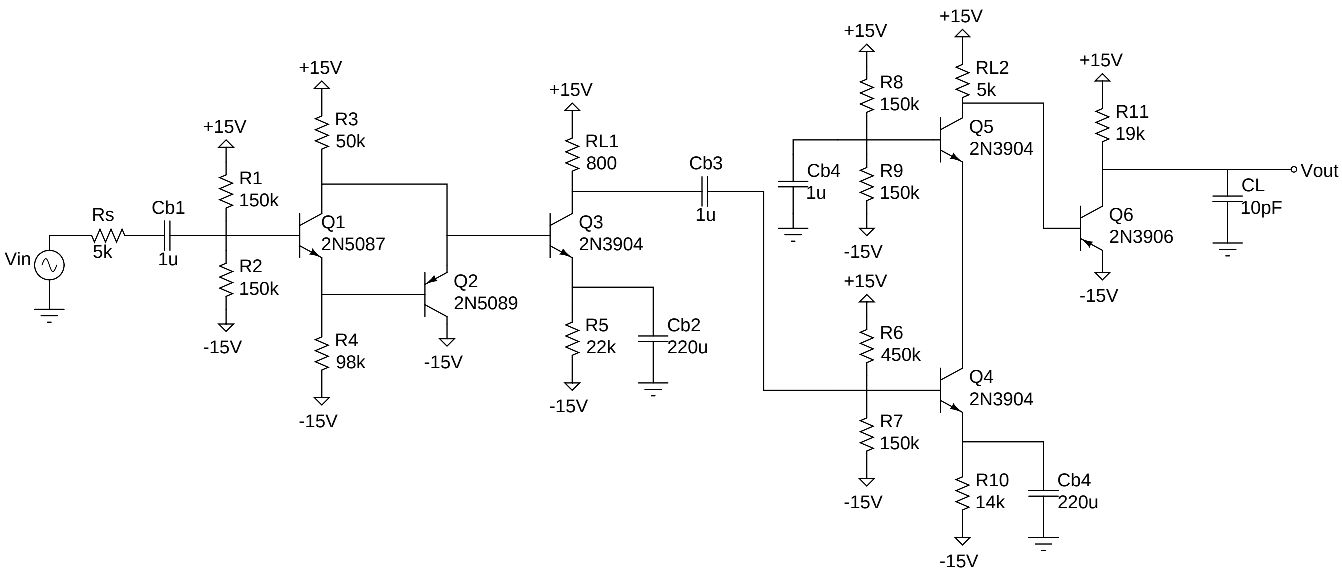


	Specification	Calculated	Simulated	Measured
Midband gain	> 800	1025	1050	1200
AC output swing	> 2 V_{pp}	3.8 V_{pp}	-	3.9 V_{pp}
Power dissipation	< 50 mW	46 mW	47 mW	49 mW
High frequency cutoff	4 MHz	2.8 MHz	-	4.25 MHz
Low frequency cutoff	10 kHz	30 Hz	50 Hz	450 kHz

Design

Topology

To begin the design, we think about the topology we will need. Our major requirements are the gain of 800, with a high frequency cutoff of at least 4 MHz. Most likely we would like to achieve this gain with at least two stages, probably three to get maximum bandwidth. However, being limited to only 6 transistors, the only way to get three stages of gain would be through a cascade of three common emitter amplifiers, which would be poor from a bandwidth standpoint. So we will attempt to work with two stages of gain, likely a cascade of cascodes, which leaves two transistors for buffering.

Looking at the requirements, we our high frequency cutoff of 4 MHz requires an OCT sum of only 40 ns. Combined with the source impedance of 5 kΩ, this very quickly leads us to problems when looking at out input stage. Considering either an input stage of an emitter follower or going directly into our first cascode, we see that both have the same OCT:

$$r_{\pi o} = (R_S + r_b)||r_\pi$$

With a source impedance of 5 kΩ, and a c_π on the order of 20 pF, this is a time constant of approximately 40 ns on its own. Since we still have 12 other time constants to manage, this is simply unacceptable. To reduce this large time constant, we use a bootstrapped emitter follower to buffer the input as well as reduce the OCTs associated with the input.

Our circuit must also be able to drive a 10 pF load capacitor. Considering our power requirement of using under 50 mW, and our output swing specification of more than 2 V_{pp}, our final gain stage will likely have a load resistor of at least 1 kΩ [1]. This would have a OCT of at least 10 ns, or 25% of our allotted OCT total, a large amount for our amplifier. As such, we will need an emitter follower to buffer the output as well, although we do not need the bootstrapping we have on the input stage.

We now have two transistors for the input bootstrapped emitter follower and one transistor for the output emitter follower, leaving only three transistors for the gain stages. This is not enough for two cascaded cascodes, so we will have to use a common emitter and a cascode. We will have the common emitter stage first, with relatively low gain, to minimize the poor OCTs, since the final stage will require a large load resistor that make the Miller capacitance far too large for a common emitter. With this topology in mind, we can begin to choose components.

Biasing

Our biggest concern is that we have only 1.66 mA to power the entire circuit, and we must divide this current among the input stage, the two gain stages, and the output stage. The majority of this current will go to powering the two gain stages, so for an initial estimate we will allocate 0.5 mA to

[1] Assuming $a_v \approx \frac{V_L}{V_{th}}$, and a current of less than 1 mA

each gain stage. This leaves 0.66 mA, of which we will use 0.3 mA to split over the input emitter followers, 0.1 mA for the output emitter follower, the remaining 0.26 mA for biasing networks.

We wish to bias the input of the bootstrapped emitter follower so the input (and hence the output) is biased to 0 V. This maximizes the base-collector voltage on each of the transistors, minimizing their c_μ's. Since the output of the follower is also biased to 0 V, we can use it to directly couple to the common emitter stage, forgoing a coupling capacitor and biasing network. Due to the small load resistor for the common emitter, the output quiescent voltage is very close to the upper power rail, so we will need another biasing stage to decouple the biasing and bias the cascode stage with a lower voltage. We will use -7.5 V to bias the common emitter of the cascode, and 0 V to bias the common base. The output of the cascode must have a DC offset of at most 14 V, to allow the required 2 V_{pp} swing. We bias it to 12.5, and then use a PNP directly coupled to the output as the output emitter follower. We use a PNP to maximize the base-collector voltage, minimizing the c_μ and its OCT.

For choice of transistors, we need to examine the differences in the transistors available to us. The 2N3904 and 2N3906 have β's around 80-100, while the 2N5087 and 2N5089 have β's ranging from 300 to 500. The downside to this high β is a much larger τ_f, leading to much larger c_μ's, on the order of 4 to 5 times larger. In this trade off, we must consider the use of each transistor. For the bootstrapped emitter follower on the input stage, we want to reduce the effective output resistance of the stage as much as possible, reducing the initial 5 kΩ input resistance. Since the effective resistance is proportional to $\frac{1}{\beta^2}$, we choose the 2N5087 and 2N5089 to make our input stage. For the two gain stages, we are greatly concerned with the capacitances, as they will form the dominant OCTs. We choose to use the 2N3904 for the three transistors in the gain stage of the amplifier. For the output follower, we need a large beta to reduce the effective output resistance seen by the load, but also a small c_π to reduce the OCT total. In the end, this smaller capacitance is more important, so we go with the 2N3906 transistor.

Frequency Response

OCT's:

$c_{\pi 1} = 25\text{ pF}, c_{\mu 1} = 1.6\text{ pF}$
$c_{\pi 2} = 29\text{ pF}, c_{\mu 2} = 2.1\text{ pF}$
$c_{\pi 3} = 20\text{ pF}, c_{\mu 3} = 1.6\text{ pF}$
$c_{\pi 4} = 20\text{ pF}, c_{\mu 4} = 2.1\text{ pF}$
$c_{\pi 5} = 20\text{ pF}, c_{\mu 5} = 1.6\text{ pF}$
$c_{\pi 6} = 10\text{ pF}, c_{\mu 6} = 1.8\text{ pF}$

$R_O = \frac{R_S+(\beta+2)(r_b+r_{\pi 1})}{(\beta+1)^2} = 166\Omega$

$r_{1o} = 1/g_{m1} = 166\Omega \rightarrow \tau_{1o} = 4.2$ ns
$r_{2o} = \frac{(R_S+R_4)R_O}{R4} = 175\Omega \rightarrow \tau_{2o} = 0.2$ ns
$r_{3o} = 1/g_{m2} = 166\Omega \rightarrow \tau_{1o} = 4.9$ ns
$r_{4o} = \frac{R_S+r_b+r_{\pi 2}}{\beta+1} = 183\Omega \rightarrow \tau_{4o} = 0.3$ ns
$r_{5o} = R_O||r_{\pi 3} = 160\Omega \rightarrow \tau_{5o} = 3.2$ ns
$r_{6o} = r_{5o} + R_{L1} + g_{m3}r_{5o}R_{L1} = 3.52\text{k}\Omega \rightarrow \tau_{6o} = 5.6$ ns
$r_{7o} = R_{L1}||r_{\pi 4} = 690\Omega \rightarrow \tau_{7o} = 9.1$ ns
$r_{8o} = r_{7o} + 1/g_{m5} + g_{m4}(1/g_{m5})r_{7o} = 1.43\text{k}\Omega \rightarrow \tau_{8o} = 3.0$ ns
$r_{9o} = 1/g_{m5} = 50\Omega \rightarrow \tau_{9o} = 1$ ns
$r_{10o} = R_{L2} = 5\text{k}\Omega \rightarrow \tau_{10o} = 10$ ns
$r_{11o} = r_{\pi 6}|| \left(\frac{R_{L2}+R_{11}}{1+g_{m6}R_{11}}\right) = 306\Omega \rightarrow \tau_{11o} = 3.0$ ns
$r_{12o} = R_{L2}||(r_{\pi 6} + (\beta+1)R_{11}) = 5\text{k}\Omega \rightarrow \tau_{12o} = 9$ ns
$r_{13o} = R_{11}||\frac{r_{\pi 6}+R_{L2}}{\beta+1} = 307\Omega \rightarrow \tau_{13o} = 3.1$ ns

$\sum \tau_{jo} = 56.6\text{ns} \rightarrow \frac{1}{2\pi \sum \tau_{jo}} = f_h = 2.8$ MHz

SCT's:

$$r_{1s} = R_S + R_1||R_2||(r_{\pi 1} + (\beta+1)(R4 + r_{\pi 2})) = 80\text{k}\Omega \rightarrow \tau_{1s} = 80 \text{ ms}$$
$$r_{2s} = R_5|| \left(1/g_{m3} + \frac{R_3|| \left(1/g_{m2} + \frac{R_4|| \left(1/g_{m1} + \frac{R_S||R_1||R_2}{\beta+1} \right)}{\beta+1} \right)}{\beta+1} \right) \approx 1/g_{m3} = 50\Omega \rightarrow \tau_{2s} = 11 \text{ ms}$$
$$r_{3s} = R_{L1} + R_6||R_7||(r_{\pi 4} + (\beta+1)R_{10} = 113\text{k}\Omega \rightarrow \tau_{3s} = 113 \text{ ms}$$
$$r_{4s} = R_{10}||(1/g_{m4} + \frac{R_{L1}||R_6||R_7}{\beta+1}) = 57\Omega \rightarrow \tau_4 2 = 13 \text{ ms}$$

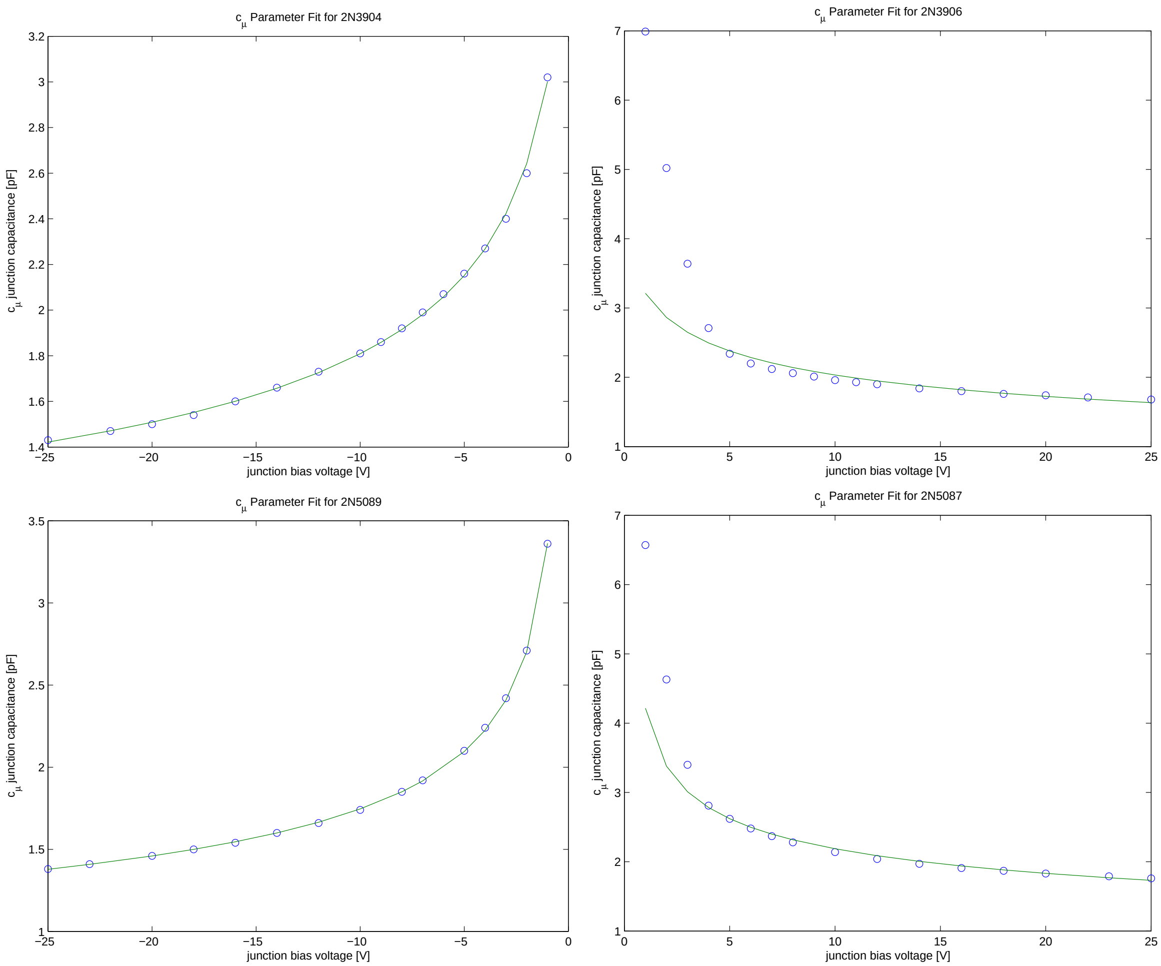
$f_l = \frac{1}{2\pi} \sum \frac{1}{\tau_{js}} = 30$ Hz

Simulation

Device Parameters

Parameter	2N3904	2N3906	2N5089	2N5087
β	100	80	500	300
c_{je}	8 pF	10 pF	10 pF	10 pF
τ_f	500 ps	136 ps	2.56 ns	3.2 ns
$c_{\mu 0}$	3.83 pF	3.99 pF	3.03 pF	3.70 pF
ψ_0	0.70 V	-0.72 V	0.27 V	-0.30 V
m_c	0.28	0.25	0.25	0.25

The values for β were found measuring sample devices on the curve tracer. The values for $c_{\mu 0}$, ψ_0, and m_c were obtained by fitting parameters to values of c_μ found for sample devices at various base-collector biases. The values for c_{je} and τ_f were extracted from the datasheets of the transistors, based of the values of f_t. In the graphs below, we see that the fit for c_μ does not conform at very low bias voltages, but we shall ignore this discrepancy as we shall keep our devices sufficiently biased.



Spice Deck

```
* 6.301 Lab 2 - Wideband Amplifier Design

.AC DEC 500 10 20e6
.op
.print ac v(11)
*.plot ac v(11)

Vhigh vcc 0 DC 15
Vlow vee 0 DC -15
Vin vin 0 AC 1 0
Rs vin 1 5k

*Stage 1 Biasing
Cblock1 1 2 1u
Rbias11 vcc 2 150k
Rbias12 vee 2 150k
*Stage 1 - Bootstrapped Emitter Follower
Q1 3 2 4 q2N5089
Q2 vee 4 3 q2N5087
Rsupp1 vcc 3 50k
Rsupp2 vee 4 96k
*Stage 2 - CE Amp (gain ~25)
Q3 5 3 6 q2N3904
Rbias21 6 vee 28.8k
Cbias21 6 0 200u
RL1 vcc 5 800
* Stage 3 - Cascode (gain ~40)
Cblock2 5 7 1u
Rbias31 vcc 7 450k
Rbias32 vee 7 150k
Rbias33 8 vee  13.8k
Cbias31 8 0 200u
Rbias34 vcc 10 150k
Rbias35 vee 10 150k
Cbias32 10 0 200u
Q4 9 7 8 q2N3904
Q5 11 10 9 q2N3904
RL2 vcc 11 5k
*Stage 4 - Emitter Follower
Q6 vee 11 12 q2N3906
Ree 12 vcc 19k
Cload 12 0 10pF

.model q2N5089 NPN
+BF=500 IS=1.5e-15
+CJE=10pF TF=2.56ns
+CJC=4.79pF

.model q2N5087 PNP
+BF=300 IS=1.5e-15
+CJE=10pF TF=3.2ns
+CJC=4.79pF

.model q2N3904 NPN
+BF=100 IS=1.5e-15
+CJE=8pF TF=500ps
+CJC=3.86pF

.model q2N3906 PNP
+BF=80 IS=1.5e-15
+CJE=10pF TF=150ps
+CJC=5.07pF

.end
```

Spice Simulation

```
****** HSPICE -- U-2003.03-SP1 (20030430) 23:36:40  03/31/2005  solaris
 Copyright (C) 2003 Synopsys, Inc. All Rights Reserved.
 Unpublished-rights reserved under US copyright laws.
 This program is protected by law and is subject to the
 terms and conditions of the license agreement found in:
   /mit/hspice/2003.03-SP1/license.txt
 Use of this program is your acceptance to be bound by this
 license agreement. HSPICE is the trademark of Synopsys, Inc.
 Input File: lab2.sp
lic:
lic: FLEXlm: v6.1g
lic: USER:   skendig             HOSTNAME: grumpy-fuzzball.mit.edu
lic: HOSTID: 8380df15            PID:      18585
lic: Using FLEXlm license file:
lic: /mit/hspice/2003.03-SP1/license.dat
lic: Checkout hspice;  Encryption code: 2D6177C6152E93D57922
lic: License/Maintenance for hspice will expire on 21-jan-2006/2004.12
lic: 1(in_use)/50 FLOATING license(s) on SERVER
lic:

1 ****** HSPICE -- U-2003.03-SP1 (20030430) 23:36:40  03/31/2005  solaris
******
* 6.301 lab 2 - wideband amplifier design
 ****** bjt   model parameters          tnom=  25.000 temp=  25.000
******

************************************************************************
*** bjt model parameters   model name:   0:q2n5089  model type:npn   ***
************************************************************************

    names  values   units     names  values   units     names  values   units
    -----  ------   -----     -----  ------   -----     -----  ------   -----

  1*** basic dc parameters ***
   level=   1.00               bf= 500.00                br=   1.00
     brs=   0.               bulk=  gnd                  is=   1.50f amps
     iss=   0.    amps         nf=   1.00                nr=   1.00
      ns=   1.00              ibe=   0.    amps         ibc=   0.    amps
    subs=   1.00            expli=   0.    amps

  2*** low current beta degradation effect parameters ***
     isc=   0.    amps        ise=   0.    amps          nc=   2.00
      ne=   1.50

  3*** base width modulation parameters ***
     vaf=   0.    volts       var=   0.    volts

  4*** high current beta degradation effect parameters ***
     ikf=   0.    amps        nkf= 500.00m              ikr=   0.    amps

  5*** parasitic resistor parameters ***
     irb=   0.    amps         rb=   0.    ohms         rbm=   0.    ohms
      re=   0.    ohms         rc=   0.    ohms          vo=   0.    volts
   gamma=   0.

  6*** junction capacitor parameters ***
```

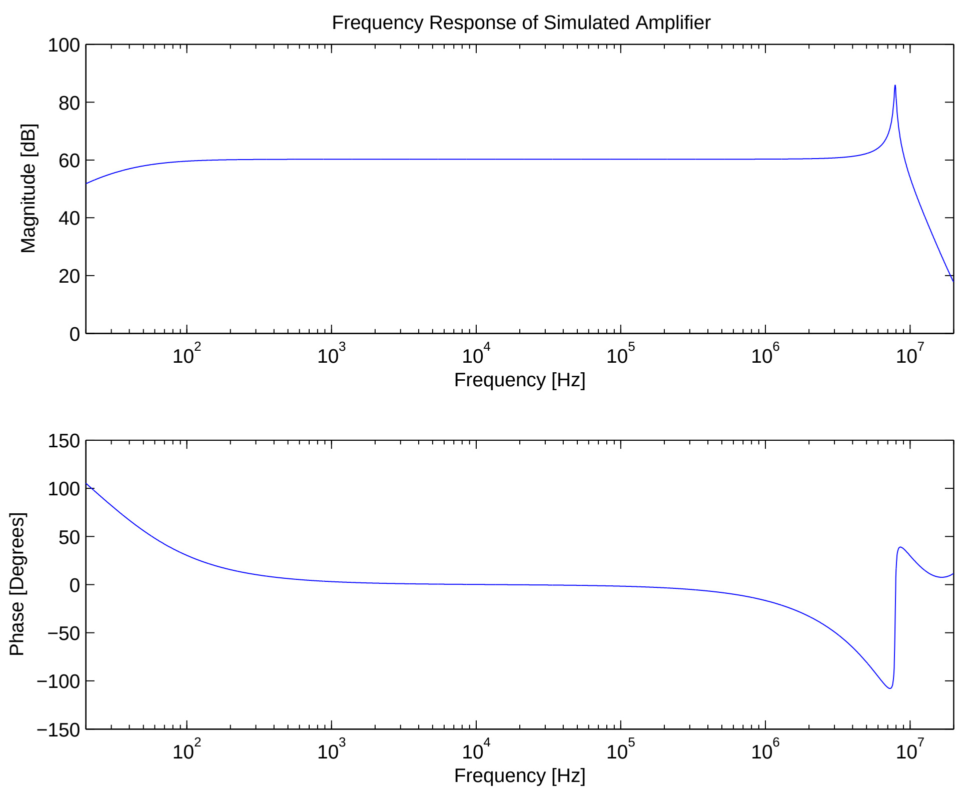
```
   cbcp=   0.    farad       cbep=   0.    farad       ccsp=   0.    farad
    cjc=   4.79p farad        cje=  10.00p farad        cjs=   0.    farad
     fc= 500.00m              mjc= 330.00m              mje= 330.00m
    mjs= 500.00m              vjc= 750.00m volts        vje= 750.00m volts
    vjs= 750.00m volts       xcjc=   1.00               qco=   0.    coul

 7*** transit time parameters ***
    itf=   0.    amps         ptf=   0.    deg k         tf=   2.56n secs
     tr=   0.    secs         vtf=   0.               xtf=   0.

 8*** temperature compensation parameters ***
   tlev=   0.               tlevc=   0.               tre1=   0.    /deg
   tre2=   0.    /deg2       trb1=   0.    /deg       trc1=   0.    /deg
   trb2=   0.    /deg2       trm1=   0.    /deg        xtb=   0.
   trm2=   0.    /deg2        xti=   3.00               cte=   0.    /deg
    ctc=   0.    /deg         cts=   0.    /deg       trc2=   0.    /deg2
   tref=  25.00   deg c       bex=   2.42              bexv=   1.90

 9*** noise parameters ***
     kf=   0.                  af=   1.00

***********************************************************************
*** bjt model parameters   model name:   0:q2n5087  model type:pnp   ***
***********************************************************************

   names  values   units     names  values   units     names  values   units
   -----  ------   -----     -----  ------   -----     -----  ------   -----

 1*** basic dc parameters ***
  level=   1.00                bf= 300.00                br=   1.00
    brs=   0.               bulk=  gnd                   is=   1.50f amps
    iss=   0.    amps          nf=   1.00                nr=   1.00
     ns=   1.00               ibe=   0.    amps         ibc=   0.    amps
   subs=  -1.00             expli=   0.    amps

 2*** low current beta degradation effect parameters ***
    isc=   0.    amps         ise=   0.    amps          nc=   2.00
     ne=   1.50

 3*** base width modulation parameters ***
    vaf=   0.    volts        var=   0.    volts

 4*** high current beta degradation effect parameters ***
    ikf=   0.    amps         nkf= 500.00m              ikr=   0.    amps

 5*** parasitic resistor parameters ***
    irb=   0.    amps          rb=   0.    ohms         rbm=   0.    ohms
     re=   0.    ohms          rc=   0.    ohms          vo=   0.    volts
  gamma=   0.

 6*** junction capacitor parameters ***
   cbcp=   0.    farad       cbep=   0.    farad       ccsp=   0.    farad
    cjc=   4.79p farad        cje=  10.00p farad        cjs=   0.    farad
     fc= 500.00m              mjc= 330.00m              mje= 330.00m
    mjs= 500.00m              vjc= 750.00m volts        vje= 750.00m volts
    vjs= 750.00m volts       xcjc=   1.00               qco=   0.    coul
```

```
 7*** transit time parameters ***
   itf=   0.    amps         ptf=   0.    deg k         tf=   3.20n secs
    tr=   0.    secs         vtf=   0.                 xtf=   0.

 8*** temperature compensation parameters ***
  tlev=   0.               tlevc=   0.                tre1=   0.    /deg
  tre2=   0.    /deg2       trb1=   0.    /deg        trc1=   0.    /deg
  trb2=   0.    /deg2       trm1=   0.    /deg         xtb=   0.
  trm2=   0.    /deg2        xti=   3.00               cte=   0.    /deg
   ctc=   0.    /deg         cts=   0.    /deg        trc2=   0.    /deg2
  tref=  25.00   deg c       bex=   2.42              bexv=   1.90

 9*** noise parameters ***
    kf=   0.                  af=   1.00

***********************************************************************
*** bjt model parameters   model name:   0:q2n3904  model type:npn   ***
***********************************************************************

   names  values   units     names  values   units     names  values   units
   -----  ------   -----     -----  ------   -----     -----  ------   -----

 1*** basic dc parameters ***
 level=   1.00                bf= 100.00                br=   1.00
   brs=   0.                bulk=  gnd                  is=   1.50f amps
   iss=   0.    amps          nf=   1.00                nr=   1.00
    ns=   1.00               ibe=   0.    amps         ibc=   0.    amps
  subs=   1.00             expli=   0.    amps

 2*** low current beta degradation effect parameters ***
   isc=   0.    amps         ise=   0.    amps          nc=   2.00
    ne=   1.50

 3*** base width modulation parameters ***
   vaf=   0.    volts        var=   0.    volts

 4*** high current beta degradation effect parameters ***
   ikf=   0.    amps         nkf= 500.00m              ikr=   0.    amps

 5*** parasitic resistor parameters ***
   irb=   0.    amps          rb=   0.    ohms         rbm=   0.    ohms
    re=   0.    ohms          rc=   0.    ohms          vo=   0.    volts
 gamma=   0.

 6*** junction capacitor parameters ***
  cbcp=   0.    farad       cbep=   0.    farad       ccsp=   0.    farad
   cjc=   3.86p farad        cje=   8.00p farad        cjs=   0.    farad
    fc= 500.00m              mjc= 330.00m              mje= 330.00m
   mjs= 500.00m              vjc= 750.00m volts        vje= 750.00m volts
   vjs= 750.00m volts       xcjc=   1.00               qco=   0.    coul

 7*** transit time parameters ***
   itf=   0.    amps         ptf=   0.    deg k         tf= 500.00p secs
    tr=   0.    secs         vtf=   0.                 xtf=   0.

 8*** temperature compensation parameters ***
  tlev=   0.               tlevc=   0.                tre1=   0.    /deg
```

```
   tre2=   0.    /deg2       trb1=   0.    /deg        trc1=   0.    /deg
   trb2=   0.    /deg2       trm1=   0.    /deg         xtb=   0.
   trm2=   0.    /deg2        xti=   3.00               cte=   0.    /deg
    ctc=   0.    /deg         cts=   0.    /deg        trc2=   0.    /deg2
   tref=  25.00   deg c       bex=   2.42              bexv=   1.90

 9*** noise parameters ***
     kf=   0.                  af=   1.00

*************************************************************************
*** bjt model parameters   model name:   0:q2n3906  model type:pnp   ***
*************************************************************************

   names  values   units     names  values   units     names  values   units
   -----  ------   -----     -----  ------   -----     -----  ------   -----

 1*** basic dc parameters ***
  level=   1.00                bf=  80.00               br=   1.00
    brs=   0.               bulk=  gnd                  is=   1.50f amps
    iss=   0.    amps          nf=   1.00               nr=   1.00
     ns=   1.00               ibe=   0.    amps        ibc=   0.    amps
   subs=  -1.00             expli=   0.    amps

 2*** low current beta degradation effect parameters ***
    isc=   0.    amps         ise=   0.    amps         nc=   2.00
     ne=   1.50

 3*** base width modulation parameters ***
    vaf=   0.    volts        var=   0.    volts

 4*** high current beta degradation effect parameters ***
    ikf=   0.    amps         nkf= 500.00m             ikr=   0.    amps

 5*** parasitic resistor parameters ***
    irb=   0.    amps          rb=   0.    ohms        rbm=   0.    ohms
     re=   0.    ohms          rc=   0.    ohms         vo=   0.    volts
  gamma=   0.

 6*** junction capacitor parameters ***
   cbcp=   0.    farad       cbep=   0.    farad       ccsp=   0.    farad
    cjc=   5.07p farad        cje=  10.00p farad        cjs=   0.    farad
     fc= 500.00m              mjc= 330.00m              mje= 330.00m
    mjs= 500.00m              vjc= 750.00m volts        vje= 750.00m volts
    vjs= 750.00m volts       xcjc=   1.00               qco=   0.    coul

 7*** transit time parameters ***
    itf=   0.    amps         ptf=   0.    deg k         tf= 150.00p secs
     tr=   0.    secs         vtf=   0.                 xtf=   0.

 8*** temperature compensation parameters ***
   tlev=   0.               tlevc=   0.                tre1=   0.    /deg
   tre2=   0.    /deg2       trb1=   0.    /deg        trc1=   0.    /deg
   trb2=   0.    /deg2       trm1=   0.    /deg         xtb=   0.
   trm2=   0.    /deg2        xti=   3.00               cte=   0.    /deg
    ctc=   0.    /deg         cts=   0.    /deg        trc2=   0.    /deg2
   tref=  25.00   deg c       bex=   2.42              bexv=   1.90
```

```
  9*** noise parameters ***
      kf=   0.                 af=   1.00
1 ******  HSPICE -- U-2003.03-SP1 (20030430) 23:36:40  03/31/2005  solaris
 ******
 * 6.301 lab 2 - wideband amplifier design
 ******  operating point information      tnom=  25.000 temp=  25.000
 ******
 ***** operating point status is all       simulation time is     0.
   node    =voltage      node    =voltage      node    =voltage

 +0:1       =   0.      0:2       = -22.2686m 0:3       = -22.5934m
 +0:4       =-672.7371m 0:5       =  14.6068  0:6       =-703.8184m
 +0:7       =  -8.0094  0:8       =  -8.6885  0:9       =  -1.0151
 +0:10      =-336.2541m 0:11      =  12.7635  0:12      =  13.3991
 +0:vcc     =  15.0000  0:vee     = -15.0000  0:vin     =   0.


 ****  voltage sources

 subckt
 element  0:vhigh    0:vlow     0:vin
  volts     15.0000   -15.0000     0.
  current   -1.5770m    1.5770m    0.
  power     23.6552m   23.6552m    0.


     total voltage source power dissipation=   47.3104m       watts

 **** resistors

 subckt
 element  0:rs       0:rbias11  0:rbias12  0:rsupp1   0:rsupp2   0:rbias21
  r value    5.0000k  150.0000k  150.0000k   50.0000k   96.0000k   28.8000k
  v drop     0.        15.0223   -14.9777    15.0226   -14.3273    14.2962
  current    0.       100.1485u  -99.8515u  300.4519u -149.2423u  496.3952u
  power      0.         1.5045m    1.4955m    4.5136m    2.1382m    7.0966m

 subckt
 element  0:rl1      0:rbias31  0:rbias32  0:rbias33  0:rbias34  0:rbias35
  r value  800.0000   450.0000k  150.0000k   13.8000k  150.0000k  150.0000k
  v drop   393.1843m   23.0094    -6.9906     6.3115    15.3363   -14.6637
  current  491.4804u   51.1321u  -46.6038u  457.3517u  102.2417u  -97.7583u
  power    193.2424u    1.1765m  325.7875u    2.8866m    1.5680m    1.4335m

 subckt
 element  0:rl2      0:ree
  r value    5.0000k   19.0000k
  v drop     2.2365    -1.6009
  current  447.2999u  -84.2580u
  power      1.0004m  134.8889u


 **** bipolar junction transistors


 subckt
 element  0:q1       0:q2       0:q3       0:q4       0:q5       0:q6
```

model	0:q2n5089	0:q2n5087	0:q2n3904	0:q2n3904	0:q2n3904	0:q2n3906
ib	296.9136n	-488.6389n	4.9148u	4.5282u	4.4834u	-1.0402u
ic	148.4568u	-146.5917u	491.4804u	452.8235u	448.3401u	-83.2178u
vbe	650.4686m	-650.1437m	681.2250m	679.1203m	678.8647m	-635.5973m
vce	650.1437m	-14.9774	15.3106	7.6734	13.7786	-28.3991
vbc	324.8224u	14.3273	-14.6294	-6.9943	-13.0998	27.7635
vs	22.5934m	672.7371m	-14.6068	1.0151	-12.7635	-12.7635
power	96.7114u	2.1959m	7.5282m	3.4778m	6.1806m	2.3640m
betad	500.0000	300.0000	100.0000	100.0000	100.0000	80.0000
gm	5.7784m	5.7058m	19.1298m	17.6252m	17.4507m	3.2391m
rpi	86.5297k	52.5784k	5.2274k	5.6737k	5.7304k	24.6984k
rx	0.	0.	0.	0.	0.	0.
ro	1.691e+13	9.551e+15	9.752e+15	4.662e+15	8.733e+15	1.850e+16
cpi	27.6547p	31.1191p	19.9628p	19.2031p	19.1149p	13.2825p
cmu	4.7907p	1.7793p	1.4245p	1.7865p	1.4746p	1.5262p
cbx	0.	0.	0.	0.	0.	0.
ccs	0.	0.	0.	0.	0.	0.
betaac	500.0000	300.0000	100.0000	100.0000	100.0000	80.0000
ft	28.3447x	27.6032x	142.3555x	133.6443x	134.8917x	34.8116x



Analysis

The results of the SPICE simulation proved rather odd. The midband gain is constant at around 60 dB, or a gain of 1000. This is consistent with our calculations. The low frequency cutoff is around 100 Hz, also consistent with our expectations. The high frequency behavior, however, does not agree with our calculations at all.

The presence of a high frequency resonance, located at about 8 MHz, indicates some sort of feedback behavior in the circuit. This is likely located (and confirmed through simulation) in the bootstrapped emitter follower. The follower has a feedback loop to reduce the effect of the input impedance of our source, which in the simulation is somehow resonating. Isolating the resonance any more than the input stage is difficult. By eliminated any single capacitance involved (either of the transistors' c_π or c_μ) we can eliminate this resonance, so it seems like it is a combination of these capacitances is causing the ringing. Unsurprisingly, the actual circuit does not experience this ringing, and instead has a dominant pole where the ringing seems to start.

Results

Once assembled, the circuit behaved mostly as expected. A midband gain of 1200 was achieved, slightly larger than our calculated and simulated gain, but within reasonable parameters. Most likely this is due to shifts in the bias conditions, particularly in the common emitter stage, as the input quiescent voltage tended to above the expected 0 V. This shifting was likely due to mismatched currents through the PNP and NPN transistors that make up the bootstrapped emitter follower that the first gain stage was directly coupled to. If these two transistors had different base-emitter drops, then the biasing would shift away from its expected value. This could be fixed by adding an extra decoupling and biasing network, but the shift was not significant enough to require rebiasing.

The measurement of the high end bandwidth proved difficult. By simply increasing the frequency of the sinusoidal input, we were able to reach the half power frequency at 4.25 MHz, but this includes the possible frequency dependent attenuation stage, which should not be included for measuring the bandwidth of the amplifier. By using the square wave method, feeding the amplifier with a low amplitude square wave and determining the bandwidth based on the rise time, we were able to find a separate measure of high frequency cutoff, which should be immune to the frequency dependencies of the attenuator. However, this stage also proved troublesome, as the rise time seemed to shift drastically depending on the input voltage of the square wave. Using an input square wave of 1 V (roughly 1 V at the amplifier output), we calculate a high frequency cutoff of approximately 22 MHz, which seems optimistically high. Using an input square wave of 2 V, we calculate a high frequency cutoff of only 2 MHz. This large shift in bandwidth makes us skeptical of the rise time approximation of bandwidth, as the bandwidth should be constant for varying input voltages.

The low frequency cutoff was a great deal higher than expected, falling off at 450 kHz instead of our calculated 30 Hz. The rolloff at 450 kHz was not constant, however, instead dropping off until about 50 kHz, at which point the gain remained constant until around 100 Hz, at which point it again dropped off steadily to zero gain. This seems to indicate that the capacitors C_2 and C_4, used to ground out the emitters of the gain stages, were failing to act as AC shorts, causing the two gain stages to drop through emitter degeneration. These capacitors also had the lowest open circuit time constants, although the poles were expected to fall around 15 Hz, instead of 450 kHz. Attempts to increase these capacitors from 220 μF to 1000 μF had no effect on the low frequency cutoff, nor did placing smaller 1 μF mica capacitors in parallel to ensure that the larger capacitors remained AC shorts in higher frequencies. More experimentation with these capacitors is needed to fully debug this problem.

The output swing reached 4 V_{pp}, although there was frequency dependent distortion when running at high swing and high frequencies (greater than 2 MHz). The high frequency distortion seemed to shift the sinusoid signal to something more like a sawtooth, which seemed to imply an uneven rising and falling slew rate. At lower frequencies, the signal remained undistorted until nearly reaching the high rail.