ECE 222 Final Project - Lab Report

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ABSTRACT

In this project, we studied how to make a headphone amplifier, using transistors, resistors, and capacitors. Special considerations were taken during the design of the amplifier to make sure that it fell within the given power constraints. Additionally, its spectral performance was manipulated with the addition of capacitors to optimize for the frequency range common to human hearing. Once the design was complete, the board was modeled using HSPICE, to make sure the power requirements were actually met. In addition to this, we varied our R and C values slightly to see if the performance of the amplifier could be optimized anymore. After the simulation in HSPICE was complete, we constructed the physical, dual channel model of the headphone amp in the lab.

1. PROCEDURE

1. Research OP-AMPs for audio usage
2. Choose OP-AMPS and configuration
3. Calculate needed R, C values for specs
4. Test model in HSPICE
5. Optimize performance in HSPICE
6. Construct breadboard prototype in lab
7. Demonstrate prototype performance
8. Solder perforation board

2. MATERIALS

- Operational Amplifiers
  - OPA2134 (dual audio channels)
  - OPA511 (buffer amplifier)
- Resistors (per channel)
  - (2) 10kΩ
  - 75kΩ
  - 1kΩ
- Capacitors (per channel)
  - $0.1\mu F$
  - $0.91nF$

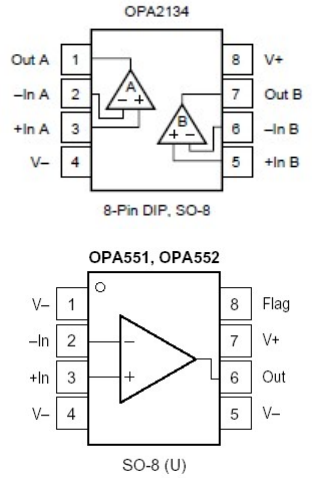


Figure 1: OP AMP Pin Diagrams

3. RESULTS

Overall, the construction of the project was a great success, with the amplifier meeting all of the design specifications that were given to us. Additionally, the perforation board was soldering to create a durable circuit for us to use.

3.1 Initial Design

Much reading was done, to familiarize ourselves with the business of making reasonable, efficient headphone amplifier design. There are many different models and versions of amplifiers, so this reading was useful in getting more of a grasp on what was right for us. This project came with a set of design specifications for our headphone amplifer:

Specifications:

- Output load impedance: 32-300 Ω, optimize for your headphone (nominal)
- Output power: > 100 mW on a 32 Ω load
- Output impedance: <5Ω
- Input signal amplitude: 0.3V (nominal Vrms), 0.9 (Vpp)
- Input impedance: > 10kΩ
- 3-dB bandwidth: 20Hz-15kHz
- Total harmonic distortion + noise (THD+N): <0.1% at 20mW on nominal load
- Power supply voltage: ±7-±9V (2x 9V batteries) or ±12V (external AC power supply + on-board regulation)
- Power consumption: <30mA (battery) or <50mA (external power supply)

Figure 2: Amplifier specifications

After spending much time thinking on the best way to implement an amplifier with these constraints, we opted to use a LPF with the classic CMOY design, which is essentially an OP-AMP gain stage with a feedback buffer to control the output resistance of the circuit. Here is the full schematic of our design:

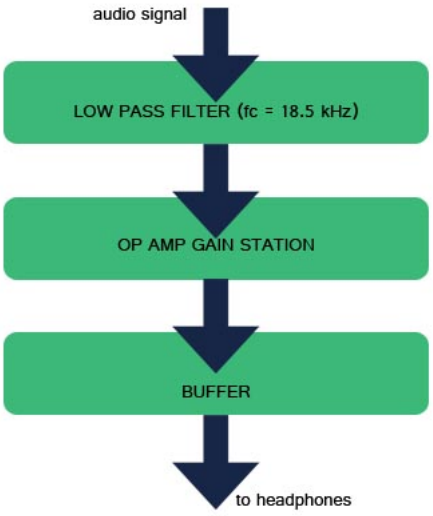
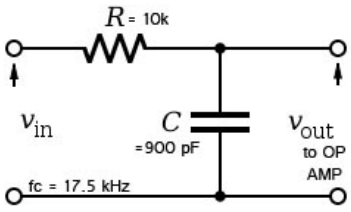
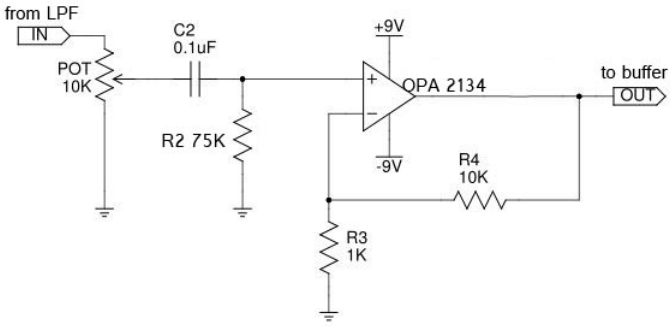


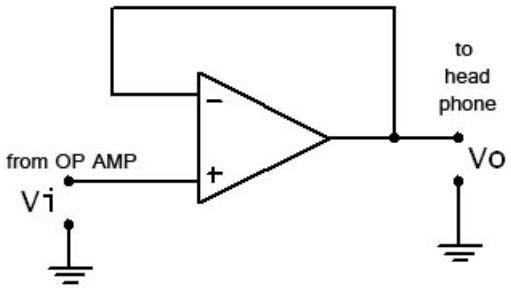
Figure 3: Comprehensive Block Diagram



(a) Low-Pass stage of circuit



(b) OP-AMP stage of circuit



(c) Buffer stage of circuit

Figure 4: Full circuit schematic

3.2 HSPICE Simulation

Using HSPICE netlists, we carefully considered the design requirements when choosing device parameters. Please note that both the source and the output of the code is also included at the end of this lab report. Below, we have the gain as a function of frequency for the circuit model. The HSPICE model was a bit different than the actual model implemented, due to the need to regain control of the bandwidth by sacrificing some gain. Here, we see that the peak amplitude of the gain of the HSPICE model very nearly approaches $20V/V$. This is while only maintaining the desired frequency range, by implementing a low-pass filter with the cutoff of about $18kHz$. Some delay occurred due to the expiration of HSPICE licenses, but overall the simulations were a success with a new understanding of IC circuit design being passed on.

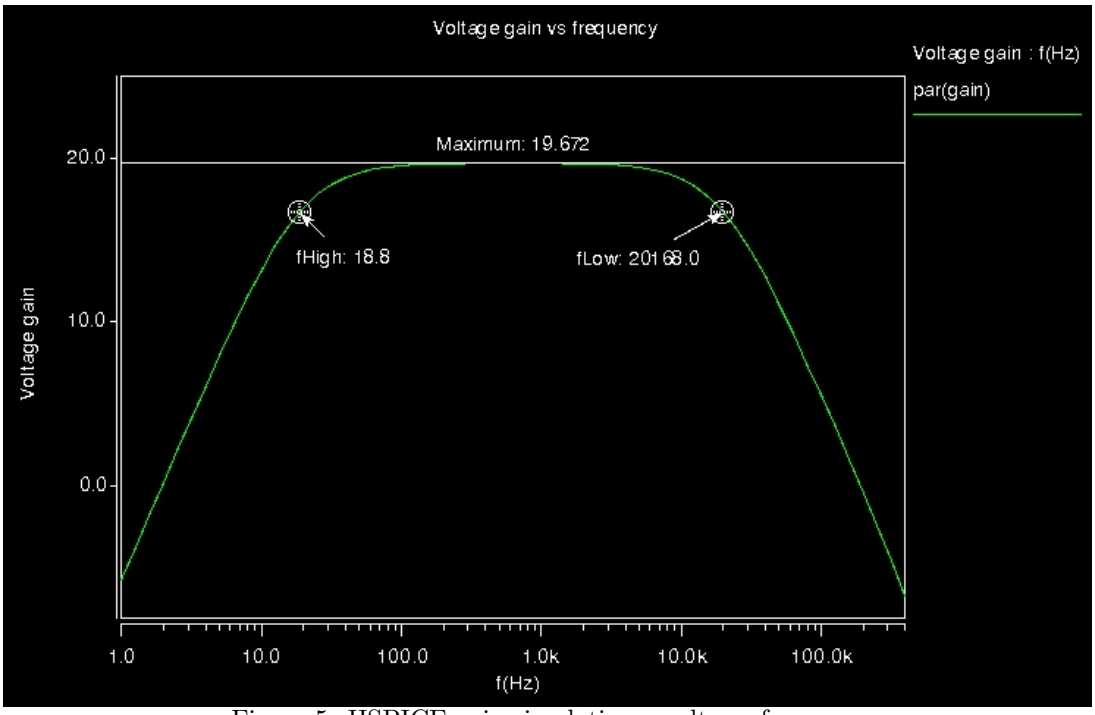


Figure 5: HSPICE gain simulation results vs frequency

3.3 Physical Construction

Working from both labs in Hopeman 202 and Gavett 305, we implemented the headphone as planned. We have included measurements of the gain at specific frequencies, showing that the amplifier characteristics do indeed satisfy those given in the lab report. Initially, the circuit was very noisy, and we discovered the cutoff frequency of our filter was too high, and was disturbing our channel. To counter this, we changed our filter parameters, so that the gain reduced from the HSPICE model, but was still reasonable, and the power constraint was adhered to. Here is a image of the working version of the circuit, first being tested out on the breadboard.

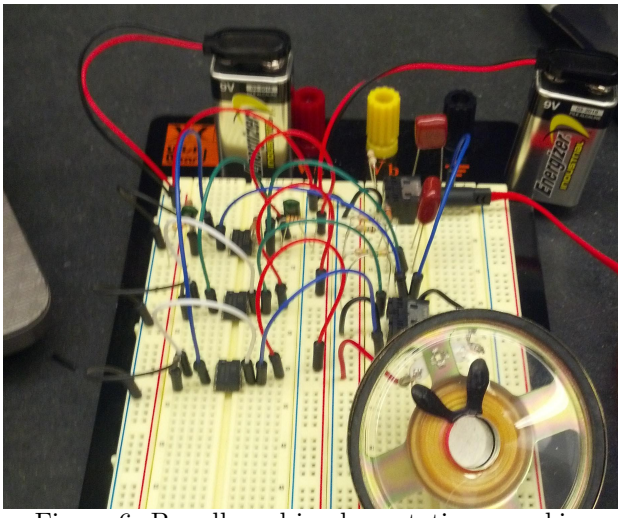
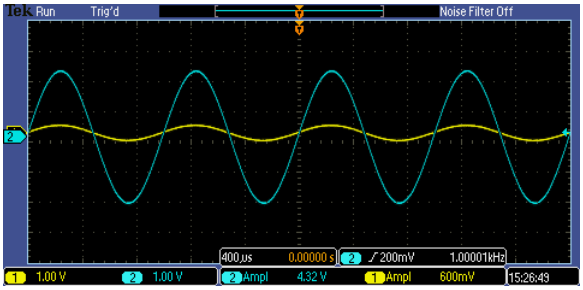
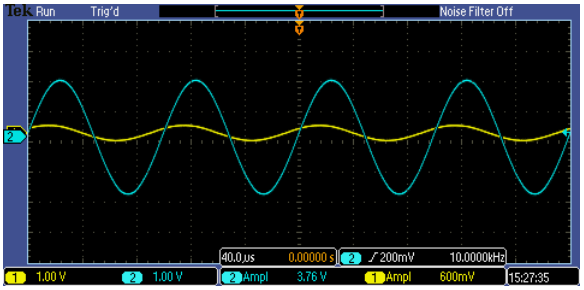


Figure 6: Breadboard implementation - working

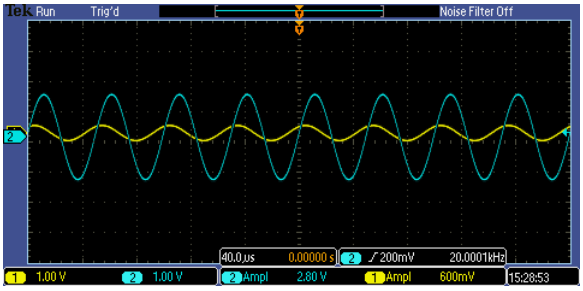
There is a cutoff frequency built in at $18.5kHz$, which is very much evident in the severe drop off in gain at the measurements $20kHz$ and $100kHz$. We were using the function generator with a simple sine wave as our input, so that we could more clearly measure the frequency dependent gain of the full circuit. The frequency of the sine wave is specified in each figure.



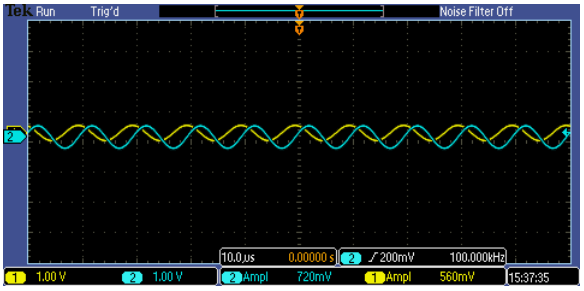
(a) Output with $1kHz$ input, gain = $7.2V/V$



(b) Output with $10kHz$ input, gain = $7.2V/V$



(c) Output with $20kHz$ input, gain = $2.8V/V$



(d) Output with $100kHz$ input, gain = $1.3V/V$

Figure 7: from oscilloscope - amplifier frequency vs gain

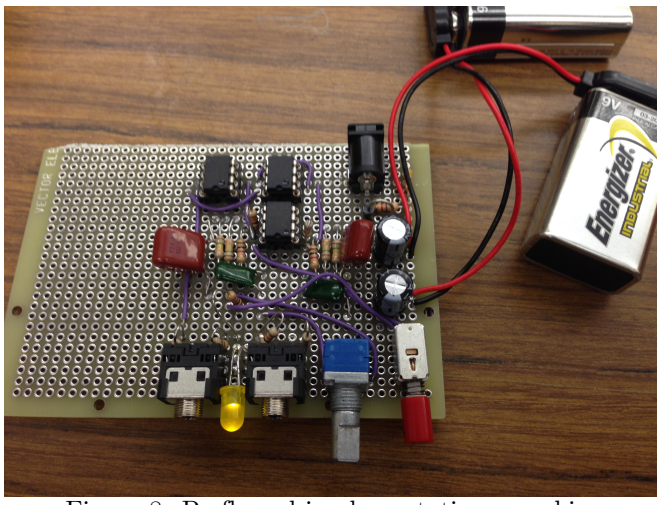


Figure 8: Perfboard implementation - working

3.4 Specifications Results

- Had 3dB freq range from 20Hz - 18.5 kHz
- Used 65 ohm headphones for testing
- Maximum power tested, $89mW$ - less than $100mW/ch$
- Output impedance found to be 3.1Ω
- Testing with $0.3V$ (rms)
- Ckt input impedance $19.2k\Omega$
- THD+N = 0.92% <0.1% at 1kHz
- Used two 9V batteries
- Power consumption = 35 mA on battery <100 mA

4. CONCLUSION

We successfully implemented the OP-AMP headphone amplifier, as specified in the lab guidelines. Throughout the design process, we were sure to pay attention to the parameter restrictions in place, which led to the entire process going fairly smoothly. Overall, this lab project was a good experience on translating a model born from parameter restrictions, to an HSPICE simulation, to a physical prototype on the breadboard. It was a good complement to the material presented in class, and furthered our understanding and familiarity with the core concepts presented in ECE 222.

5. HSPICE SOURCE CODE

Here is the HSPICE design file we used for the model simulation. Please note that output of the code is also included at the end of this section.

```
*jeremy warner & eddie samuels
*ece 22 final project
*headphone amplifier w/ params:
*       output load impedance = 32-300ohm
*       output power = 100mW/chan (battery) 200mW/chan (ac)
*       output impedance = <5ohm
*       input amplitude = 0.3V
*       input impedance = >10kohm
*       3db BW = 20Hz - 15kHz
*       THDN = <0.1% w/ 10omW on nominal load @1kHz
*       power consumption = <30mA (battery), <50mA (ac)

*         node
*input -  1
*output - 9

*include library files
```

```
.include '../sedra_lib.lib'
*.include 'OPamps/LF411C.lib'
.include 'OPamps/OPA551.LIB'
.include 'OPamps/OPA2134.LIB'

*DC Sources
Vplus 8 0 DC 9V
Vminus 0 7 DC 9V

Vsweep 1 0 AC 1V

*OP amps
*Xopamp1 3 4 8 7 6 LF411C
Xopamp1 3 4 8 7 6 OPA2134
Xbuffer 6 9 8 7 9 10 OPA551

*R values
R1 1 2 10k
R2 3 0 75k
R3 4 0 1k
R4 4 5 10k
R5 6 5 .0001

*C values
C1 2 3 .1u
C2 3 0 0.0009u

*analysis
.OP
.AC DEC 10 1 500k
.PRINT gain = PAR('Vdb(9)-Vdb(1)')

.OPTION NOMOD POST
.END
```

5.1 Terminal Output

```
Using: /usr/bin/time -p /usr/ece/synopsys/hspice_vD-2010.03-SP1/hspice/
    linux/hspice final.sp
 ****** HSPICE -- D-2010.03-SP1 32-BIT (May 27 2010) linux ******
  Copyright (C) 2010 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 from Synopsys.
  Use of this program is your acceptance to be bound by the
  license agreement. HSPICE is the trademark of Synopsys, Inc.
  Input File: final.sp
 lic:
 lic: FLEXlm: v8.5b
 lic: USER:    esamuels              HOSTNAME: laplace
 lic: HOSTID: 001b245d5b09           PID:      15752
 lic: Using FLEXlm license file:
 lic: 5280@val2
 lic: Checkout 1 hspice
 lic: License/Maintenance for hspice will expire on 19-apr-2015/2013.12
 lic: FLOATING license(s) on SERVER val2
 lic:
 Init: read install configuration file: /usr/ece/synopsys/hspice_vD
     -2010.03-SP1/hspice/meta.cfg
  **warning** (OPamps/OPA2134.LIB:54) dc      may cause confusion with .dc
1****** HSPICE -- D-2010.03-SP1 32-BIT (May 27 2010) linux ******
 ******


  ******  circuit name directory
 circuit number to circuit name directory
   number circuitname                      definition          multiplier
        0 main circuit
        1 xopamp1.                         opa2134             1.00
        2 xbuffer.                         opa551              1.00

 **warning** To avoid producing hard-to-solve matrix equations, connect
    gdcpath from node        0:2                 defined in subckt 0

 ******************************************************************
 ******  option summary
 ******
 runlvl  = 3         bypass  = 2
  Opening plot unit= 15
 file=final.pa0


 **info** dc convergence failure,
 resetting dcon option to 1 and retrying
```

```
 no convergence with standard algorithm,  trying damped pseudo-transient

  *** initial damped pseudo transient completed. ***
  *** final try started ***
  *** final try succeeded ***

 **info** This was a difficult operating point.
             You can speed up your simulation by specifying:
             .OPTION CONVERGE=1

1****** HSPICE -- D-2010.03-SP1 32-BIT (May 27 2010) linux ******
 ******


  ******  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       =    0.       0:3       =-714.2351n
 +0:4       =    4.3486u  0:5       =   47.9303u  0:6       =   47.9303u
 +0:7       =   -9.0000   0:8       =    9.0000   0:9       =  189.3387u
 +0:10      =    8.1104   1:6       =  -31.2227n  1:7       =   48.0239u
 +1:8       =   48.0239u  1:9       =    0.       1:10      =-718.0544m
 +1:11      =   -8.8001   1:12      =   -8.8001   1:53      =    7.8000
 +1:54      =   -8.1000   1:90      =    4.6812u  1:91      =   40.0000
 +1:92      =  -40.0000   1:99      =    0.       2:33      =    8.9998
 +2:34      =  930.7178u  2:35      =    9.0002   2:36      =  930.7175u
 +2:37      =  999.9959m  2:38      =  664.6727m  2:39      =  665.2790m
 +2:40      =    1.9337m  2:41      =  189.3396u  2:42      =    1.4748
 +2:43      =    1.4756   2:44      =    1.4748   2:45      =    1.9336m
 +2:46      =   -1.5550m  2:47      =   -1.5550m  2:48      =    8.9999
 +2:49      =   -8.9999   2:50      =  591.5766m  2:51      =  591.5766m
 +2:52      =   -9.0000   2:53      =    9.0000   2:54      =  709.8919m
 +2:55      =  709.8919m  2:56      =  189.3387u  2:57      =  -10.5635u
 +2:58      =    9.0000   2:59      =   -9.0000   2:60      =   89.3876u
 +2:61      =   89.3876u  2:62      =  899.9100u  2:63      =-899.9100u
 +2:64      =    8.9379n  2:65      =   47.9307u  2:66      =  189.3387u
 +2:67      =  -10.5635u  2:68      =  -33.0612u  2:69      =    0.
 +2:70      =    0.       2:71      =   -7.8000   2:72      =  189.4365u
 +2:73      =   -7.8000   2:74      =  189.3387u  2:75      =  769.1386m
 +2:76      =-664.9003m   2:77      =  -10.5635u  2:78      =    3.2756
 +2:79      =    7.9902   2:80      =    9.0000   2:81      =   -6.0000
 +2:82      =  302.6325n  2:83      =    2.6337n  2:84      =  664.6700m
 +2:85      =  650.6727m  2:87      =  450.6727m  2:88      =   29.9999
 +2:89      =  -29.9999   2:90      =  -14.9999   2:91      =   14.9999
 +2:92      =  877.9142p  2:93      =  877.8809p  2:94      =   -8.9949
 +2:95      =    9.0000   2:96      =   -8.0000   2:97      =   -8.0000
 +2:98      =    8.2859   2:99      =   -8.0000   2:100     =    8.3763m
 +2:101     =    8.3766m  2:102     =   28.9208   2:103     =   28.9150
 +2:104     =   28.9091   2:105     =   28.7081   2:106     =   28.9209
```

```
+2:107      =   28.9150   2:108      =   28.9091   2:109      = 148.7526
+2:110      =   15.7753   2:111      = 300.0000   2:112      =   8.9945
+2:113      =   -8.8218   2:114      =   -8.9999   2:115      = 157.8431
+2:116      =   15.6862   2:117      =   1.2892k   2:118      =  15.0000
+2:119      =  -15.0000   2:120      =   53.9672   2:121      =   6.7753
+2:122      =   15.7753   2:123      =   -8.9986   2:124      = 157.8431
+2:125      =   15.6862   2:126      =   1.2892k   2:127      =  15.0000
+2:128      =  -15.0000   2:129      =   53.9672   2:130      = 650.7356m
+2:131      =  -51.2644m  2:132      =   9.0000    2:133      = 610.6727m
+2:134      = -768.7599m  2:135      = 189.3445u   2:136      = 769.1286m
+2:137      = -768.7499m  2:138      = -189.3445u  2:139      = -63.7264m
+2:140      = 189.3445u   2:141      = -63.9158m   2:142      =  64.1051m
+2:143      = 189.3445u   2:144      =   2.0363    2:145      =  -1.7359
+2:146      = 650.7342m   2:147      = -63.7264m   2:148      = 189.3451u
+2:149      =  64.1051m   2:150      =   1.7300    2:151      = 650.7355m
+2:152      =  -49.2645m  2:153      =  28.1300    2:154      =  28.1300
+2:155      =  26.9507    2:156      = -49.2645m   2:157      = 650.7355m
+2:158      =  -49.2645m  2:159      =   7.3237    2:160      =   8.1100
+2:161      =   4.1110u   2:162      = -999.9959m  2:163      =   0.


****  voltage sources

subckt                                          xopamp1     xopamp1     xopamp1
element  0:vplus     0:vminus    0:vsweep       1:vb        1:vc        1:ve
 volts     9.0000      9.0000      0.             0.          1.2000    900.0000m
 current  -9.0583m    -9.0588m    0.          -312.2265f     7.8008p     8.1008p
 power    81.5243m    81.5295m    0.             0.         -9.3609p    -7.2908p

subckt   xopamp1     xopamp1     xbuffer     xbuffer     xbuffer     xbuffer
element  1:vlp       1:vln       2:v63       2:v66       2:v67       2:v70
 volts     40.0000     40.0000   300.0000    -15.0000     15.0000    -15.0000
 current  -40.0008p   -40.0008p -284.3138u    61.4814p  131.3150m    61.4814p
 power      1.6000n     1.6000n   85.2942m  922.2213p    -1.9697    922.2213p

subckt   xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element  2:v71       2:v72       2:v74       2:v75       2:v76       2:v78
 volts     15.0000   702.0000m     0.          3.0000   -160.0000m     1.8000
 current  131.3150m  -51.2644n   36.0396p    24.0404p     1.9400u     7.2741p
 power     -1.9697    35.9876n     0.        -72.1211p  310.4029n   -13.0934p

subckt   xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element  2:v79       2:v80       2:v112      2:v113      2:v114      2:v115
 volts     2.1000   -714.6500m  700.0000m    27.0000     26.4000    700.0000m
 current   6.9737p    63.9158f  -49.2645n     1.1893p     1.7300p   -49.2645n
 power   -14.6448p    45.6774f   34.4851n   -32.1107p   -45.6726p    34.4851n

subckt   xbuffer     xbuffer     xopamp1     xbuffer     xbuffer     xbuffer
element  2:v116      2:v117      1:vlim      2:v18       2:v21       2:v23
 volts   890.0000m     1.0000      0.       -200.0000u     1.8000    200.0000m
```

```
 current    50.5014n    −4.1110f     4.6812n     0.        799.9957u     2.3907u
 power     −44.9463n     4.1110f     0.          0.         −1.4400m −478.1382n

subckt    xbuffer     xbuffer     xbuffer     xbuffer
element   2:v49       2:v50       2:v51       2:v52
 volts      15.0000    −15.0000      1.0000      1.1110u
 current     0.          0.        −3.0000p   999.9959f
 power       0.          0.         3.0000p    −1.1110a

    total voltage source power dissipation=    −3.6925        watts



***** current sources

subckt    xopamp1     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   1:iss       2:i8        2:i9        2:i10       2:i11       2:i19
 volts       9.7181   −591.5766m −591.5766m −709.8919m −709.8919m −650.6727m
 current   160.0000u   100.0000u   100.0000u   100.0000u   100.0000u     1.0000m
 power      −1.5549m    59.1577u    59.1577u    70.9892u    70.9892u   650.6727u

subckt    xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:i20       2:i21       2:i22       2:i25       2:i41       2:i46
 volts      17.2859     18.0000   −650.7356m −650.7342m  −10.5635u −650.7355m
 current   200.0000n   250.0000u     1.0000m     1.0000m   10.0000p     1.0000m
 power      −3.4572u    −4.5000m   650.7356u   650.7342u  105.6346a   650.7355u

subckt    xbuffer     xbuffer     xbuffer
element   2:i47       2:i48       2:i49
 volts    −650.7355m   189.3387u     7.3237
 current     1.0000m    10.0000p    50.0000n
 power     650.7355u    −1.8934f −366.1826n


    total current source power dissipation=   −2.5448m        watts

**** resistors

subckt                                                              xopamp1
element   0:r1        0:r2        0:r3        0:r4        0:r5        1:r2
 r value    10.0000k    75.0000k     1.0000k    10.0000k   100.0000u   100.0000k
 v drop      0.        −714.2351n     4.3486u   −43.5816u   435.8162f   −31.2227n
 current     0.          −9.5231p     4.3486n    −4.3582n     4.3582n −312.2265f
 power       0.           6.8018a    18.9107f   189.9358f   1.899e−21   9.749e−21

subckt    xopamp1     xopamp1     xopamp1     xopamp1     xopamp1     xopamp1
element   1:rd1       1:rd2       1:ro1       1:ro2       1:rp        1:rss
 r value     2.4900k     2.4900k    20.0000     20.0000     7.5000k     1.2500x
 v drop   −199.9116m −199.9188m    93.6243n    48.0239u    18.0000  −718.0544m
 current   −80.2858u   −80.2887u     4.6812n     2.4012u     2.4000m −574.4435n
```

power	16.0501u	16.0512u	438.2759a	115.3147p	43.2000m	412.4817n
subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r144	2:r158	2:r3	2:r4	2:r10	2:r11
r value	24.0000	24.0000	2.0000	2.0000	1.0000k	1.0000k
v drop	201.0308m	201.0392m	−799.9956u	−799.9958u	661.7009p	−661.7009p
current	8.3763m	8.3766m	−399.9978u	−399.9979u	661.7009f	−661.7009f
power	1.6839m	1.6840m	319.9965n	319.9966n	4.378e−22	4.378e−22
subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r12	2:r13	2:r22	2:r30	2:r31	2:r32
r value	100.0000m	100.0000m	100.0000x	1.0000x	1.0000x	1.0000x
v drop	−93.0718u	−93.0717u	−18.0000	8.9991	−8.9991	89.3786u
current	−930.7178u	−930.7175u	−180.0000n	8.9991u	−8.9991u	89.3786p
power	86.6236n	86.6235n	3.2400u	80.9838u	80.9838u	7.9885f
subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r33	2:r34	2:r35	2:r36	2:r37	2:r46
r value	100.0000	100.0000	100.0000	1.0000k	1.0000k	3.0000k
v drop	−899.9100u	899.9100u	−8.9379n	99.9511u	99.9510u	−1.2000
current	−8.9991u	8.9991u	−89.3786p	99.9511n	99.9510n	−399.9978u
power	8.0984n	8.0984n	7.989e−19	9.9902p	9.9902p	479.9947u
subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r47	2:r59	2:r60	2:r62	2:r74	2:r75
r value	3.0000k	1.8700	1.8700	10.0000k	1.0000x	1.0000g
v drop	−1.2000	−1.7443m	−1.7443m	299.9988n	−664.6727m	−22.4978u
current	−399.9979u	−932.7860u	−932.7857u	29.9999p	−664.6727n	−22.4978f
power	479.9950u	1.6271u	1.6271u	8.9999a	441.7899n	5.061e−19
subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r76	2:r77	2:r78	2:r79	2:r83	2:r127
r value	1.0000g	1.0000g	1.0000g	1.0000g	1.0000g	1.000e+12
v drop	80.9919u	−429.0174p	0.	−2.6337n	89.3876u	29.9999
current	80.9919f	−4.290e−19	0.	−2.6337a	89.3876f	29.9999p
power	6.5597a	1.841e−28	0.	6.936e−27	7.9901a	899.9926p
subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r128	2:r129	2:r130	2:r131	2:r132	2:r133
r value	1.000e+12	1.000e+12	1.000e+12	10.0000k	1.0000x	1.000e+12
v drop	−29.9999	877.9142p	877.8809p	−17.9949	−3.0000u	−999.9959m
current	−29.9999p	8.779e−22	8.779e−22	−1.7995m	−3.0000p	−999.9959f
power	899.9926p	0.	0.	32.3815m	8.9999a	999.9918f
subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r136	2:r137	2:r138	2:r139	2:r140	2:r141
r value	1.0000x	1.0000x	1.0000x	1.0000x	1.0000x	1.0000x
v drop	−8.9998	−930.7178u	−8.3763m	−9.0002	−930.7175u	−8.3766m
current	−8.9998u	−930.7178p	−8.3763n	−9.0002u	−930.7175p	−8.3766n
power	80.9966u	866.2356f	70.1621p	81.0034u	866.2350f	70.1680p

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r142	2:r143	2:r156	2:r157	2:r165	2:r166
r value	700.0000m	700.0000m	700.0000m	700.0000m	1.0000x	8.4000x
v drop	5.8634m	5.8634m	5.8636m	5.8636m	−157.7526	−8.9945
current	8.3763m	8.3763m	8.3766m	8.3766m	−157.7526u	−1.0708u
power	49.1135u	49.1135u	49.1176u	49.1176u	24.8859m	9.6311u

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r167	2:r169	2:r172	2:r173	2:r174	2:r175
r value	100.0000k	1.0000x	1.0000x	1.0000x	10.0000k	100.0000x
v drop	−17.9999	−178.1633m	142.1569	142.1569	1.2734k	5.4677m
current	−179.9986u	−178.1633n	142.1569u	142.1569u	127.3447m	54.6765p
power	3.2400m	31.7422n	20.2086m	20.2086m	162.1668	298.9525f

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r176	2:r177	2:r178	2:r180	2:r181	2:r182
r value	10.0000k	1.0000x	100.0000k	1.0000x	1.0000x	10.0000k
v drop	−38.2810	−15.7753	−17.9986	142.1569	142.1569	1.2734k
current	−3.8281m	−15.7753u	−179.9857u	142.1569u	142.1569u	127.3447m
power	146.5436m	248.8588u	3.2395m	20.2086m	20.2086m	162.1667

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r183	2:r184	2:r185	2:r186	2:r187	2:r188
r value	10.0000k	100.0000x	1.0000x	1.0000x	1.0000g	1.0000g
v drop	−38.2810	−17.8164	51.2644m	−28.7081	−53.9672	1.2892k
current	−3.8281m	−178.1637n	51.2644n	−28.7081u	−53.9672n	1.2892u
power	146.5436m	3.1742u	2.6280n	824.1542u	2.9125u	1.6621m

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r189	2:r190	2:r195	2:r196	2:r199	2:r201
r value	1.0000g	1.0000g	1.0000g	1.0000x	400.0000k	100.0000k
v drop	−53.9672	1.2892k	−999.9959m	664.6727m	−6.0648u	−2.1018u
current	−53.9672n	1.2892u	−999.9959p	664.6727n	−15.1620p	−21.0180p
power	2.9125u	1.6621m	999.9918p	441.7899n	91.9548a	44.1755a

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r302	2:r304	2:r305	2:r308	2:r309	2:r314
r value	3.0000	1.0000x	1.0000x	1.0000g	1.0000g	1.0000g
v drop	961.1648p	−450.6727m	−610.6727m	−664.6700m	−664.6700m	−1.0098
current	320.3883p	−450.6727n	−610.6727n	−664.6700p	−664.6700p	−1.0098n
power	3.079e−19	203.1059n	372.9212n	441.7862p	441.7862p	1.0198n

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:r315	2:r316	2:r317	2:r318	2:r319	2:r320
r value	1.0000g	10.0000m	10.0000m	10.0000	10.0000	2.0000k
v drop	714.1168m	−9.9793u	−9.9793u	189.3445u	−189.3445u	600.7575p
current	714.1168p	−997.9276u	−997.9276u	18.9344u	−18.9345u	300.3787f
power	509.9628p	9.9586n	9.9586n	3.5851n	3.5851n	1.805e−22

```
subckt    xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:r321      2:r325      2:r326      2:r327      2:r328      2:r329
 r value     2.0000g     1.0000g     1.0000g   1.000e+12   1.000e+12   1.000e+12
 v drop   -189.3451u    63.9158m    63.9158m   189.3445u    63.7264m   -64.1051m
 current   -94.6725f    63.9158p    63.9158p   189.3445a    63.7264f   -64.1051f
 power      17.9258a     4.0852p     4.0852p   3.585e-20     4.0611f     4.1095f

subckt    xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:r330      2:r331      2:r332      2:r333      2:r334      2:r335
 r value   1.000e+12     1.0000x     1.0000x     1.0000x     1.0000x     1.0000g
 v drop     63.9158m    49.2645m   -28.1300     -2.9193u    49.2645m    49.2645m
 current    63.9158f    49.2645n   -28.1300u    -2.9193p    49.2645n    49.2645p
 power       4.0852f     2.4270n   791.2983u     8.5224a     2.4270n     2.4270p

subckt    xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:r336      2:r337      2:r339      2:r340      2:r341      2:r342
 r value   1.000e+12     1.0000g     1.0000g     1.0000g     4.4000k     4.4000k
 v drop     -1.7300   -786.3470m   999.9959m    -4.1110u   1.694e-21     0.
 current    -1.7300p  -786.3470p   999.9959p    -4.1110f   3.850e-25     0.
 power       2.9930p   618.3416p   999.9918p   1.690e-20     0.          0.

subckt    xbuffer     xbuffer
element   2:r343      2:r344
 r value   200.0000     1.000e+12
 v drop      0.          8.1104
 current     0.          8.1104p
 power       0.         65.7785p


**** voltage-controlled current sources


subckt      xopamp1     xopamp1     xbuffer     xbuffer     xbuffer     xbuffer
element   1:ga        1:gcm       2:g2        2:g11       2:g14       2:g16
 v drop    -31.2227n    31.2227n  -199.9021u    18.0000     16.9902     28.9208
 current    -2.8863n    -2.8866n    0.          5.3174m   799.9967u    -8.3763m



subckt      xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:g17       2:g19       2:g20       2:g21       2:g22       2:g23
 v drop     28.9209   -189.3445u   189.3445u   189.3451u     8.2309      8.2312
 current    -8.3766m    18.9344u   -18.9344u  -395.0513f   999.9959u   999.9959u



subckt      xbuffer     xbuffer     xbuffer
element   2:g35       2:g36       2:g37
 v drop    -10.5635u   189.3387u     7.3237
 current   346.0043p   346.0043p   493.3189p
```

**** voltage-controlled voltage sources

subckt	xopamp1	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	1:egnd	2:e53	2:e56	2:e75	2:e2	2:e3
volts	0.	8.3763m	8.3766m	664.6700m	−9.0000	9.0000
current	−579.1247n	−8.3763n	−8.3766n	−1.3293n	5.7556m	−5.7567m

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:e4	2:e5	2:e6	2:e7	2:e10	2:e11
volts	0.	9.0000	−9.0000	89.3876u	429.0174p	−80.9919u
current	−320.3883p	−8.9991u	8.9991u	−89.3786p	−322.7545p	−322.6735p

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:e12	2:e14	2:e17	2:e18	2:e20	2:e48
volts	22.4978u	9.0000	−10.5635u	189.3387u	302.6325n	29.9999
current	−350.0267p	6.3668p	99.9510n	−99.9511n	−29.9999p	−29.9999p

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:e49	2:e50	2:e51	2:e52	2:e54	2:e55
volts	−29.9999	999.9959m	930.7178u	8.9998	930.7175u	9.0002
current	29.9999p	−999.9959p	−930.7178p	−8.9998u	−930.7175p	−9.0002u

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:e63	2:e64	2:e65	2:e66	2:e67	2:e68
volts	157.7526	1.2892k	53.9672	15.7753	1.2892k	53.9672
current	−157.7526u	−127.3460m	−3.8282m	−15.7753u	−127.3460m	−3.8282m

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:e69	2:e76	2:e79	2:e80	2:e81	2:e83
volts	28.7081	54.0000m	−63.9158m	−63.9158m	189.3445u	−63.9158m
current	16.7242m	−1.3293u	70.8895p	71.1899p	−568.0321a	136.8112f

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer

```
element   2:e84       2:e93       2:e94       2:e95       2:e96
 volts      63.9158m    28.1300    -49.2645m -999.9959m     0.
 current  -137.1899f   -28.1300u    50.4538p  999.9918p     0.




**** current-controlled current sources


  subckt    xopamp1
element   1:fb
 current    -2.4059u




**** current-controlled voltage sources


subckt      xopamp1
element   1:hlim
 volts       4.6812u
 current    -9.3624a




**** diodes


subckt      xopamp1     xopamp1     xopamp1     xopamp1     xopamp1     xbuffer
element   1:dc        1:de        1:dlp       1:dln       1:dp        2:d5
model     1:dx        1:dx        1:dx        1:dx        1:dx        2:dd
 id       -800.0000a -800.0000a -800.0000a -800.0000a -800.0000a  -10.0000f
 vd         -7.8000    -8.1000    -40.0000    -40.0000    -18.0000    -8.9998
 req         0.          0.          0.          0.          0.          0.
 cap         0.          0.          0.          0.          0.          0.



subckt      xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:d6        2:d7        2:d8        2:d9        2:d10       2:d11
model     2:dd        2:din       2:din       2:dvn       2:dvn       2:dd
 id       -10.0000f   100.0000u   100.0000u   100.0000u   100.0000u  -10.0000f
 vd         -9.0002   591.5766m   591.5766m   709.8919m   709.8919m   -9.0000
 req         0.        256.9184    256.9184    256.9184    256.9184     0.
 cap         0.          0.          0.          0.          0.          0.
```

```
subckt      xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:d12       2:d13       2:d19       2:d24       2:d25       2:d26
model     2:dd        2:dd        2:dd        2:dd        2:dd        2:dd
 id        -10.0000f   559.6927f   997.6093u   -9.9902f    127.3447m   -10.0000f
 vd         -9.0000    103.8596m   650.6727m  -178.0257m   775.2600m   -30.7753
 req          0.        45.0977g    25.7534    2.625e+15   201.7504m     0.
 cap          0.          0.          0.          0.          0.          0.


subckt      xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:d27       2:d28       2:d29       2:d30       2:d31       2:d32
model     2:dd        2:dd        2:dd        2:dd        2:dd        2:dd
 id          3.9703m   -10.0000f    -9.9897f   127.3447m   -10.0000f     3.9703m
 vd        686.1590m   -30.6862   -176.7305m   775.2600m   -30.7753    686.1590m
 req         6.4711      0.        2.496e+15   201.7504m     0.          6.4711
 cap         0.          0.          0.          0.          0.          0.


subckt      xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:d33       2:d34       2:d36       2:d37       2:d38       2:d39
model     2:dd        2:dd        2:dd        2:dd        2:dd        2:dd
 id        -10.0000f     1.0001m   559.6927f   -10.0000f   -10.0000f     1.0000m
 vd        -30.6862    650.7356m   103.8596m    -6.9637     -7.2641    650.7342m
 req         0.          25.6905     45.0977g     0.          0.          25.6918
 cap         0.          0.          0.          0.          0.          0.


subckt      xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:d40       2:d41       2:d44       2:d45       2:d46
model     2:dd        2:dd        2:dd        2:dd        2:dd
 id         -9.1691f    -9.1691f     1.0000m   -10.0000f     1.0000m
 vd        -63.9158m   -63.9158m   650.7355m    -1.1793    650.7355m
 req       3.091e+13   3.091e+13    25.6906      0.         25.6906
 cap         0.          0.          0.          0.          0.


**** bipolar junction transistors


subckt      xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
element   2:q20       2:q15       2:q21       2:q22       2:q23       2:q24
model     2:qnl       2:qpl       2:qno       2:qpo       2:qpo       2:qno
 ib        -99.9297a    99.9297a     2.0683u    -2.0683u    -2.2127u     2.2127u
 ic        207.0251a  -207.0251a   930.7178u  -930.7174u  -995.7149u   995.7149u
```

```
 vbe          1.7443m    -1.7443m   767.2049m  -767.2049m  -768.9392m   768.9392m
 vce        665.0896m  -665.0896m     8.9980     -8.9984     -9.7691      9.7687
 vbc       -663.3453m   663.3453m    -8.2308      8.2311      9.0002     -8.9998
 vs        -665.2790m     1.5550m    -8.9999   768.7599m  -189.3445u     -9.0000
 power      137.5160a  137.5160a     8.3762m     8.3765m     9.7290m      9.7286m
 betad       -2.0717    -2.0717    450.0000    450.0000    450.0000     450.0000
 gm            4.0150f    4.0150f   36.2262m    36.2262m    38.7561m     38.7561m
 rpi        2.400e+16  2.400e+16    12.4220k    12.4220k    11.6111k     11.6111k
 rx            0.         0.          0.          0.          0.           0.
 ro         6.633e+15  6.633e+15  8.230e+16   8.231e+16   9.000e+16    8.999e+16
 cpi           0.         0.          0.          0.          0.           0.
 cmu           0.         0.          0.          0.          0.           0.
 cbx           0.         0.          0.          0.          0.           0.
 ccs           0.         0.          0.          0.          0.           0.
 betaac     96.3812    96.3812    450.0000    450.0000    450.0000     450.0000
 ft         615.0100m  615.0100m  5.765e+12   5.765e+12   6.168e+12    6.168e+12



**** jfets


subckt       xopamp1     xopamp1
element    1:j1        1:j2
model      1:jx        1:jx
 ids        -80.2858u   -80.2887u
 igs          2.5000f     2.5000f
 igd          2.5000f     2.5000f
 vgs        718.0588m   718.0537m
 vds         -8.0820     -8.0820
 gm         569.8061u   569.8163u
 gmbs          0.          0.
 gds           0.          0.
 cgs           0.          0.
 cgd           0.          0.




**** jfets


subckt       xbuffer     xbuffer     xbuffer     xbuffer
element    2:j1        2:j2        2:j3        2:j4
model      2:jc        2:jc        2:jc        2:jc
 ids           0.          0.          0.          0.
 igs        -10.0000f   -10.0000f   -10.0000f   -10.0000f
 igd        -10.0000f   -10.0000f   -10.0000f   -10.0000f
 vgs         -9.0000     -8.9998     -6.0002     -6.0000
```

vds	0.	0.	0.	0.
gm	0.	0.	0.	0.
gmbs	0.	0.	0.	0.
gds	0.	0.	0.	0.
cgs	0.	0.	0.	0.
cgd	0.	0.	0.	0.

**** mosfets

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:m4	2:m5	2:m19	2:m23	2:m41	2:m42
model	2:pin	2:pin	2:pin	2:pin	2:psw	2:nsw
region	Saturati	Saturati	Saturati	Saturati	Cutoff	Cutoff
id	−399.9978u	−399.9979u	−799.9957u	−799.9957u	0.	0.
ibs	0.	0.	0.	0.	−6.834e−26	3.417e−26
ibd	92.7479f	92.7479f	57.2442f	10.0984f	8.779e−28	−1.756e−27
vgs	−1.4746	−1.4746	−1.0098	−1.0098	14.9999	−14.9999
vds	−9.2748	−9.2748	−5.7244	−1.0098	−2.6337n	2.6337n
vbs	0.	0.	0.	0.	−1.7558n	877.8809p
vth	−700.0000m	−700.0000m	−700.0000m	−700.0000m	−7.5000	7.5000
vdsat	−774.5945m	−774.5946m	−309.8378m	−309.8378m	0.	0.
vod	−774.5945m	−774.5946m	−309.8378m	−309.8378m	22.4999	−22.4999
beta	1.3333m	1.3333m	16.6667m	16.6667m	20.0000m	13.3333m
gam eff	527.6252m	527.6252m	527.6252m	527.6252m	527.6252m	527.6252m
gm	1.0328m	1.0328m	5.1640m	5.1640m	0.	0.
gds	0.	0.	0.	0.	0.	0.
gmb	357.8116u	357.8116u	1.7891m	1.7891m	0.	0.
cdtot	256.2188a	256.2188a	7.9069f	1.3949f	5.4119a	3.6080a
cgtot	14.2030f	14.2030f	714.7019f	708.1899f	77.7088f	51.8059f
cstot	13.8126f	13.8126f	690.6322f	690.6322f	7.6669a	5.1113a
cbtot	134.1841a	134.1841a	16.1628f	16.1628f	77.6957f	51.7972f
cgs	13.8126f	13.8126f	690.6322f	690.6322f	7.6669a	5.1113a
cgd	256.2188a	256.2188a	7.9069f	1.3949f	5.4119a	3.6080a

subckt	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer	xbuffer
element	2:m43	2:m44	2:m45	2:m46	2:m57	2:m58
model	2:nen	2:nen	2:pen	2:pen	2:pin	2:nin
region	Linear	Cutoff	Saturati	Linear	Linear	Cutoff
id	1.7995m	0.	−199.2845n	−111.8745p	−1.2489u	0.
ibs	0.	0.	0.	0.	0.	0.
ibd	−5.142e−21	−1.000e−18	7.141e−19	3.963e−24	54.7162a	−179.9453f
vgs	18.0000	5.1421m	−714.1168m	−714.1168m	−17.8218	178.1633m
vds	5.1421m	999.9970m	−714.1168m	−3.9630u	−5.4716m	17.9945

```
   vbs          0.          0.          0.          0.          0.          0.
   vth      500.0000m   500.0000m  -700.0000m  -700.0000m  -700.0000m   700.0000m
   vdsat      5.1421m          0.  -14.1168m    -3.9630u    -5.4716m          0.
   vod       17.5000   -494.8579m  -14.1168m   -14.1168m   -17.1218   -521.8367m
   beta      20.0000m   200.0000m    2.0000m     2.0000m    13.3333u    13.3333u
   gam eff  527.6252m   527.6252m  527.6252m   527.6252m   527.6252m   527.6252m
   gm       102.8429u          0.   28.2336u     7.9260n    72.9549n          0.
   gds      349.8971m          0.          0.   28.2257u   228.2182u          0.
   gmb       35.6300u          0.    9.7816u     2.7460n    25.2753n          0.
   cdtot    155.3770f   160.9680a   118.3661a    17.1484f   414.3352a   1.835e-19
   cgtot    310.8758f     1.1798p   101.7454f    56.5375f   829.0074a    80.4062a
   cstot    155.4075f    80.4842f    82.8759f    20.6378f   414.4235a     5.0985a
   cbtot     91.2860a     1.0992p    18.7512f    18.7512f   2.488e-19    75.1243a
   cgs      155.4075f    80.4842f    82.8759f    20.6378f   414.4235a     5.0985a
   cgd      155.3770f   160.9680a   118.3661a    17.1484f   414.3352a   1.835e-19



 subckt    xbuffer     xbuffer     xbuffer     xbuffer     xbuffer     xbuffer
 element   2:m59       2:m64       2:m65       2:m66       2:m67       2:m68
 model     2:nin       2:nin       2:nin       2:nin       2:pin       2:pin
 region       Linear      Linear      Cutoff      Cutoff      Linear   Saturati
  id       179.9986u   179.9857u          0.          0.   455.1435p   -49.7054n
  ibs          0.          0.          0.          0.          0.          0.
  ibd       -1.3753a   -14.3277a  -179.9999f  -180.0000f  -154.4637a    7.8635f
  vgs      157.7526     15.7753    178.1633m   178.1633m  -786.3470m  -786.3470m
  vds      137.5325u     1.4328m     18.0000     18.0000   393.8120u  -786.3470m
  vbs          0.          0.          0.          0.          0.          0.
  vth      700.0000m   700.0000m   700.0000m   700.0000m  -699.8636m  -700.0000m
  vdsat    137.5325u     1.4328m          0.          0.  -393.8120u   -86.3470m
  vod      157.0526     15.0753   -521.8367m  -521.8367m   -86.4835m   -86.3470m
  beta       8.3333m     8.3333m    26.6667u   133.3333u    13.3333u    13.3333u
  gam eff  527.6252m   527.6252m  527.6252m   527.6252m   527.6252m   527.6252m
  gm         1.1461u    11.9397u          0.          0.     5.2508n     1.1513u
  gds        1.3088    125.6152m          0.          0.     1.1531u          0.
  gmb      397.0685n     4.1365u          0.          0.     1.8198n   398.8663n
  cdtot     64.7468f    64.7447f   3.671e-19     1.8354a   372.5983a   8.689e-19
  cgtot    129.4978f   129.5377f   160.8126a   804.0630a   780.5999a   593.4781a
  cstot     64.7468f    64.7488f    10.1969a    50.9845a   368.0871a   552.5058a
  cbtot      4.2425a    44.1455a   150.2486a   751.2430a    39.9145a    40.1034a
  cgs       64.7468f    64.7488f    10.1969a    50.9845a   368.0871a   552.5058a
  cgd       64.7468f    64.7447f   3.671e-19     1.8354a   372.5983a   8.689e-19



 ******


  ******  ac analysis tnom=  25.000 temp=  25.000 *****
x
```

freq	gain
1.00000	−5.7199
1.25893	−3.7272
1.58489	−1.7388
1.99526	242.8905m
2.51189	2.2141
3.16228	4.1688
3.98107	6.0980
5.01187	7.9880
6.30957	9.8193
7.94328	11.5646
10.00000	13.1893
12.58925	14.6538
15.84893	15.9208
19.95262	16.9652
25.11886	17.7824
31.62278	18.3904
39.81072	18.8229
50.11872	19.1199
63.09573	19.3182
79.43282	19.4482
100.00000	19.5322
125.89254	19.5860
158.48932	19.6203
199.52623	19.6420
251.18864	19.6555
316.22777	19.6639
398.10717	19.6688
501.18723	19.6713
630.95734	19.6719
794.32823	19.6708
1.00000k	19.6678
1.25893k	19.6621
1.58489k	19.6526
1.99526k	19.6373
2.51189k	19.6129
3.16228k	19.5744
3.98107k	19.5140
5.01187k	19.4199
6.30957k	19.2748
7.94328k	19.0543
10.00000k	18.7262
12.58925k	18.2521
15.84893k	17.5929
19.95262k	16.7179
25.11886k	15.6143
31.62278k	14.2924
39.81072k	12.7813

```
   50.11872k      11.1193
   63.09573k       9.3446
   79.43282k       7.4891
  100.00000k       5.5766
  125.89254k       3.6227
  158.48932k       1.6361
  199.52623k    -380.5306m
  251.18864k      -2.4303
  316.22777k      -4.5223
  398.10717k      -6.6724
  501.18723k      -8.9037
y

          ***** job concluded
1****** HSPICE -- D-2010.03-SP1 32-BIT (May 27 2010) linux ******
 ******


  ******  job statistics summary tnom=  25.000 temp=  25.000 *****


 ******  Machine Information  ******
 CPU:
 model name      : Dual-Core AMD Opteron(tm) Processor 2220
 cpu MHz         : 2814.498

 OS:
 Linux version 2.6.18-348.6.1.el5 (mockbuild@builder10.centos.org) (gcc
     version
 4.1.2 20080704 (Red Hat 4.1.2-54)) #1 SMP Tue May 21 15:29:55 EDT 2013


  ******  HSPICE Threads Information  ******

  Command Line Threads Count                  :      1
  Available CPU Count                         :      4
  Actual Model Evaluation(Load) Threads Count :      1
  Actual Solver Threads Count                 :      1


  ******  Circuit Statistics  ******
  # nodes       =     154 # elements   =     318
  # resistors   =     116 # capacitors =      30 # inductors   =       0
  # mutual_inds =       0 # vccs       =      15 # vcvs        =      41
  # cccs        =       1 # ccvs       =       1 # volt_srcs   =      34
  # curr_srcs   =      15 # diodes     =      35 # bjts        =       6
  # jfets       =       6 # mosfets    =      18 # U elements  =       0
  # T elements  =       0 # W elements =       0 # B elements  =       0
  # S elements  =       0 # P elements =       0 # va device   =       0
```

```
******  Runtime Statistics (seconds)  ******

analysis            time    # points   tot. iter  conv.iter
op point            0.05           1         516
ac analysis         0.01          58          58
readin              0.02
errchk              0.00
setup               0.00
output              0.00


          total memory used          722  kbytes
          total cpu time            0.08 seconds
          total elapsed time        0.28 seconds
          job started at      23:20:31 05/03/2014
          job ended   at      23:20:32 05/03/2014


lic: Release hspice token(s)
```