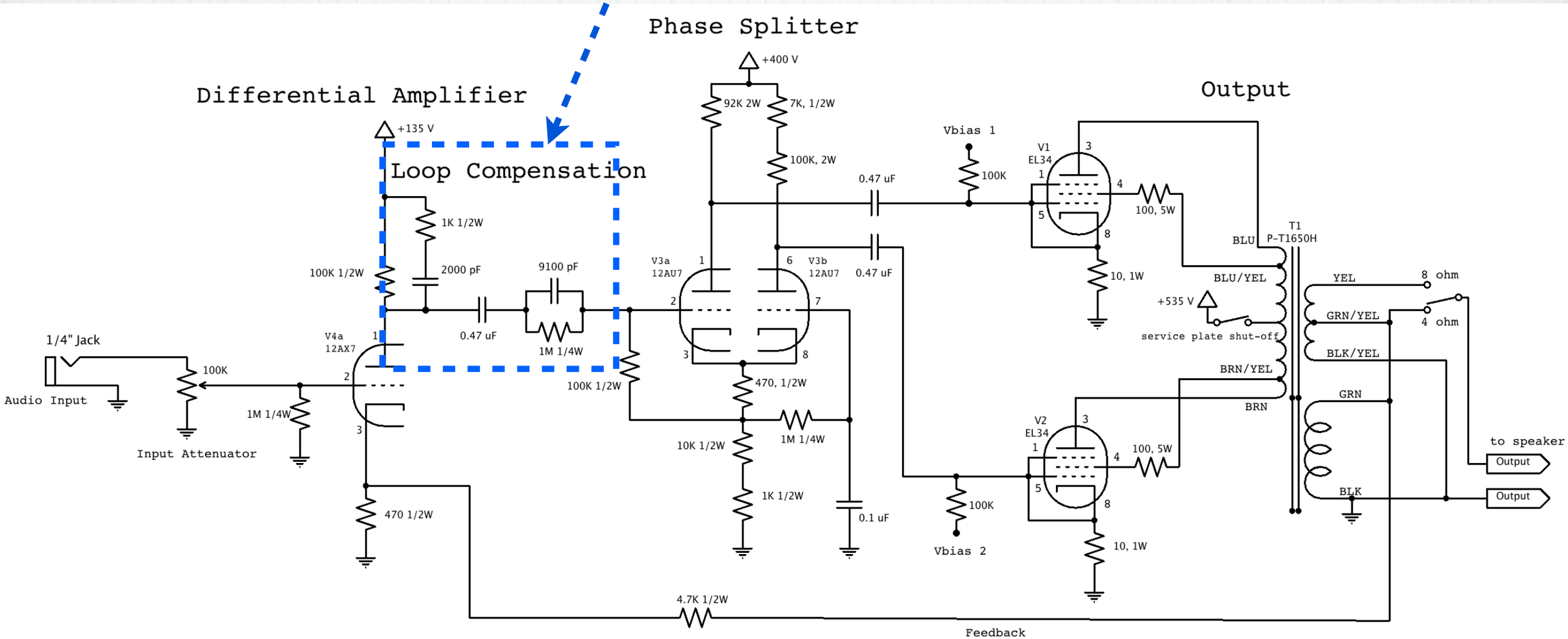


* temporarily remove the feedback resistor
* measure in decades (1-10, 100-1K, 10K-100K, 100K-300K)
* magnitude (dB relative) = 20*log10(Vout/Vin) with 8 ohm load at output
* phase (deg) = 360*frequency*tdelay_between_peaks

Design a Loop Compensator

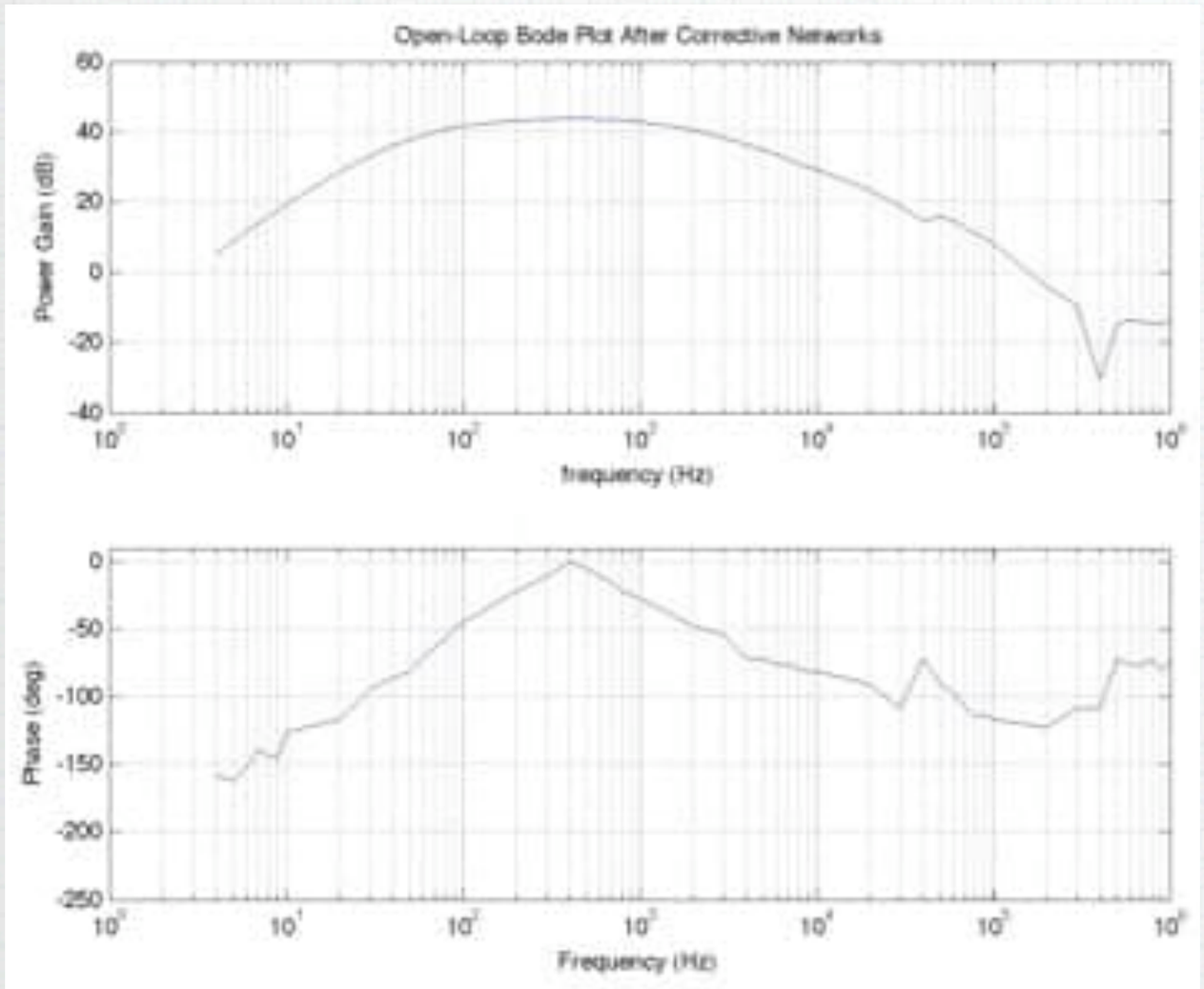
* Preferred method: Learned, V. "Corrective networks for feedback circuits," Proc. I.R.E. 32.7, (July 1944), 403.
  * attenuation and phase slopes to reduce gain and control phase
  * developed for placement between tube stages
  * summarized in: F. Langford-Smith, Radio Designer's Handbook 4th Ed., Reed Educational and Professional Publishing Ltd, London, 1997, pp. 369-371.
* Matlab program www.mit.edu/~gr20603 click on 'Quad Tube Amplifier,' scroll down and click on 'Bode plots and loop compensation network calculations using matlab'
  * manually enter high and low frequencies just before -180 deg

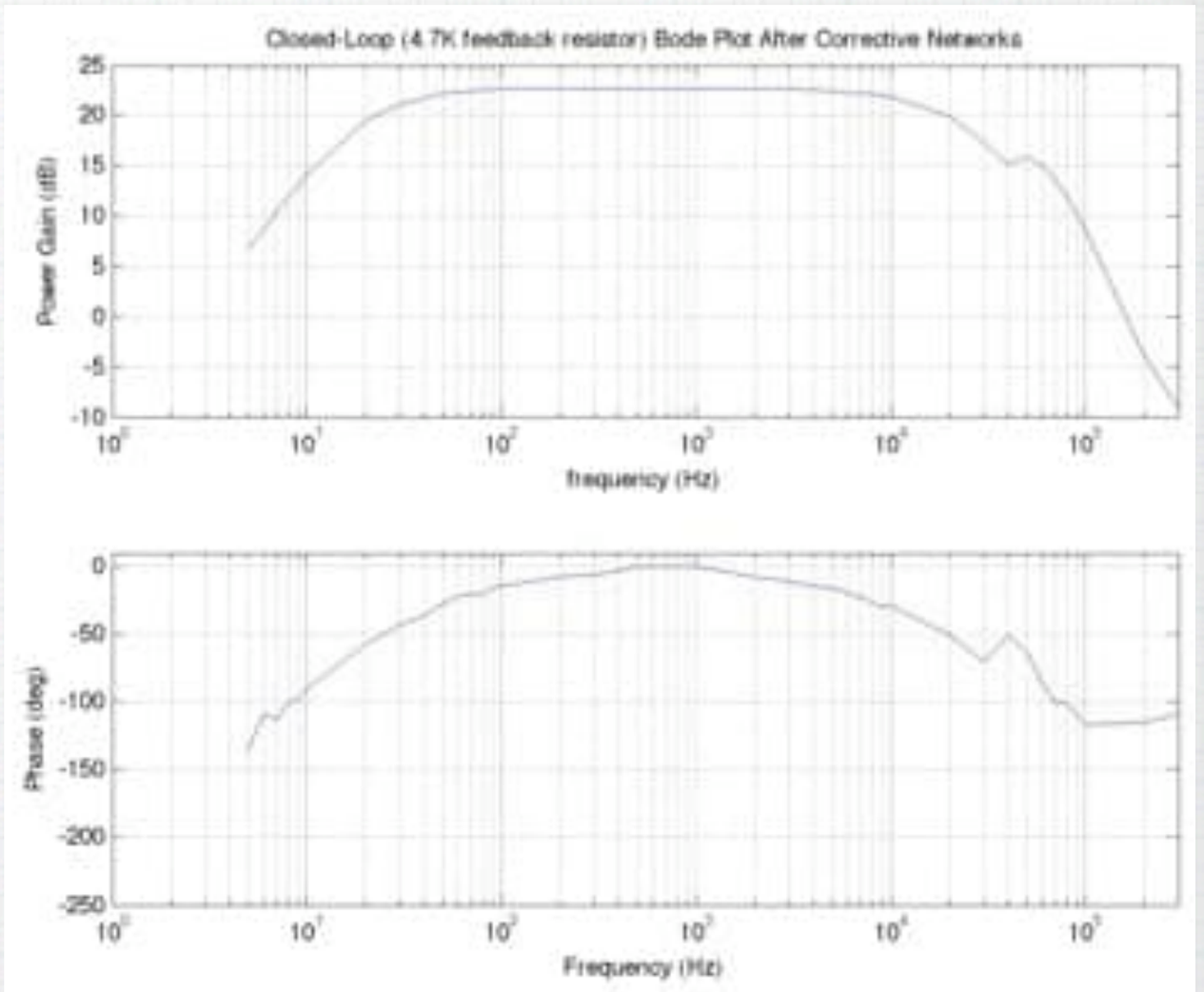
Install Compensation Circuit Between Diff Amp. and Phase Splitter



Re-Plot to Verify Stability and Measure Performance

phase > -180 deg everywhere there is gain > 0 dB





Open-Loop Transfer Function

Closed-Loop Transfer Function

Now you are ready to rock!

Performance

* 480 watts peak power output/ch
* 0.45 % THD at 1 KHz
* 20 Hz - 25 KHz BW
* 4 channel amplifier

* 293.7 watts peak power output
* 0.65 % THD at 1 KHz
* 10 Hz - 25 KHz
* single-channel amplifier

Summary

* Simple pre-amp shown
* Power-Amp design procedure
* Resources:
  * Radio Designer's Handbook
  * Audio Express Magazine
  * gregory.charvat@ll.mit.edu