ECE 304: Computer Lab Project 1

“Classic” Common Emitter Amplifier Design

ECE 304: Computer Lab Project 1

"Classic" Common Emitter Amplifier Design[1]

Schematic

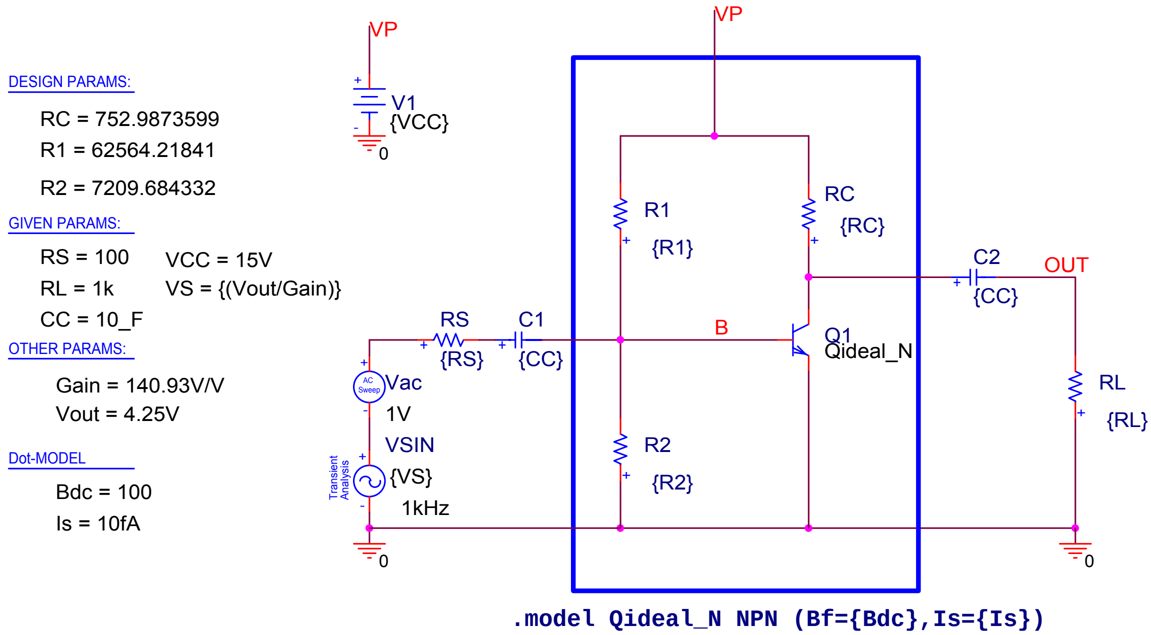


FIGURE 1

Common emitter amplifier with potentiometer bias resistors R_1 and R_2

Figure 1 shows a common emitter amplifier (inside the box). The amplifier is connected to a voltage driver that can be either the small-signal source V_{AC} or the large-signal sinusoidal source V_{SIN} of amplitude V_S. The small-signal source is selected by PSPICE automatically (and the large-signal source disabled) if an AC SWEEP/NOISE simulation profile is run. The large-signal source is chosen (and the small-signal source disabled) if a TRANSIENT simulation profile is run.

The amplifier also is connected to a load resistor of size R_L.

Both driver and load are connected via large coupling capacitors, chosen to have the unrealistically large value of 10F. In PSPICE we use 10_F, and not 10F, because PSPICE interprets 10F as 10f = 10 *femto*farads. We choose a very large value for the capacitance because we are not interested at the moment in the low-frequency response of the amplifier. A value of 10F insures that these capacitors are short-circuits for AC frequencies of interest (for example, for frequencies above 1 Hz).

Design goal

We want to develop a combined PSPICE / EXCEL design tool that will allow us to determine the appropriate values of the circuit components R_1, R_2 and R_C when we are given some combination of desired circuit properties, or specifications (specs), such as those listed under SPECIFICATIONS below.

Specifications

We are given the load resistance R_L = 1 kΩ, the source resistance R_S = 100 Ω, a requirement for a maximum transient output voltage swing of V_{out} = 5 V, and a request for a maximum compatible small-signal voltage gain A_υ.

[1]For some other details on using these programs, see Low-pass Filter Design using PSPICE with EXCEL and WORD on the Web Page at http://www.ece.arizona.edu/~ece304/UserManuals/Appendices.pdf

Deliverables

1. Hand analysis for values of R_1, R_2 and R_C
2. Spreadsheet incorporating the hand analysis
3. PSPICE verification of the spreadsheet
4. Report describing the above items using template Lab.dot

Procedure

To set up the design tool, we first do hand analysis to determine formulas for the various quantities that are specified. For example, we find the swing limitations and the small-signal gain.

Next we set up a spreadsheet that incorporates these equations, and that plots the dependence of the possible specs against the variables under our control. These graphs are used to pick off the necessary values of R_1, R_2 and R_C based upon the specs.

Next, we implement the given specs, determine the corresponding R_1, R_2 and R_C, and copy these values from the spreadsheet into the PSPICE circuit shown in Figure 1. Then we run PSPICE and see if the specs are really met. If they are, our spreadsheet is working. If they are not, we have to decide where the discrepancy comes from.

We use an *ideal* transistor in PSPICE so we know that any discrepancies do not come from the transistor model used in PSPICE: the spreadsheet and PSPICE use the same transistor model. That means any error comes either from entry errors like mistyping a formula or from some algebraic error, or from a basic misconception in our analysis: for example, the circuit is not placing the transistor in active mode, or we do not understand the large-signal swing limitations.

Hand analysis

1. For good gain we want the input resistance R_{IN} of the amplifier to be large to obtain a favorable value for the input divider $R_{IN}/(R_S+R_{IN})$
2. For good gain we also want the output resistance of the amplifier to be as low as possible, so we get a good value for the output divider $R_L/(R_L+R_C)$
3. We assume that the transistor can support a forward bias in saturation of $\upsilon_{CB} = -V_{SAT} = -400\text{mV}$ without causing clipping of the signal.
4. We want as big a small-signal voltage gain A_υ as is compatible with the other specifications.
5. We interpret the output swing as a downswing of V_{out} = 5V. We will take whatever upswing we happen to get. See the swing analysis below for an explanation of why upswing and downswing will not be the same.

APPROXIMATE SWING ANALYSIS

If the base voltage under the influence of an AC signal changes by the AC voltage υ_b, then the collector current will change to the value ι_C below.

EQ. 1

$$\iota_C = I_S\, e^{(V_B+\upsilon_b)/V_{TH}} = I_C e^{\upsilon_b/V_{TH}},$$

where I_C = Q-point collector current. The transient collector current is then

EQ. 2

$$\iota_{ac} = I_C\left(e^{\upsilon_b/V_{TH}} - 1\right).$$

Consequently the transient variation in output voltage at the collector is

EQ. 3

$$\iota_{ac}(R_C // R_L) = I_C(R_C // R_L)\left(e^{\upsilon_b/V_{TH}} - 1\right).$$

Consequently the downswing in output voltage, which occurs when $\upsilon_b = V_s$, say, and the upswing in output voltage, which occurs when $\upsilon_b = -V_s$, say[2], are in the ratio given by

[2] It is an approximation to assume the base goes up and down by the same voltage V_s.

EQ. 4

$$\frac{V_{down}}{V_{up}} = \frac{\left(e^{V_s / V_{TH}} - 1\right)}{\left(1 - e^{-V_s / V_{TH}}\right)} = e^{V_s / V_{TH}} .$$

For an undistorted output signal, we want $V_{up} \approx V_{down}$, or an up/down ratio as close to 1 as possible. To keep the up/down ratio near 1 requires a small V_S. For a selected <u>out</u>put swing, the larger the gain, the smaller V_s will be. Because the gain cannot be made extremely large, we may not be able to stay in the small-signal regime and still have an output swing of the specified V_{out} = 5V. If we need an input V_S of more than a fraction of V_{TH}, the downswing will be considerably larger than the upswing.

HAND ANALYSIS ADAPTED TO SPREADSHEET USE

The design requires values for R_1, R_2 and R_C. If we do hand analysis by itself, we have to solve for all the resistor values explicitly. We also have to find the maximum gain.

When we use a spreadsheet, we proceed differently. We select an independent variable: say the Q-point collector current I_C. We make a list of values of I_C the first column of the spreadsheet. Then we find the Q-point V_{BE} in terms of I_C as the next column. Then we find the transistor input resistance r_π in terms of I_C as the next column, and so forth. That is, each column is a simple step in the solution, rather than a lot of algebra to find explicit expressions for each resistor.

Once the spreadsheet is constructed, we can scan down the gain column and find the maximum gain.

CHOICE OF VARIABLES

The circuit itself involves three variables: R_1, R_2 and R_C. We are free to choose any values for any of these resistors. However, the resulting circuit will not necessarily satisfy the specifications. That is, there are only some particular values of R_1, R_2 and R_C that result in a satisfactory circuit. Moreover, to meet the circuit specifications, it may be that a change in one of the variables R_1, R_2 and R_C implies sympathetic changes in the others: the variables R_1, R_2 and R_C are interrelated by the specifications: the variables R_1, R_2 and R_C are <u>not</u> independent.

In the course of hand analysis we can see which variables make a good choice for interpreting the design. These variables, which we will call the <u>design</u> variables, are not necessarily the values of the circuit components R_1, R_2 and R_C. The choice of design variables is not unique, and may include some of the circuit component values like R_1, R_2 and R_C. However, a happy choice of design variables can simplify the understanding of the circuit and the organization of the spreadsheet.

It has been suggested above that the Q-point collector current I_C is a good choice for a design variable. We also will see that the Q-point current I_2 in resistor R_2 is a good design variable. Because the specification for maximum gain determines the value of I_C, we find that, in fact, I_2 is the <u>only</u> independent design variable.

ANALYSIS

Many bipolar parameters depend upon the Q-point collector current I_C, so this seems a likely variable choice. We propose to make I_C the first column in the spreadsheet. For convenience, we make the first column I_C in mA, and convert it to units of A in the second column. Given I_C we can find the Q-point base voltage as $V_B = V_{BE}$ given by the diode law as

EQ. 5

$$V_{BE} = V_{TH}\, \ell n(I_C/I_S),$$

with I_S = bipolar scale current, found from the bipolar dot-model statement in Figure 1, and V_{TH} = thermal voltage, $V_{TH} = k_BT/q \approx 25.86$ mV.

The output downswing is V_{out}, and the transistor will saturate unless $\upsilon_{CB} > -V_{SAT}$. The collector voltage with the AC downswing is $\upsilon_C = V_O - V_{out}$. The base voltage is $V_B + V_b \approx V_B + V_{out}/G$, where G is approximately the small-signal gain V_{out}/V_b and V_b is the transient increase in base voltage due to the signal. Therefore, the condition that the transistor does not go too far into saturation is

EQ. 6

$$\upsilon_{CB} = -V_{SAT} = V_O - V_{out} - V_B - V_{out}/G \rightarrow V_O = V_{out}(1+1/G) + V_B - V_{SAT}.$$

At the moment, we do not know the value of G. However, G is large, so in this column of the spreadsheet we neglect the term in G to obtain a first approximation to V_O, say V_{O1} given by

EQ. 7

$$V_{O1} = V_{out} + V_B - V_{SAT}.$$

Given V_{O1}, we find the first approximation to the collector resistance using Ohm's law:

EQ. 8

$$R_{C1} = (V_{CC} - V_{O1})/I_C.$$

EQ. 8 is an estimate for one of the three resistor values. We turn to the other two values R_1 and R_2. As we know $V_B = V_{BE}$, we can find R_2 from Ohm's law as

EQ. 9

$$R_2 = V_{BE}/I_2.$$

We do not know the Q-point current I_2 in R_2, which becomes a <u>second</u> design variable. From Kirchhoff's current law at the base, we find R_1 as

EQ. 10

$$R_1 = (V_{CC} - V_{BE})/(I_2 + I_C/\beta).$$

We now turn attention to the small-signal voltage gain. From a small-signal analysis, we find the gain G to be

EQ. 11

$$G \equiv \frac{V_{out}}{V_b} = -\left(\frac{I_C R_C}{V_{TH}}\right)\left(\frac{R_L}{R_C + R_L}\right).$$

In EQ. 11 the leading factor is the maximum gain G_{MAX} possible with this amplifier, found when $R_L \rightarrow \infty$, given in EQ. 12.

EQ. 12

$$G_{MAX} = -\left(\frac{I_C R_C}{V_{TH}}\right)$$

The second factor in EQ. 11 is the output voltage divider made up of the amplifier output resistance R_C in series with the load resistance R_L. In the spreadsheet we use the magnitude of G to obtain a revised estimate of V_O. Let the first estimate of G be G_1 given by

EQ. 13

$$G_1 = -\left(\frac{I_C R_{C1}}{V_{TH}}\right)\left(\frac{R_L}{R_{C1} + R_L}\right).$$

Then the revised estimate of V_O is V_{O2} given by EQ. 6 as

EQ. 14

$$V_{O2} = V_{out}(1+1/G_1) + V_B - V_{SAT}.$$

The revised estimate of R_C is R_{C2} given by EQ. 8 as

EQ. 15

$$R_{C2} = (V_{CC} - V_{O2})/I_C.$$

The revised estimate of G is then G_2 given by EQ. 13 as

EQ. 16

$$G_2 = -\left(\frac{I_C R_{C2}}{V_{TH}}\right)\left(\frac{R_L}{R_{C2} + R_L}\right),$$

and so forth. We put in as many columns as it takes to get the correction in R_C to be negligible. Finally, we find the overall gain A_υ by putting in the input voltage divider as

EQ. 17

$$A_\upsilon \equiv \frac{V_{out}}{V_S} = -\left(\frac{R_{IN}}{R_{IN} + R_S}\right)\left(\frac{I_C R_{C2}}{V_{TH}}\right)\left(\frac{R_L}{R_{C2} + R_L}\right),$$

where the input resistance of the amplifier R_{IN} is found from small-signal analysis as

EQ. 18

$$R_{IN} = (R_1 // R_2 // r_\pi),$$

and r_π is given by

EQ. 19

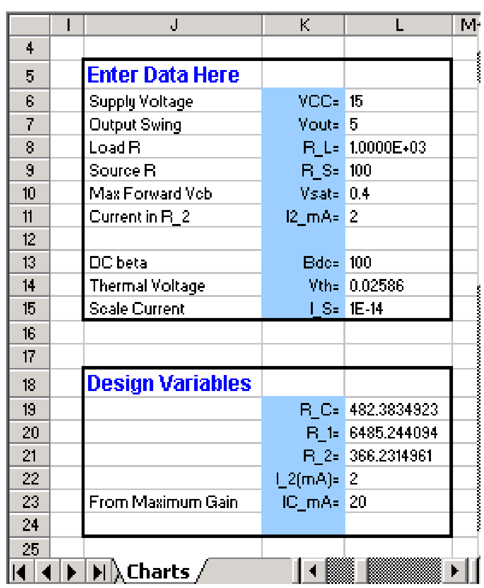
$$r_\pi = \frac{\beta V_{TH}}{I_C}.$$

Given the estimate of EQ. 16 for G, we find the approximate output upswing from EQ. 4 as [3]

EQ. 20

$$V_{up} \approx V_{down} \exp(-V_s/V_{TH}) \approx V_{out} \exp[-V_{out}/(GV_{TH})].$$

Spreadsheet construction



	I	J	K	L	M
4					
5		Enter Data Here			
6		Supply Voltage	VCC=	15	
7		Output Swing	Vout=	5	
8		Load R	R_L=	1.0000E+03	
9		Source R	R_S=	100	
10		Max Forward Vcb	Vsat=	0.4	
11		Current in R_2	I2_mA=	2	
12					
13		DC beta	Bdc=	100	
14		Thermal Voltage	Vth=	0.02586	
15		Scale Current	I_S=	1E-14	
16					
17					
18		Design Variables			
19			R_C=	482.3834923	
20			R_1=	6485.244094	
21			R_2=	366.2314961	
22			I_2(mA)=	2	
23		From Maximum Gain	IC_mA=	20	
24					
25					

FIGURE 2

The data entry box and design summary on the “Charts” worksheet

A general architecture for such spreadsheets uses a main data input worksheet that also contains any trade-off plots we want. We'll call this worksheet “Charts”. Most spreadsheets will have

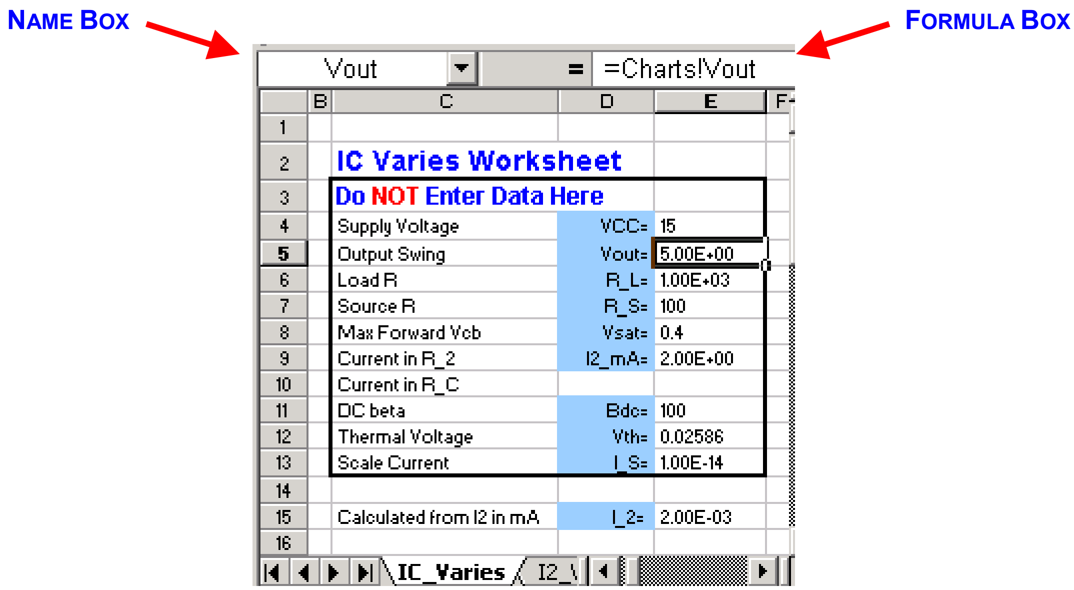
[3] An accurate analysis is described in Appendix 2.

several worksheets, and using only one data input sheet insures that all the worksheets are using the same data. Another advantage is that when data is input on “Charts”, we immediately see the change in the trade-off plots on the same worksheet, which makes it easy to evaluate the benefit of any change, and also avoids switching from one worksheet to another.

An example of the data input area on “Charts” is shown in Figure 2. The “design variables” feature of Figure 2 is described in Appendix 1.

THE “IC_VARIES” WORKSHEET

Besides “Charts” we will have a worksheet in which I_C varies, that is, I_C is a column variable. The data input to this worksheet is copied from “Charts”, as shown in Figure 3.



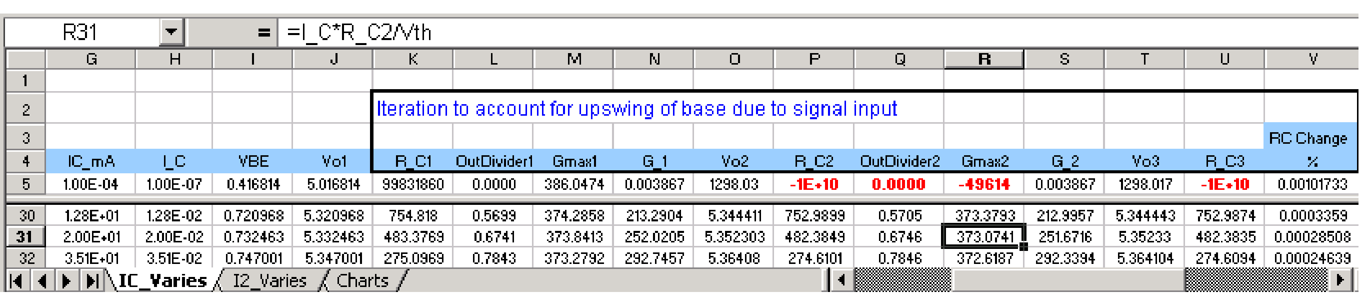
	B	C	D	E
1				
2		IC Varies Worksheet		
3		Do NOT Enter Data Here		
4		Supply Voltage	VCC=	15
5		Output Swing	Vout=	5.00E+00
6		Load R	R_L=	1.00E+03
7		Source R	R_S=	100
8		Max Forward Vcb	Vsat=	0.4
9		Current in R_2	I2_mA=	2.00E+00
10		Current in R_C		
11		DC beta	Bdc=	100
12		Thermal Voltage	Vth=	0.02586
13		Scale Current	I_S=	1.00E-14
14				
15		Calculated from I2 in mA	I_2=	2.00E-03
16				

FIGURE 3

Data input to the “IC_Varies” worksheet is copied from “Charts” as indicated for the variable V_{out} in the FORMULA BOX

The FORMULA BOX in Figure 3 shows that the value placed in E5 is taken from the cell named Vout on worksheet “Charts”. This method transfers data from the data-input worksheet “Charts” to this worksheet “IC_Varies”. The NAME BOX in Figure 3 shows that cell E5 has been named Vout on this worksheet. How to name cells is discussed shortly.

The worksheet “IC_Varies” also contains all the formulas of hand analysis already presented in the equations above. To capture the dependence of the various variables on I_C, variable I_C is made a column variable, and all variables that depend on I_C also are made column variables. The structure of the worksheet is shown in Figure 4 and Figure 5.



	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1																
2					Iteration to account for upswing of base due to signal input											
3																RC Change
4	IC_mA	I_C	VBE	Vo1	R_C1	OutDivider1	Gmax1	G_1	Vo2	R_C2	OutDivider2	Gmax2	G_2	Vo3	R_C3	%
5	1.00E-04	1.00E-07	0.416814	5.016814	99831860	0.0000	386.0474	0.003867	1298.03	-1E+10	0.0000	-49614	0.003867	1298.017	-1E+10	0.00101733
30	1.28E+01	1.28E-02	0.720968	5.320968	754.818	0.5699	374.2858	213.2904	5.344411	752.9899	0.5705	373.3793	212.9957	5.344443	752.9874	0.0003359
31	2.00E+01	2.00E-02	0.732463	5.332463	483.3769	0.6741	373.8413	252.0205	5.352303	482.3849	0.6746	373.0741	251.6716	5.35233	482.3835	0.00028508
32	3.51E+01	3.51E-02	0.747001	5.347001	275.0969	0.7843	373.2792	292.7457	5.36408	274.6101	0.7846	372.6187	292.3394	5.364104	274.6094	0.00024639

FIGURE 4

Column variables in the “IC_Varies” worksheet; the FORMULA BOX shows the second iteration of G_{MAX} from EQ. 12.

Negative entries have been flagged in red type using the menu FORMAT/CONDITIONAL FORMATTING, and filling out the resulting menu. How to do conditional formatting is shown shortly.

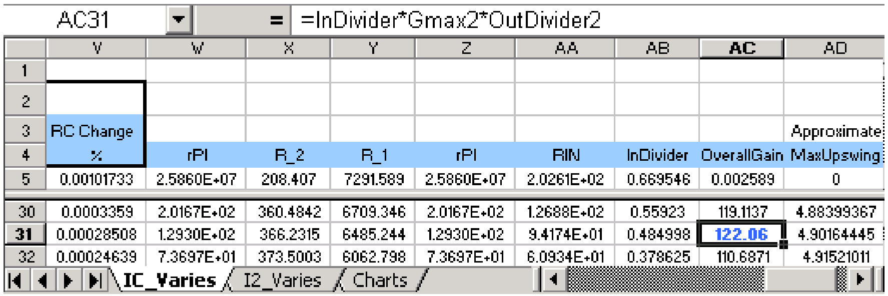


FIGURE 5

The other half of the "IC_Varies" column variables; the FORMULA BOX shows EQ. 17 for the overall small-signal voltage gain A_υ

NAMED VARIABLES

Named variables are used throughout the spreadsheet. By using NAMED variables, all formulas are shown in the FORMULA BOX in algebraic form, which makes it easy to check the results against the formulas from hand analysis. As an example of the utility of NAMED variables, in Figure 4 the formula for G_{MAX} is shown in the FORMULA BOX. This equation is easy to check against EQ. 12. Likewise, in Figure 5 the formula for the overall gain appears in the FORMULA BOX.

Here is an example of how to make NAMED variables. By highlighting the cells D5 and E5 in Figure 3 and using the menu INSERT/NAME/CREATE, we name cell E5 as Vout, as shown in the NAME BOX.

Column variables also can be named. Figure 6. shows naming of the column OVERALL GAIN. The entire column and its name are highlighted before selecting the menu.

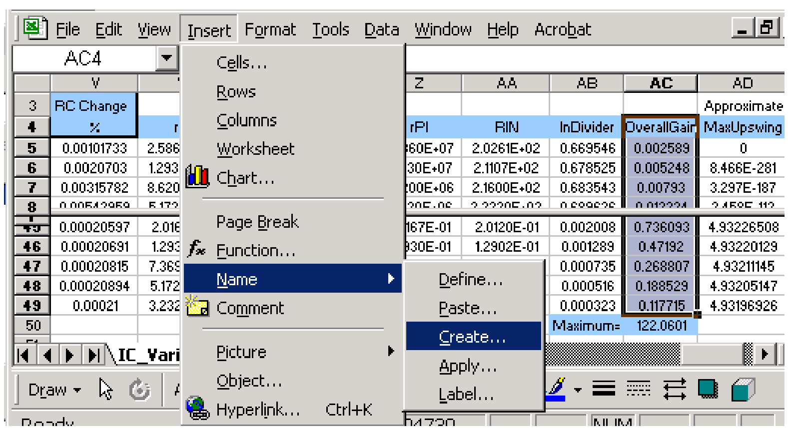


FIGURE 6

Naming the OVERALL GAIN column using INSERT/NAME/CREATE

Named variables also make it easy to make additional worksheets, for example an "I2_Varies" worksheet where I_2 is a variable instead of I_C. We simply use the EDIT/MOVE OR COPY SHEET menu to obtain the menu of Figure 7.

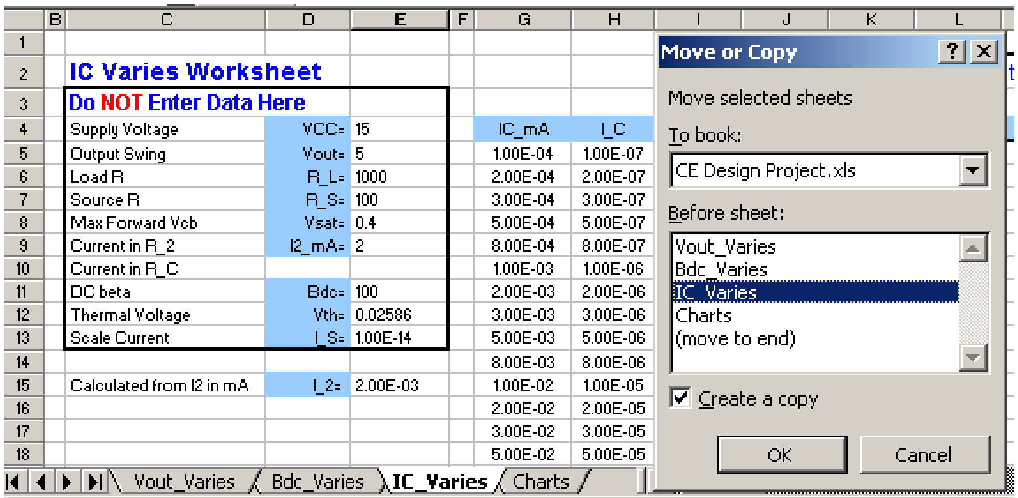


FIGURE 7

Checking the MAKE A COPY box creates a copy of the selected worksheet

The beauty of named variables when creating a new worksheet is that nothing has to be changed on the copy to convert from an I_C variable to an I_2 variable except the I_C(mA) column on "IC_Varies" is replaced with an I_2(mA) column on "I2_Varies".[4] This column is NAMED I2_mA, replacing the single-valued entry for I2_mA in Figure 3. Then the single-valued entry for I2_mA in Figure 3 is replaced by a single-valued entry for IC_mA, and NAMED IC_mA. See Figure 8 below.

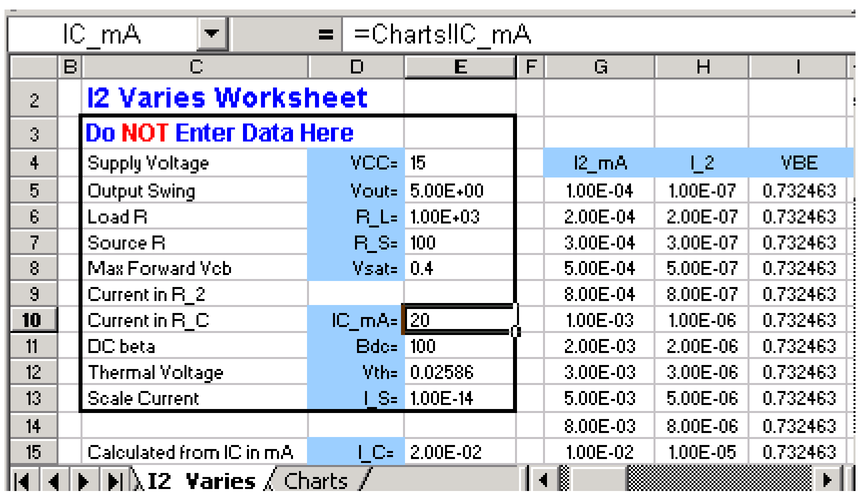


FIGURE 8

A worksheet with I_2 as a column variable instead of I_C

CONDITIONAL FORMATTING

In Figure 5 the maximum gain is automatically highlighted in bold blue font to make it easily identifiable in the GAIN column. To do this formatting, first the maximum number in the GAIN column is found using the EXCEL function MAX(), as shown in Figure 9.

[4] See Appendix 3 for more detailed instructions on creating the "I2_Varies" worksheet.

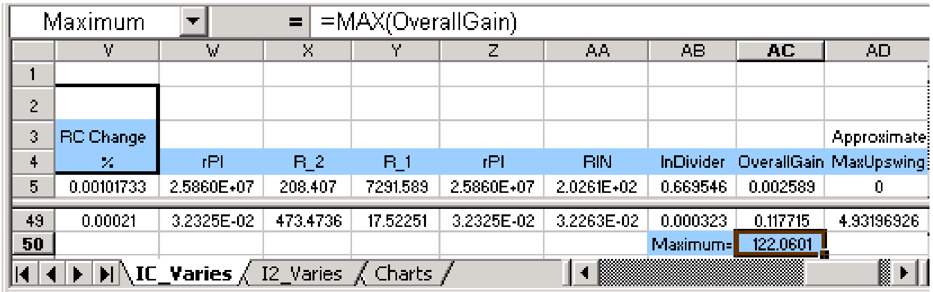


FIGURE 9

Finding the maximum gain in the OVERALL GAIN column using EXCEL function MAX(), as shown in the FORMULA Box.

The cell AC50 is named MAXIMUM, as shown in the NAME BOX. Because the OVERALL GAIN column has been named OVERALLGAIN, the argument of the function MAX() is shown in the FORMULA BOX as OverallGain: the argument of MAX() is the entire column. To cause the maximum gain to be highlighted in the GAIN column, we next highlight the entire gain column and select FORMAT/CONDITIONAL FORMATTING. We then fill out the menu as shown in Figure 10. As a result of the conditional formatting in Figure 10, when a cell in the OVERALL GAIN column contains a value equal to the maximum gain, its contents are formatted as indicated in the FORMAT box in Figure 10.

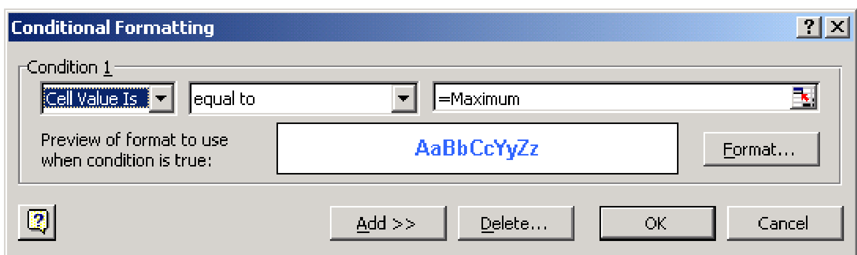


FIGURE 10

Formatting the GAIN column to bold-face the maximum gain in the column in blue font

CHARTS

The “Charts” worksheet also has plots of three circuit variables of some interest to the designer. These charts are shown in Figure 11.

The top panel in Figure 11 shows the overall gain as function of I_C. A maximum is evident. The middle panel shows the estimated maximum upswing at the output, as approximated by EQ. 20. The bottom panel shows the input and output voltage divider ratios as a function of I_C, demonstrating that they have opposite tendencies: the input divider goes down with I_C, while the output divider goes up.

Perhaps you did not expect to see a peak in the overall gain. But now the chart has brought this to your attention, it requires explanation, which will increase your understanding of the circuit. The bottom panel showing opposite trends of the dividers provides a clue: the product of these two factors will show a peak, and as the overall gain involves this product, we suspect the opposite trends of the two dividers lead to the peak in the gain in the top panel of Figure 11. It remains to understand just why the dividers behave oppositely.

In general, understanding the trends of the trade-off curves is a big step toward understanding the circuit behavior.

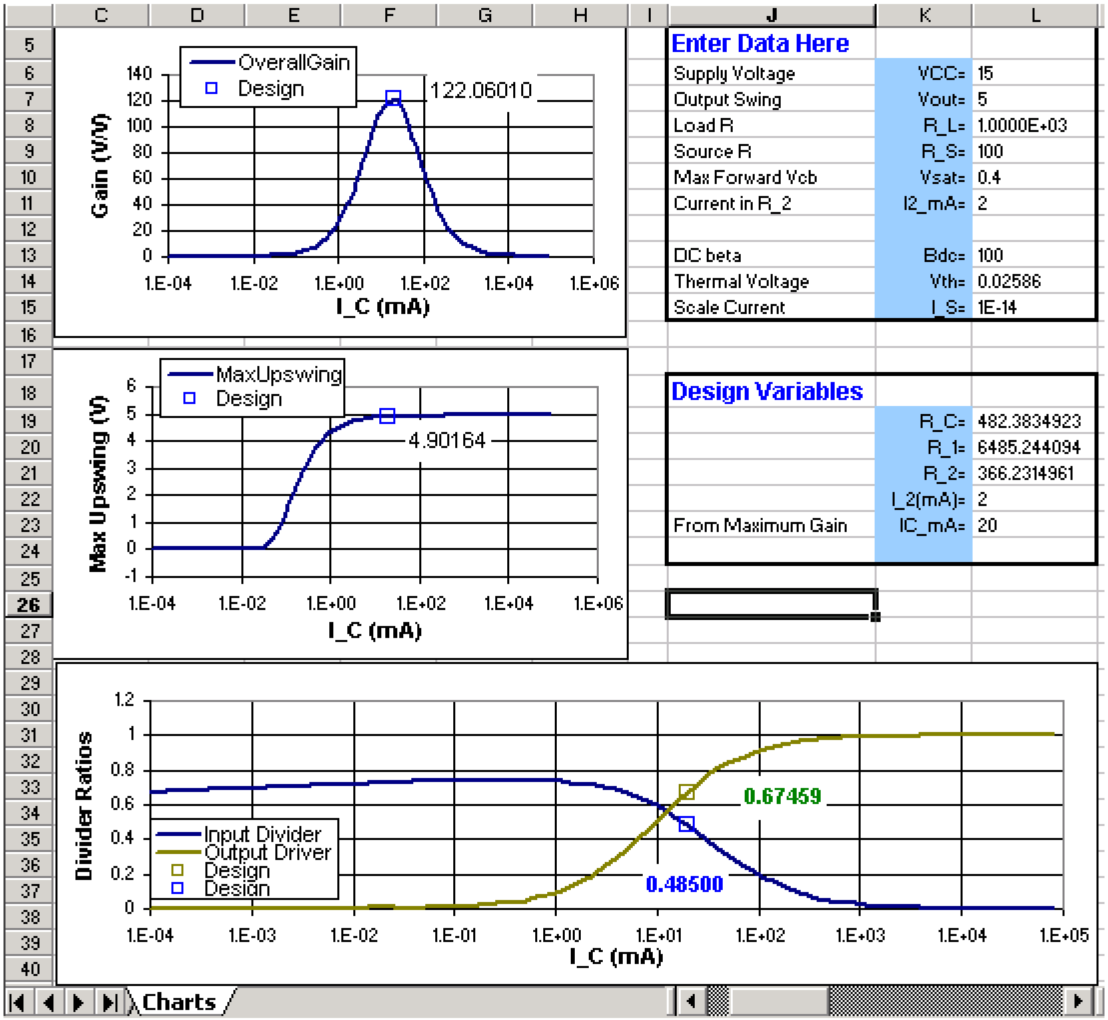


FIGURE 11

Charts displayed in the “Charts” worksheet

Selecting the design

As pointed out in connection with EQ. 4, the least distortion will result if the gain is maximized. A large gain is also one of the specifications. Therefore, we choose the design with the maximum gain in Figure 11. This choice determines I_C. At this point the only unspecified variable is I_2, the current in R_2. We can explore the effect of I_2 on the design by typing different values of I_2 into the Data Input box on “Charts”, shown in Figure 2. Alternatively, we can add an additional worksheet “I2_Varies” and look at the trade-off curves as a function of I_2.[5] Example charts are shown in Figure 12.

[5] See Appendix 3 for details.

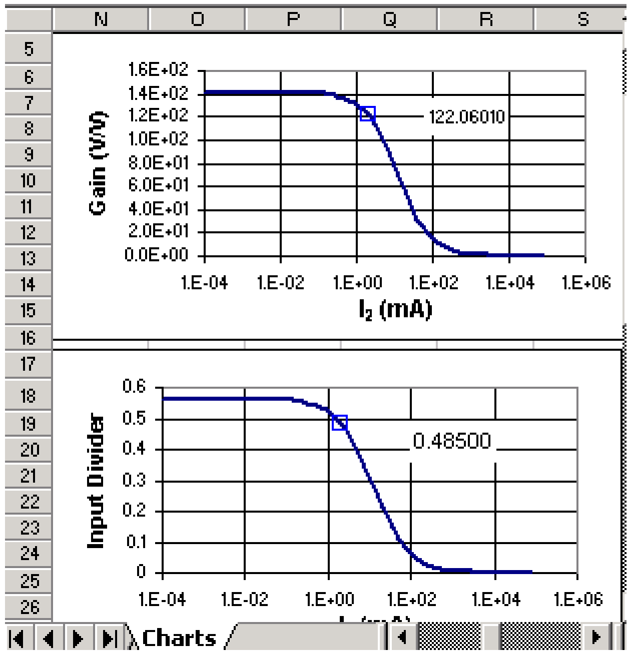


FIGURE 12

Trade-off charts from a second worksheet, I2-Varies

From the top panel in Figure 12 it appears that a low value of I_2 is advantageous. The selected design is fairly high up the trade-off curve (the design marker is near the top of the gain curve), but we might ask what happens if we go higher. It is easy to generate such a design, just type in a different value for I_2. Decreasing I_2 to 0.1 mA results instantly in the design shown in Figure 13.

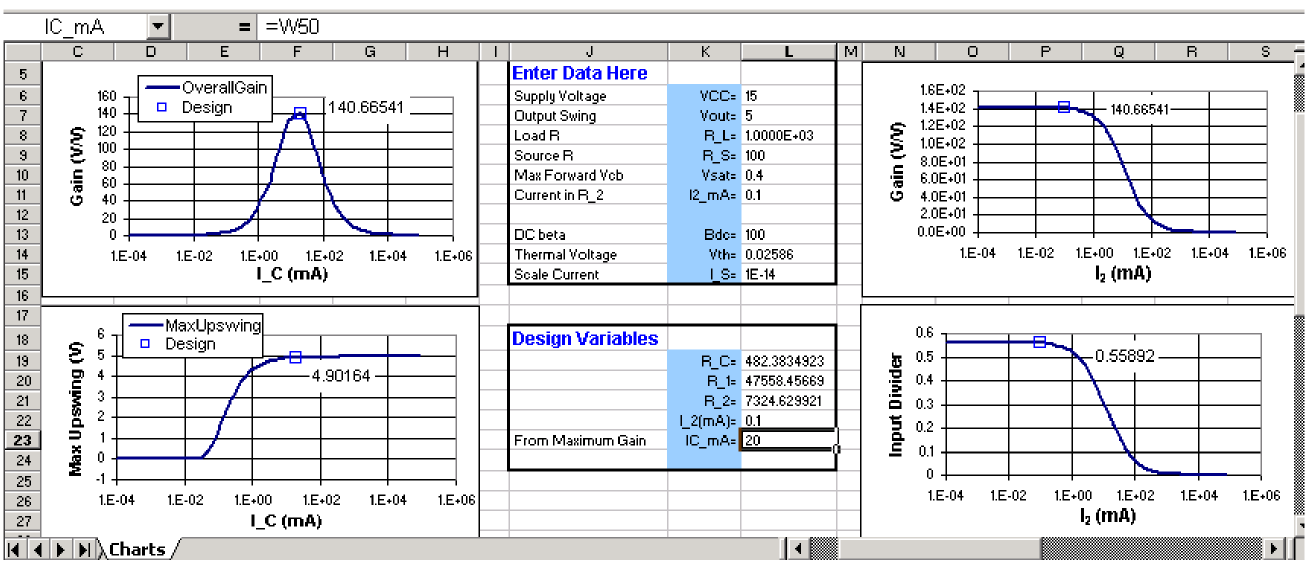


FIGURE 13

Design with a modified I_2 = 0.1 mA

It is clear that a higher gain results for the lower value of I_2.

SOLVER

This design can be optimized further using the EXCEL tool SOLVER. Going to the worksheet "IC_Varies", we select the cell with maximum gain. Then we use the menu selection TOOLS/SOLVER to obtain the menu in Figure 14.

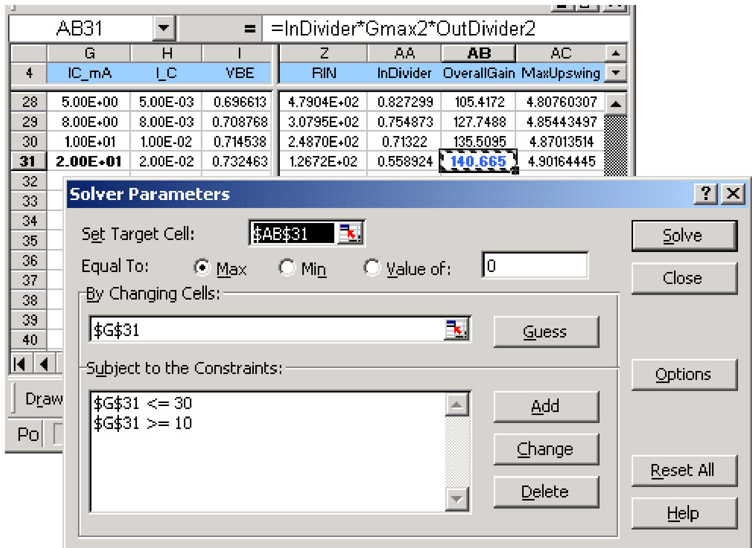
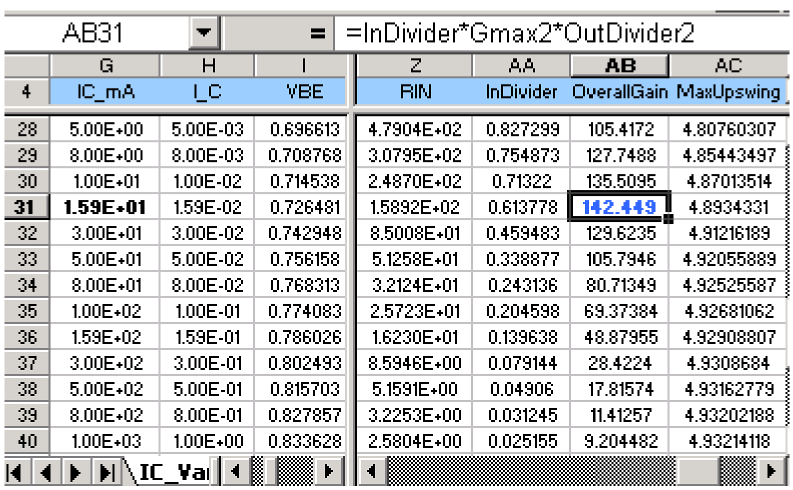


FIGURE 14

Using SOLVER to maximize the gain

In Figure 14 the TARGET CELL is the gain cell AB31. SOLVER is instructed to maximize this cell by changing the collector current cell G31. SOLVER also has been instructed to search only in the region near the present maximum by the constraints 10 mA ≤ I_C ≤ 30mA. The result of running SOLVER is shown in Figure 15.



AB31 =InDivider*Gmax2*OutDivider2

	G	H	I	Z	AA	AB	AC
4	IC_mA	I_C	VBE	RIN	InDivider	OverallGain	MaxUpswing
28	5.00E+00	5.00E-03	0.696613	4.7904E+02	0.827299	105.4172	4.80760307
29	8.00E+00	8.00E-03	0.708768	3.0795E+02	0.754873	127.7488	4.85443497
30	1.00E+01	1.00E-02	0.714538	2.4870E+02	0.71322	135.5095	4.87013514
31	**1.59E+01**	1.59E-02	0.726481	1.5892E+02	0.613778	142.449	4.8934331
32	3.00E+01	3.00E-02	0.742948	8.5008E+01	0.459483	129.6235	4.91216189
33	5.00E+01	5.00E-02	0.756158	5.1258E+01	0.338877	105.7946	4.92055889
34	8.00E+01	8.00E-02	0.768313	3.2124E+01	0.243136	80.71349	4.92525587
35	1.00E+02	1.00E-01	0.774083	2.5723E+01	0.204598	69.37384	4.92681062
36	1.59E+02	1.59E-01	0.786026	1.6230E+01	0.139638	48.87955	4.92908807
37	3.00E+02	3.00E-01	0.802493	8.5946E+00	0.079144	28.4224	4.9308684
38	5.00E+02	5.00E-01	0.815703	5.1591E+00	0.04906	17.81574	4.93162779
39	8.00E+02	8.00E-01	0.827857	3.2253E+00	0.031245	11.41257	4.93202188
40	1.00E+03	1.00E+00	0.833628	2.5804E+00	0.025155	9.204482	4.93214118

FIGURE 15

SOLVER solution: the maximum gain for I_2 = 0.1 mA occurs for I_C = 15.9 mA where the gain is 142.4 V/V

The resulting design summary from "Charts" is shown in Figure 16 below.

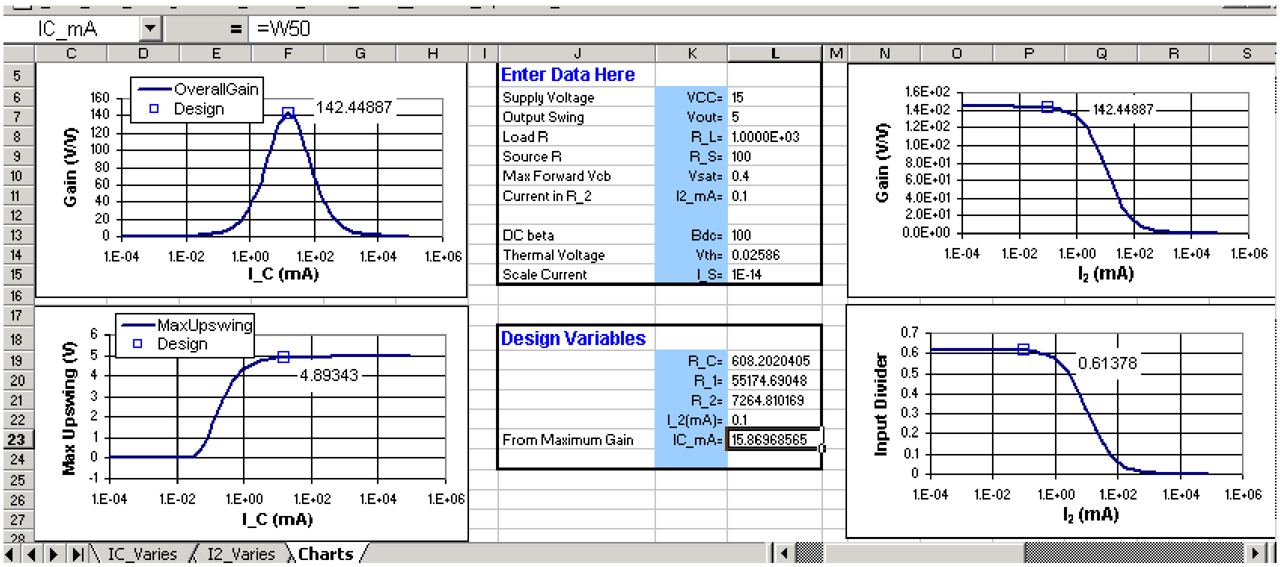


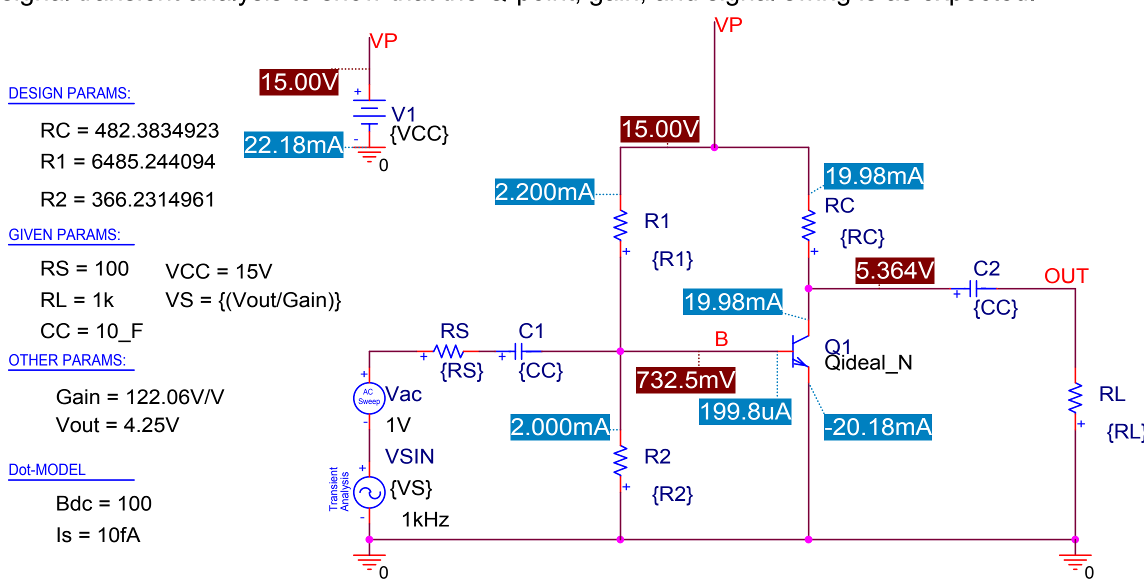
FIGURE 16

Optimized design for I_2 = 0.1 mA

Compared to the design for I_2 = 2 mA, this design for I_2 = 0.1mA has higher gain and a lower value of I_C =15.9 mA, which will lead to lower power consumption. It would appear that this design is better than the earlier design with I_2 = 2 mA. A decision between these designs could be based upon power consumption, distortion, β-sensitivity or some other criterion that has not been brought up yet.

PSPICE verification

The spreadsheet is verified by pasting the resistor values from the spreadsheet into the schematic of Figure 1, running a Q-point, running a small-signal gain plot, and running a large-signal transient analysis to show that the Q-point, gain, and signal swing is as expected.




```
.model Qideal_N NPN (Bf={Bdc},Is={Is})
```

FIGURE 17

Q-point schematic from a BIAS simulation profile showing the Q-point output voltage is 5.364 V compared to the spreadsheet value of 5.352V; the base voltage of 732.5 mV compared to the spreadsheet value of 732.5 mV and a current I_C = 19.98 mA, compared to the spreadsheet value of I_C =20 mA

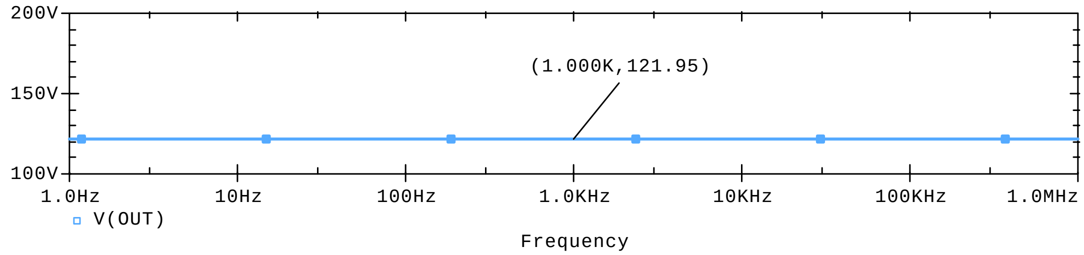


FIGURE 18

Small-signal gain plot from an AC SWEEP/NOISE simulation profile showing overall gain of 121.95 V/V, compared to spreadsheet value of 122.06 V/V

Figure 18 shows the small-signal gain from PSPICE agrees with the spreadsheet. Figure 19 below shows that the downswing of 5V is realized before the saturation of the transistor causes clipping (flat-bottoming) of the output waveform. Figure 20 shows the output for the second design with I_2 = 0.1 mA. There is a slightly better up/down ratio (less distortion) in this design.

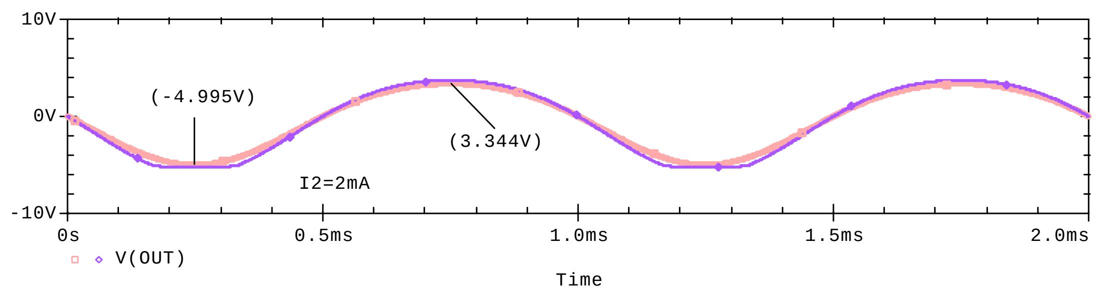


FIGURE 19

Large-signal transient plot from a TIME DOMAIN (TRANSIENT) simulation profile showing downswing of –5V is realized for V_S = 34.4 mV; clipping occurs for a larger input signal, V_S = 40 mV

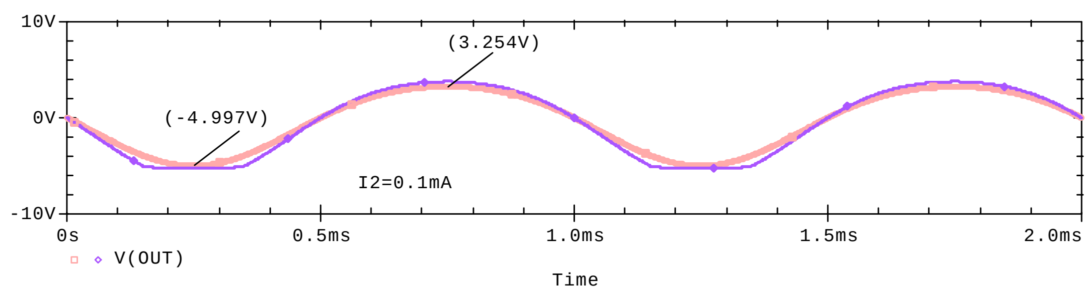


FIGURE 20

Output from a TIME DOMAIN (TRANSIENT) simulation profile for the lower I_2 = 0.1 mA design; V_S = 29.1 mV; clipping for V_S = 36 mV

However, Figure 19 and Figure 20 show that the maximum output upswing is only $V_{up} \approx$ 3.3V, compared to an anticipated upswing of 4.9V from the spreadsheet. We explore this discrepancy by looking at the base voltage.[6]

[6] A more accurate upswing approach is described in Appendix 2.

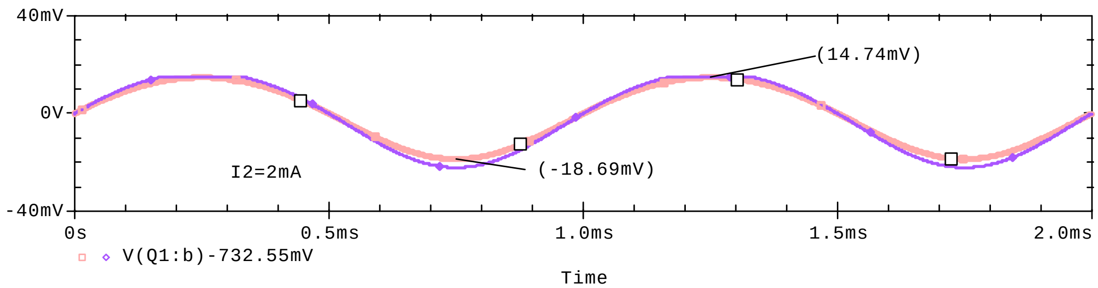


FIGURE 21

Base voltage variation from a TIME DOMAIN (TRANSIENT) simulation profile shows a gain of 339 V/V on the upswing of the base (downswing of the output), and 174V/V on the downswing of the base, compared to G = 252 V/V from the spreadsheet

Comparison of Figure 19 with Figure 21 shows that the gain is larger on the downswing of the output, as might be expected since the maximum gain varies as $G_{MAX} = \iota_C R_C / V_{TH}$, so the gain is larger when the $\iota_C R_C$ drop is greater, that is, on the downswing of the output. The approximate swing analysis of EQ. 20 ignores this fact.

Advantages of using EXCEL with PSPICE

Combining EXCEL with PSPICE has several advantages:

1. No matter how good we are at algebra, there is a suspicion in our minds that some errors could have been made. Putting our analysis into the spreadsheet and checking it with PSPICE tests our formulation very easily to be sure it is working, or over what range of values it is working. Knowing our formulation is correct is real empowerment: we know we can explore this design!!
2. If errors do crop up, our attention is immediately focused upon what is wrong with our concept of how the circuit works. This focus on concept is much more fruitful (and faster) than making trial-and-error adjustments directly in PSPICE. Finding a conceptual error is an expansion of understanding; finding some accidental numerical “fix” by tinkering in PSPICE does nothing for understanding.
3. We can change the specs, and the spreadsheet effortlessly and immediately generates R_1, R_2 and R_C values; allowing immediate generation of the PSPICE crosscheck. The ease of the procedure encourages exploration for as wide a range of cases we might like to attempt.
4. We obtain immediate assessment of trade-off changes when parameter values are changed, because the graphs in EXCEL are immediately updated. Seeing the graphs can alert us to important circuit behavior we might otherwise not notice. For this example, the peak in gain has been discussed.
5. We can use the spreadsheet tools as well as the PSPICE tools. We have used SOLVER to optimize the gain in the example here.
6. The spreadsheet can be used in conjunction with PSPICE to treat real transistors. We plug the real transistors into PSPICE and read out the transistor variables we need for the spreadsheet from the PSPICE output file, for example, the values of β and r_π. These PSPICE results are input to the spreadsheet, leading to new spreadsheet values for R_1, R_2 and R_C. A few iterations and we have a spreadsheet consistent with PSPICE. Any unfixable inconsistencies teach us that some facet of the real circuit has escaped our analysis. For example, maybe an approximation neglecting output resistance is too coarse, or our calculations of small-signal parameters are inaccurate.

Summary

A design tool has been developed that makes resistor selection for the circuit of Figure 1 easy. The tool also shows the gain and signal-swing design trade-offs involved in this selection, so it is clear what direction the design must go to meet gain and swing specifications. Understanding these trade-off curves leads to understanding of how the circuit works.

Assignment

Construct the above spreadsheet (don't bother with the I_2-worksheet). Do the design for an output downswing of V_{out} = 8V and a series resistance of R_S = 20 Ω. Use I_2 = 1 mA, and optimize I_C using SOLVER. Resistor R_L is unchanged. Make a report, following the instructions below.

REPORT

The report is made using the template Lab.dot available on the class web page. Headings, subheadings, figure captions, and all other formats are done as described in the instructions on the template.

A DERIVATIONS section should include derivations of the above formulas, including EQ. 12. If you need sketches of the circuit, you can paste hand drawings, or you can use the schematic editor in PSPICE and annotate using WORD. PSPICE output is copied by computer into the report along with screenshots of the spreadsheet. There are keyboard shortcuts in the template to do this.

A DESCRIPTION section should describe your spreadsheet. Show all figures needed to document the spreadsheet and PSPICE simulations that verify it, but drop the purely explanatory stuff. It should be possible for someone already familiar with EXCEL and PSPICE, but not with the CE amplifier, to duplicate your work using your report.

A DISCUSSION section should explain the trends of the trade-off curves in Figure 11 and Figure 13. Why is there a maximum in overall gain as a function of I_C? Why the opposite trends in divider ratios as a function of I_C? Why the monotonic increase in maximum swing with I_C? Why the drop in gain with I_2? And so forth.

A SUMMARY section should be included recapitulating the final values for the resistors and tabulating the comparisons between the specifications, spreadsheet values and PSPICE values. Comment on the origins of any discrepancies, and the adequacy of the hand analysis for this case.

Appendix 1: Design summary on "Charts" worksheet

It is perfectly feasible to read the resistor values off the "IC_Varies" worksheet that correspond to the maximum gain. However, it is a nice addition to have the selected design point displayed on the charts of Figure 11, and to have the resistor values summarized in the "Design Variables" box of the "Charts" worksheet in Figure 2 for convenient pasting into PSPICE.

These features of "Charts" can be obtained using a Visual Basic program in EXCEL. However, here we describe a different approach that does not require Visual Basic. Instead, we create a "Design Report" section of "Charts", as shown in Figure 22.

Y31 = =IF(X31=Maximum,IC_Varies!AB31,0)

	W	X	Y	Z	AA	AB	AC	AD	AE
2	Design Report from Other Worksheets								
3			Gain	Max					
4	IC_mA	Gain	Design	UpSwing	R_C3	R_1	R_2	OutDivider2	InDivider
31	20	1.22E+02	122.0600957	4.901644	482.3835	6485.244	366.2315	0.674588646	0.484998
32	0	1.15E+02	0	0	0	0	0	0	0
33	0	9.71E+01	0	0	0	0	0	0	0
34	0	7.59E+01	0	0	0	0	0	0	0
35	0	6.59E+01	0	0	0	0	0	0	0
36	0	3.93E+01	0	0	0	0	0	0	0
37	0	2.79E+01	0	0	0	0	0	0	0
38	0	1.76E+01	0	0	0	0	0	0	0
39	0	1.13E+01	0	0	0	0	0	0	0
40	0	9.15E+00	0	0	0	0	0	0	0
41	0	4.66E+00	0	0	0	0	0	0	0
42	0	3.13E+00	0	0	0	0	0	0	0
43	0	1.88E+00	0	0	0	0	0	0	0
44	0	1.18E+00	0	0	0	0	0	0	0
45	0	9.44E-01	0	0	0	0	0	0	0
46	0	4.72E-01	0	0	0	0	0	0	0
47	0	3.14E-01	0	0	0	0	0	0	0
48	0	1.89E-01	0	0	0	0	0	0	0
49	0	1.18E-01	0	0	0	0	0	0	0
50	20		122.0600957	4.901644	482.3835	6485.244	366.2315	0.674588646	0.484998
51	Maximum	1.22E+02	Gain	Swing	RC	R1	R2	OutDivider(rev)	InDivider

Charts

FIGURE 22

Design report section of "Charts" worksheet

The GAIN column in Figure 22 copies the GAIN column from the worksheet "IC_Varies". At the bottom of this column, the maximum gain is found using EXCEL function MAX(), and named MAXIMUM. In the GAIN DESIGN column an IF() statement is used to print only the maximum gain, and zeros otherwise. Likewise, in all the other columns, the only entry printed from worksheet "IC_Varies" is the entry corresponding to the maximum gain. At the bottom of each column, a sum is made of the entire column using the EXCEL function SUM(), which simply is a device to get all the entries corresponding to the maximum gain in the same row, Row 50.

Now we use Row 50 in two ways. First, we report the values for the resistors back to the DESIGN VARIABLE box on "Charts", as shown in Figure 23.

IC_mA = =W50

	I	J	K	L
17				
18		Design Variables		
19			R_C=	482.3834923
20			R_1=	6485.244094
21			R_2=	366.2314961
22			I_2(mA)=	2
23		From Maximum Gain	IC_mA=	20
24				
25				

Charts

FIGURE 23

Value of IC_mA is copied into the Design Variables summary from cell W50 in Figure 22

The same is done for the other entries in the “Design Variables” box.

The second use of Row 50 in Figure 22 is to put a boxed point on the trade-off curves corresponding to the design in the “Design Variables” box. The point is added simply by plotting the point in Row 50 that belongs on the chart. An example is shown in Figure 24 for the gain plot.

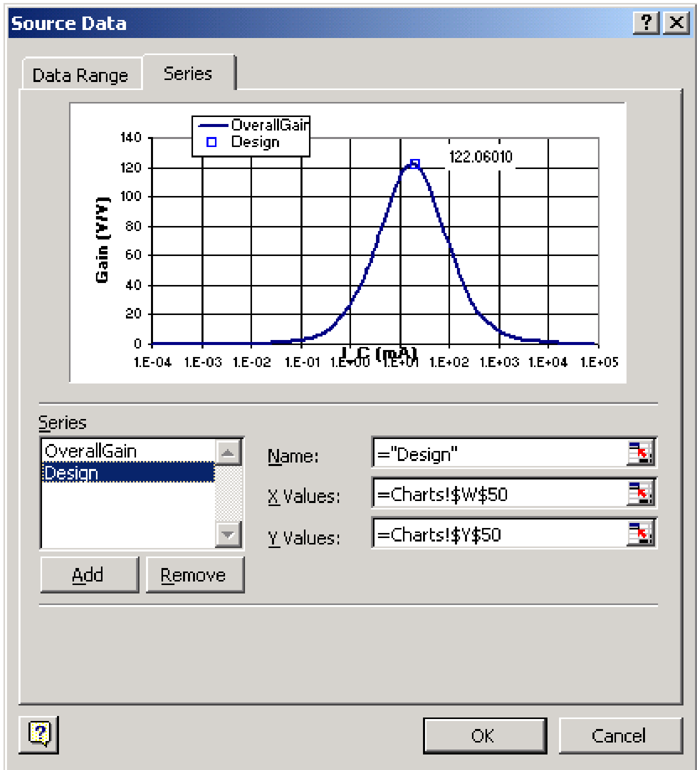


FIGURE 24

Adding the boxed point for the selected design to the gain chart

The added point can then be formatted as a box. Simply right click on the point and format it as shown in Figure 25.

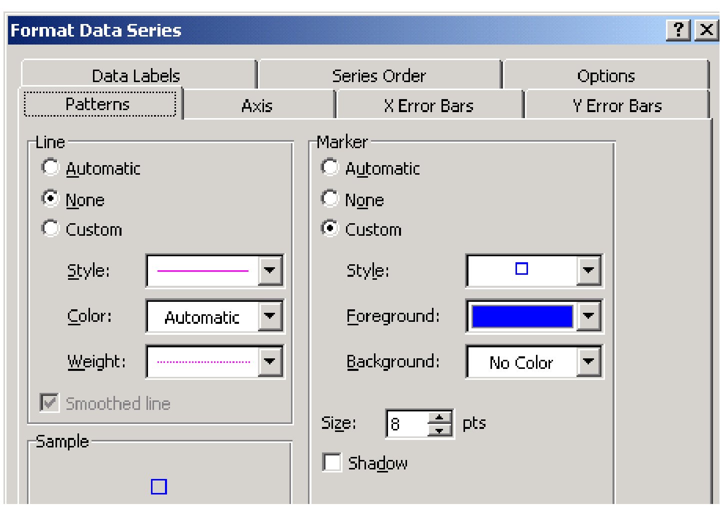


FIGURE 25

Formatting the symbol for the displayed point in the gain plot

The DATA LABELS tab allows attachment of a tag to the design point that displays its numerical value.

Appendix 2: Improved upswing analysis

The upswing analysis based upon EQ. 20 is not accurate. If we want to design the circuit based on both upswing and downswing behavior, we need a better estimate. A better estimate is found here using the large-signal relationships for current. On the downswing of the output node, the diode law gives the transient collector current ι_C in terms of the transient portion of the base voltage V_b as

EQ. 21

$$\iota_C = I_C\left(e^{V_b / V_{TH}} - 1\right),$$

and this transient current flows through the coupling capacitors (which are short circuits for transient current) and through R_C and R_L in parallel. Therefore, the downward output swing is

EQ. 22

$$V_{out} = \iota_C(R_C//R_L).$$

EQ. 21 and EQ. 22 combine to relate V_b to the given output downswing V_{out} as

EQ. 23

$$V_{out} = I_C\left(e^{V_b / V_{TH}} - 1\right)(R_C // R_L).$$

EQ. 23 can be rearranged as EQ. 24 to find the base swing V_b that produces an output downswing V_{out}, namely

EQ. 24

$$V_b = V_{TH}\ \ell n[1+V_{out}/(I_C(R_C//R_L)].$$

where V_{out} is given by the swing specification of the circuit. For the output downswing V_{out}, we need a specific input signal V_S. From Kirchhoff's current law at the base we find

EQ. 25

$$V_S = R_S(V_b/(R_S//R_1//R_2) + I_b),$$

where I_b is the upswing in base current given by EQ. 21 and the transistor β as

EQ. 26

$$I_b = \left(\frac{I_C}{\beta}\right)\left(e^{V_b / V_{th}} - 1\right).$$

Given V_b from EQ. 24, and I_b from EQ. 26, with EQ. 25 we can find V_S.

Knowing V_S, we now can find the output upswing. We apply a negative signal of size V_S, and find the corresponding downward base swing as V_u, say[7]. We apply Kirchhoff's current law to the base to find

EQ. 27

$$\frac{V_u}{R_S // R_1 // R_2} + \frac{I_C}{\beta_{DC}}\left(1 - e^{-V_u / V_{TH}}\right) = \frac{V_S}{R_S},$$

where we have used the diode law to find the transient collector current ι_C on the upswing of the output node as

EQ. 28

$$\iota_C = I_C\left(1 - e^{-V_u / V_{TH}}\right).$$

[7] The base swings down, which might suggest using V_d, but I want to keep track of this case being the upswing of the output node, so I used V_u.

The upswing collector current from EQ. 28 differs considerably from the downswing collector current of EQ. 21.

EQ. 27 determines V_u, but it is a very nonlinear implicit equation. To solve it, notice that it simplifies for the cases $V_u >> V_{TH}$ and $V_u << V_{TH}$, because the exponential is negligible in the first case and becomes approximately $1 - V_u / V_{TH}$ in the other case. We refer to these two cases as the upper and lower asymptotes of EQ. 27. To solve EQ. 27 we note that the two asymptotes cross each other at the value $V_u = V_{TH}$. Therefore, we find a first guess for V_u from the lower asymptote if $V_u < V_{TH}$ and from the upper asymptote if $V_u > V_{TH}$. Of course, at the beginning we do not know which case applies, so we solve for V_u using the lower asymptote as

EQ. 29

$$V_u \approx \frac{V_S / R_S}{1/(R_S // R_1 // R_2) + I_C /(\beta_{DC} V_{TH})} = V_u^1 .$$

Now we check to see if this estimate is less than V_{TH}. If so, we keep this as our first guess at V_u, V_u^1 and generate the next guess V_u^2 by putting the exponential back into the equation as

EQ. 30

$$V_u^2 \approx \frac{(V_S / R_S)\left(1 - V_u^1 / V_{TH} - e^{-V_u^1 / V_{TH}}\right)}{1/(R_S // R_1 // R_2) + I_C /(\beta_{DC} V_{TH})} .$$

We continue iterating like this to convergence (about four tries).

If we find our estimate from EQ. 29 is larger than V_{TH}, we are on the upper asymptote, so we switch to the upper asymptote solution, which is

EQ. 31

$$V_u \approx (V_S/R_S - I_C/\beta)(R_S//R_1//R_2) = V_u^1.$$

Then to generate the next guess for V_u, we reinsert the exponential as

EQ. 32

$$V_u^2 = \left(\frac{V_S}{R_S} - \frac{I_C}{\beta}\right)(R_S // R_1 // R_2)\left(1 - e^{-V_u^1 / V_{TH}}\right).$$

Again, we iterate to convergence. We put V_u into EQ. 28 and find the upward output voltage swing is then

EQ. 33

$$V_{out}(up) = \iota_C(R_C//R_L),$$

which is the final result we are after.

Notice that the difference in output upswing and output downswing is due to the appearance of $\exp(V_b/V_{TH})$ in the downswing analysis and $\exp(-V_u/V_{TH})$ in the upswing analysis, which leads in turn to different values V_b and V_u for the base swing in the two cases. That is, the difference in up and downswings is a nonlinear effect.

Once this upswing modification is inserted into the spreadsheet, we get a much more accurate upswing graph, as shown in Figure 26 below.

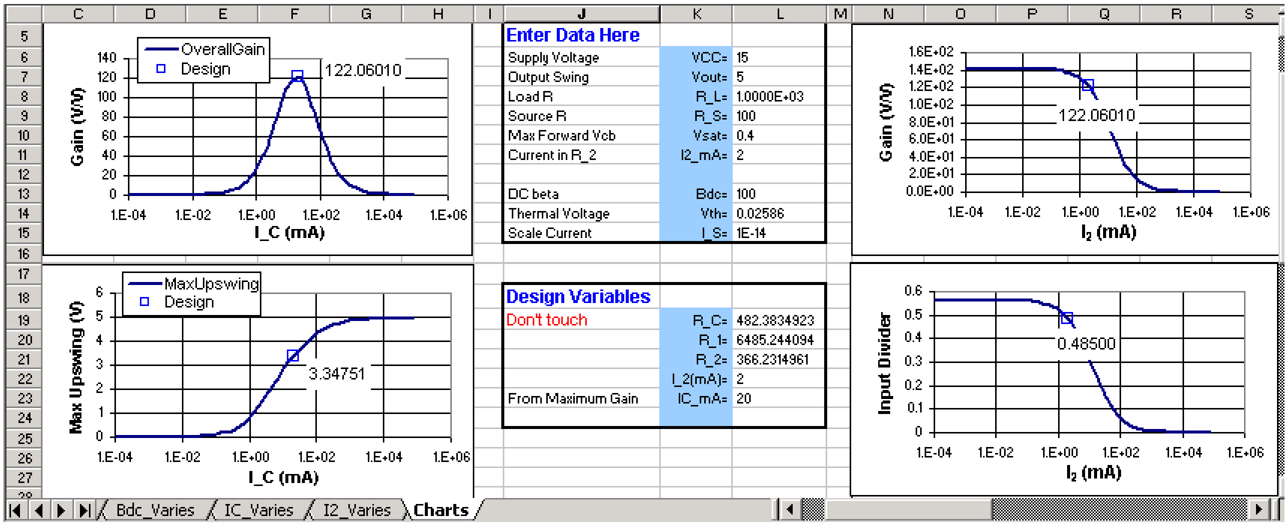
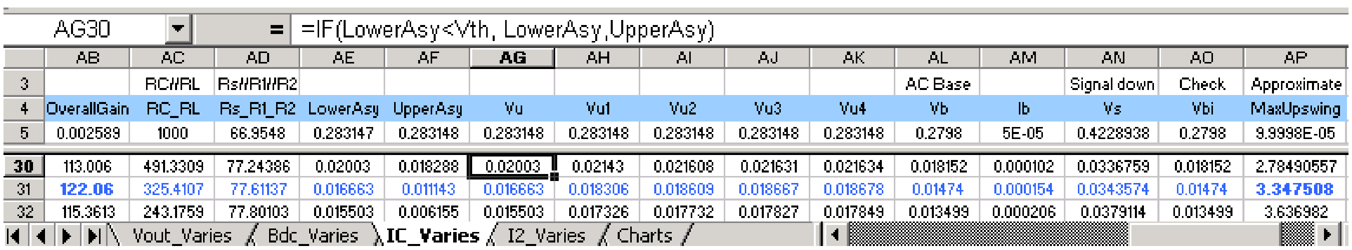


FIGURE 26

Charts worksheet with improved upswing plot (lower left) that now agrees with PSPICE

The implementation of the algorithm on worksheet "IC_Varies" is shown in Figure 27 and Figure 28.

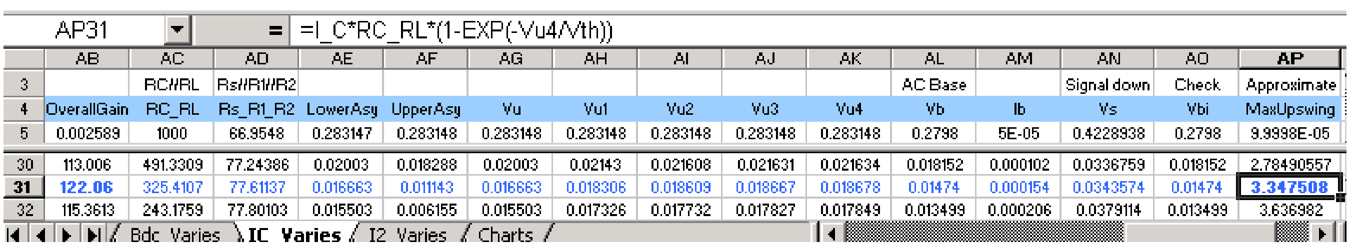


AG30 =IF(LowerAsy<Vth, LowerAsy,UpperAsy)

	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
3		RC//RL	Rs//R1//R2								AC Base		Signal down	Check	Approximate
4	OverallGain	RC_RL	Rs_R1_R2	LowerAsy	UpperAsy	Vu	Vu1	Vu2	Vu3	Vu4	Vb	Ib	Vs	Vbi	MaxUpswing
5	0.002589	1000	66.9548	0.283147	0.283148	0.283148	0.283148	0.283148	0.283148	0.283148	0.2798	5E-05	0.4228938	0.2798	9.9998E-05
30	113.006	491.3309	77.24386	0.02003	0.018288	0.02003	0.02143	0.021608	0.021631	0.021634	0.018152	0.000102	0.0336759	0.018152	2.78490557
31	122.06	325.4107	77.61137	0.016663	0.011143	0.016663	0.018306	0.018609	0.018667	0.018678	0.01474	0.000154	0.0343574	0.01474	3.347508
32	115.3613	243.1759	77.80103	0.015503	0.006155	0.015503	0.017326	0.017732	0.017827	0.017849	0.013499	0.000206	0.0379114	0.013499	3.636982

FIGURE 27

Use of an IF-statement to select asymptote depending on value of V_u



AP31 =I_C*RC_RL*(1-EXP(-Vu4/Vth))

	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
3		RC//RL	Rs//R1//R2								AC Base		Signal down	Check	Approximate
4	OverallGain	RC_RL	Rs_R1_R2	LowerAsy	UpperAsy	Vu	Vu1	Vu2	Vu3	Vu4	Vb	Ib	Vs	Vbi	MaxUpswing
5	0.002589	1000	66.9548	0.283147	0.283148	0.283148	0.283148	0.283148	0.283148	0.283148	0.2798	5E-05	0.4228938	0.2798	9.9998E-05
30	113.006	491.3309	77.24386	0.02003	0.018288	0.02003	0.02143	0.021608	0.021631	0.021634	0.018152	0.000102	0.0336759	0.018152	2.78490557
31	122.06	325.4107	77.61137	0.016663	0.011143	0.016663	0.018306	0.018609	0.018667	0.018678	0.01474	0.000154	0.0343574	0.01474	3.347508
32	115.3613	243.1759	77.80103	0.015503	0.006155	0.015503	0.017326	0.017732	0.017827	0.017849	0.013499	0.000206	0.0379114	0.013499	3.636982

FIGURE 28

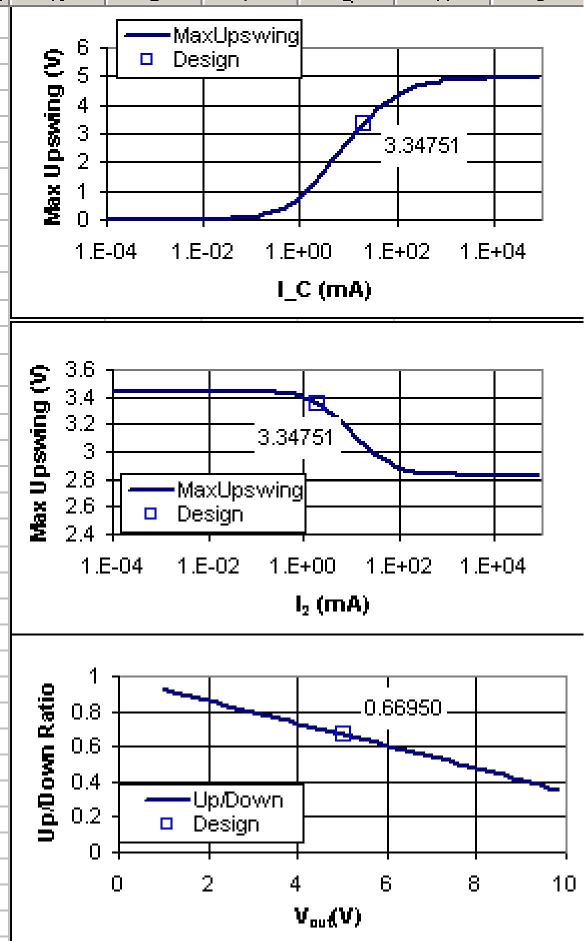
Implementation of improved upswing analysis

To show the utility of the upswing analysis, consider the plots shown below in Figure 29. These plots show how to modify the design in order to get an on-off ratio nearer to one, and hence less distortion in the output signal.

These plots require three worksheets, the IC_Varies, I2_Varies and Vout_Varies worksheets. They show that to get a better on-off ratio you can (i) increase I_C, or (ii) decrease I_2 or (iii) decrease the output swing. This last choice is pretty obvious: a lower output swing means a lower base signal, and lessens the nonlinear effect of $\exp(V_b/V_{TH})$.[8] Explanation of the other two trade-offs requires more thought.

[8] Recall that for $V_b << V_{TH}$, $\exp(V_b/V_{TH}) \approx 1 + V_b/V_{TH}$, a linear function.

	J	K	L
5	**Enter Data Here**		
6	Supply Voltage	VCC=	15
7	Output Swing	Vout=	5
8	Load R	R_L=	1.0000E+03
9	Source R	R_S=	100
10	Max Forward Vcb	Vsat=	0.4
11	Current in R_2	I2_mA=	2
12			
13	DC beta	Bdc=	100
14	Thermal Voltage	Vth=	0.02586
15	Scale Current	I_S=	1E-14
16			
17			
18	**Design Variables**		
19	Don't touch	R_C=	482.3834923
20		R_1=	6485.244094
21		R_2=	366.2314961
22		I_2(mA)=	2
23	From Maximum Gain	IC_mA=	20
24			



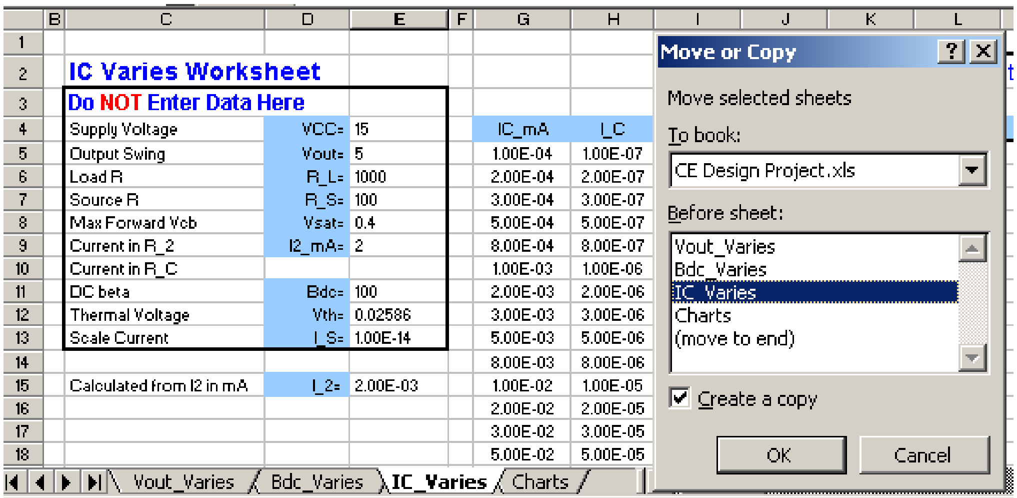
I2_Varies | **Charts**

FIGURE 29

Tradeoff plots making use of the upswing analysis; these plots show the design changes needed to obtain less output signal distortion

Appendix 3: Making a new worksheet "I2_Varies"

This appendix fills in some details related to the discussion of making the worksheet on which I_2 is the column variable instead of I_C. We begin with the menu obtained with EDIT/MOVE OR COPY SHEET leading to Figure 7, repeated below:

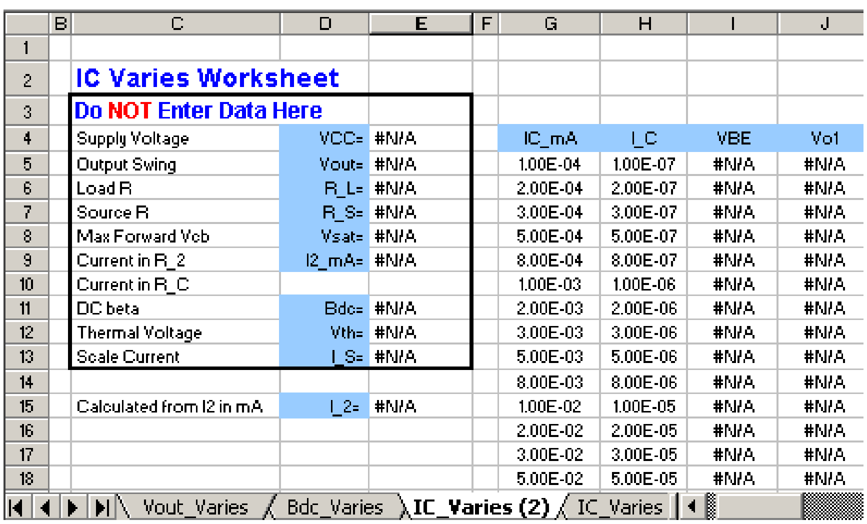


	C	D	E	G	H
1					
2	IC Varies Worksheet				
3	Do NOT Enter Data Here				
4	Supply Voltage	VCC=	15	IC_mA	I_C
5	Output Swing	Vout=	5	1.00E-04	1.00E-07
6	Load R	R_L=	1000	2.00E-04	2.00E-07
7	Source R	R_S=	100	3.00E-04	3.00E-07
8	Max Forward Vcb	Vsat=	0.4	5.00E-04	5.00E-07
9	Current in R_2	I2_mA=	2	8.00E-04	8.00E-07
10	Current in R_C			1.00E-03	1.00E-06
11	DC beta	Bdc=	100	2.00E-03	2.00E-06
12	Thermal Voltage	Vth=	0.02586	3.00E-03	3.00E-06
13	Scale Current	I_S=	1.00E-14	5.00E-03	5.00E-06
14				8.00E-03	8.00E-06
15	Calculated from I2 in mA	I_2=	2.00E-03	1.00E-02	1.00E-05
16				2.00E-02	2.00E-05
17				3.00E-02	3.00E-05
18				5.00E-02	5.00E-05

FIGURE 30

Copying the IC_Varies worksheet

Immediately after clicking "OK", the copy of "IC_Varies" looks like Figure 31.



	C	D	E	G	H	I	J
1							
2	IC Varies Worksheet						
3	Do NOT Enter Data Here						
4	Supply Voltage	VCC=	#N/A	IC_mA	I_C	VBE	Vo1
5	Output Swing	Vout=	#N/A	1.00E-04	1.00E-07	#N/A	#N/A
6	Load R	R_L=	#N/A	2.00E-04	2.00E-07	#N/A	#N/A
7	Source R	R_S=	#N/A	3.00E-04	3.00E-07	#N/A	#N/A
8	Max Forward Vcb	Vsat=	#N/A	5.00E-04	5.00E-07	#N/A	#N/A
9	Current in R_2	I2_mA=	#N/A	8.00E-04	8.00E-07	#N/A	#N/A
10	Current in R_C			1.00E-03	1.00E-06	#N/A	#N/A
11	DC beta	Bdc=	#N/A	2.00E-03	2.00E-06	#N/A	#N/A
12	Thermal Voltage	Vth=	#N/A	3.00E-03	3.00E-06	#N/A	#N/A
13	Scale Current	I_S=	#N/A	5.00E-03	5.00E-06	#N/A	#N/A
14				8.00E-03	8.00E-06	#N/A	#N/A
15	Calculated from I2 in mA	I_2=	#N/A	1.00E-02	1.00E-05	#N/A	#N/A
16				2.00E-02	2.00E-05	#N/A	#N/A
17				3.00E-02	3.00E-05	#N/A	#N/A
18				5.00E-02	5.00E-05	#N/A	#N/A

FIGURE 31

Copy of IC_Varies worksheet now named IC_Varies(2)

The #N/A entries in column E result because the addresses of these cells are on the "Charts" worksheet, and not on the sheet we copied. To get the correct addresses referring to the "Charts" worksheet, we go back to "IC_Varies" and copy the cells E4 – E13, then return and paste the addresses into "IC_Varies(2)" as shown in Figure 32 below.

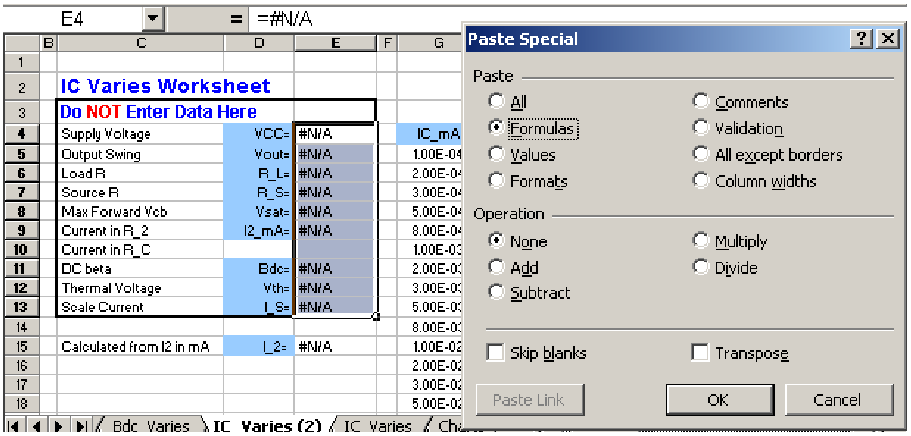


FIGURE 32

Pasting the addresses to “Charts” in the data entry section of “IC_Varies(2)” using PASTE SPECIAL with the FORMULAS box checked

Next we rename the worksheet as “I2_Varies” by putting the cursor in the name tab and right clicking to obtain the RENAME option. After renaming, and changing the title to “I2 Varies”, the data entry part of the new worksheet “I2_Varies” looks like Figure 33.

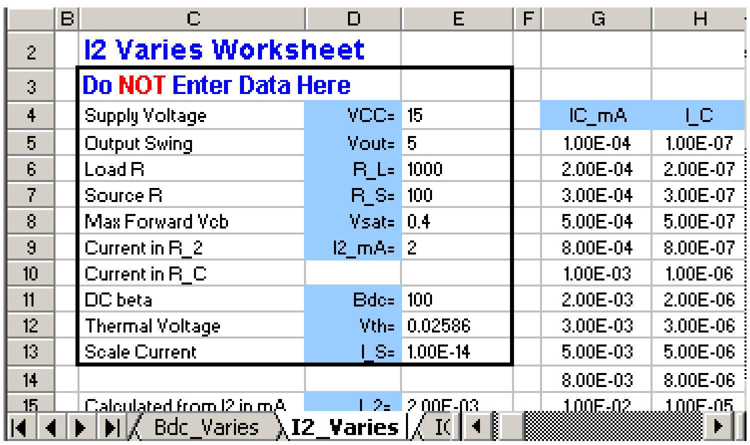


FIGURE 33

New worksheet with name changed to “I2_Varies”

Next, we delete I2_mA from cells D9- E9, and add IC_mA to cell D10 with address in cell E10 given as Charts!IC_mA. See Figure 34. The cell E10 has been named IC_mA , as shown in the NAME box.

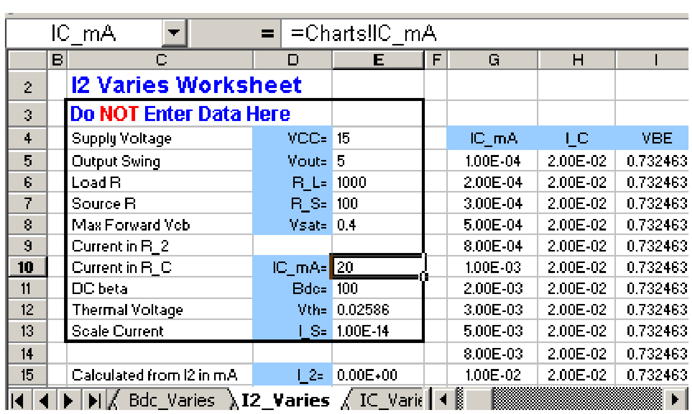
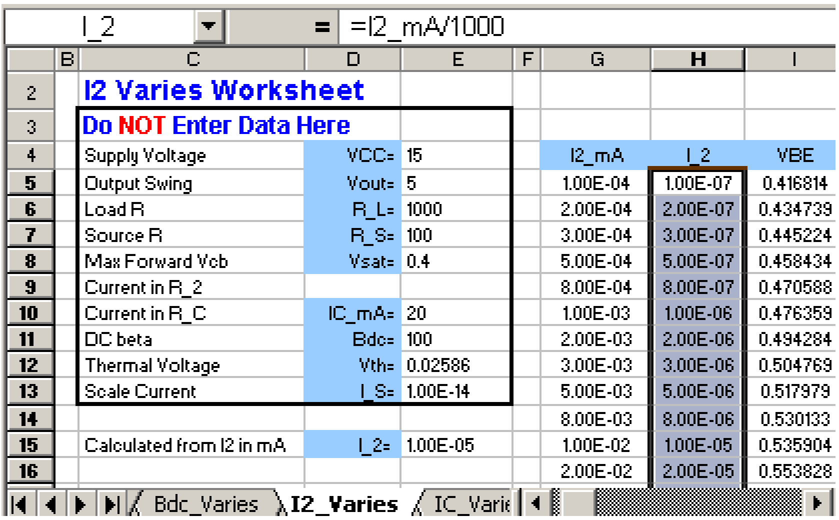


FIGURE 34

Insertion of IC_mA with address shown in the FORMULA box as Charts!IC_mA

Because we have used INSERT/NAME/CREATE to rename IC_mA as a single variable with a value taken from “Charts”, the column titled IC_mA no longer is a column variable. Therefore, the I_C column is all the same number, namely the new IC_mA from E10 converted to A from mA.

We want I_2 to become the new column variable, so we change the title of cell G4 to I2_mA, of cell H4 to I_2, and change the formula in the I_2 column to convert I2_mA to A. Then we rename these columns by highlighting the columns and their new names and using INSERT/NAME/CREATE. See Figure 35.



I_2 = =I2_mA/1000

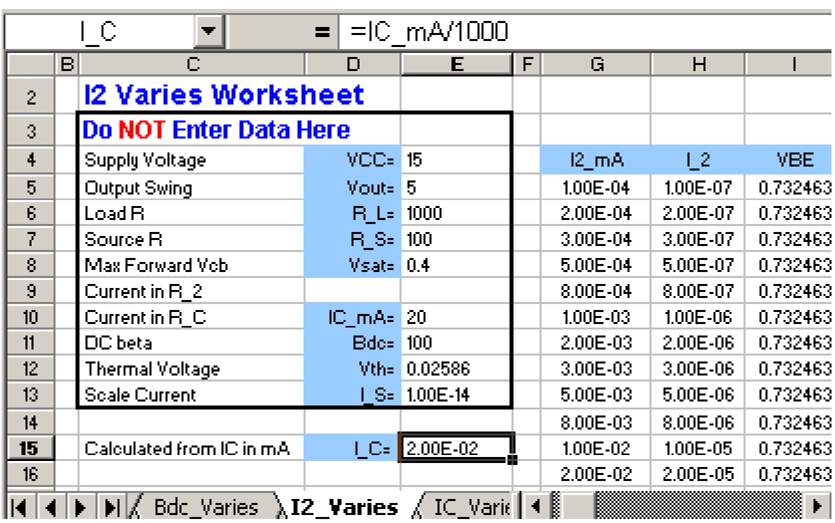
	B	C	D	E	F	G	H	I
2		I2 Varies Worksheet						
3		Do NOT Enter Data Here						
4		Supply Voltage	VCC=	15		I2_mA	I_2	VBE
5		Output Swing	Vout=	5		1.00E-04	1.00E-07	0.416814
6		Load R	R_L=	1000		2.00E-04	2.00E-07	0.434739
7		Source R	R_S=	100		3.00E-04	3.00E-07	0.445224
8		Max Forward Vcb	Vsat=	0.4		5.00E-04	5.00E-07	0.458434
9		Current in R_2				8.00E-04	8.00E-07	0.470588
10		Current in R_C	IC_mA=	20		1.00E-03	1.00E-06	0.476359
11		DC beta	Bdc=	100		2.00E-03	2.00E-06	0.494284
12		Thermal Voltage	Vth=	0.02586		3.00E-03	3.00E-06	0.504769
13		Scale Current	I_S=	1.00E-14		5.00E-03	5.00E-06	0.517979
14						8.00E-03	8.00E-06	0.530133
15		Calculated from I2 in mA	I_2=	1.00E-05		1.00E-02	1.00E-05	0.535904
16						2.00E-02	2.00E-05	0.553828

Bdc_Varies / I2_Varies / IC_Varie

FIGURE 35

Renaming the first two columns to represent values of I_2: to show the result, the entire column I2 is highlighted to make its name appear in the NAME BOX, and its formula, =I2_mA/1000, appears in the FORMULA BOX

By renaming the column I_C as I_2, the variable I_C now has been removed from the worksheet. To reinstate it, we replace cells D15 and E15 with I_C and its formula, as shown in Figure 36.



I_C = =IC_mA/1000

	B	C	D	E	F	G	H	I
2		I2 Varies Worksheet						
3		Do NOT Enter Data Here						
4		Supply Voltage	VCC=	15		I2_mA	I_2	VBE
5		Output Swing	Vout=	5		1.00E-04	1.00E-07	0.732463
6		Load R	R_L=	1000		2.00E-04	2.00E-07	0.732463
7		Source R	R_S=	100		3.00E-04	3.00E-07	0.732463
8		Max Forward Vcb	Vsat=	0.4		5.00E-04	5.00E-07	0.732463
9		Current in R_2				8.00E-04	8.00E-07	0.732463
10		Current in R_C	IC_mA=	20		1.00E-03	1.00E-06	0.732463
11		DC beta	Bdc=	100		2.00E-03	2.00E-06	0.732463
12		Thermal Voltage	Vth=	0.02586		3.00E-03	3.00E-06	0.732463
13		Scale Current	I_S=	1.00E-14		5.00E-03	5.00E-06	0.732463
14						8.00E-03	8.00E-06	0.732463
15		Calculated from IC in mA	I_C=	2.00E-02		1.00E-02	1.00E-05	0.732463
16						2.00E-02	2.00E-05	0.732463

Bdc_Varies / I2_Varies / IC_Varie

FIGURE 36

Cell E15 has be NAMED I_C, as seen in the NAME BOX and its formula is changed to compute I_C in mA, as shown in the FORMULA BOX

The “I2_Varies” worksheet now is complete.

CHARTS ON WORKSHEET "CHARTS"

Next, we want to introduce some charts on worksheet :"Charts" to report the results from the new "I2_Varies" worksheet. We illustrate using the GAIN chart.

To avoid reformatting a new chart from scratch, we copy the chart for I_C by highlighting the I_C-Chart, right clicking and using COPY/PASTE. The result is shown in Figure 37.

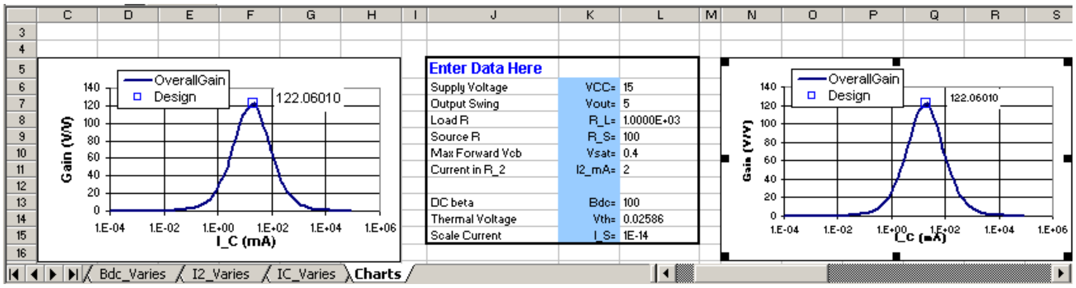


FIGURE 37

Creating a new Gain chart on worksheet "Charts" to be modified to report the gain from worksheet "I2_Varies"

Next we change the label on the x-axis to I_2 (mA). Then we click on the curve in the chart and right-click to get the SOURCE DATA menu shown in Figure 38.

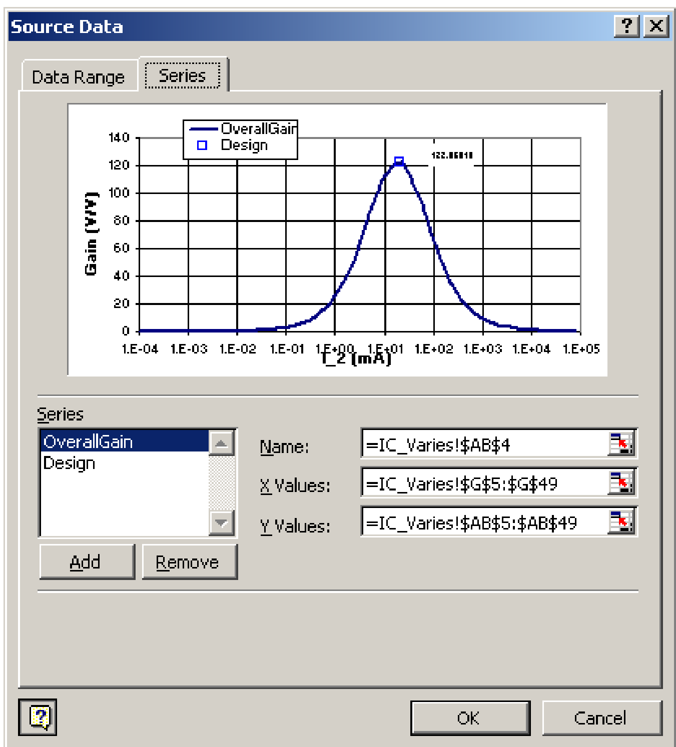


FIGURE 38

The SOURCE DATA menu for the data in the copied chart

We want to change the X-VALUES and Y-VALUES entries for the Gain data from the worksheet "IC_Varies" to the worksheet "I2_Varies". In the menu of Figure 38, we highlight the portion of each label that says IC_Varies!, and then click on the I2_Varies worksheet name tab. The IC-Varies changes to I2_Varies, and the chart now appears as in Figure 39 below.

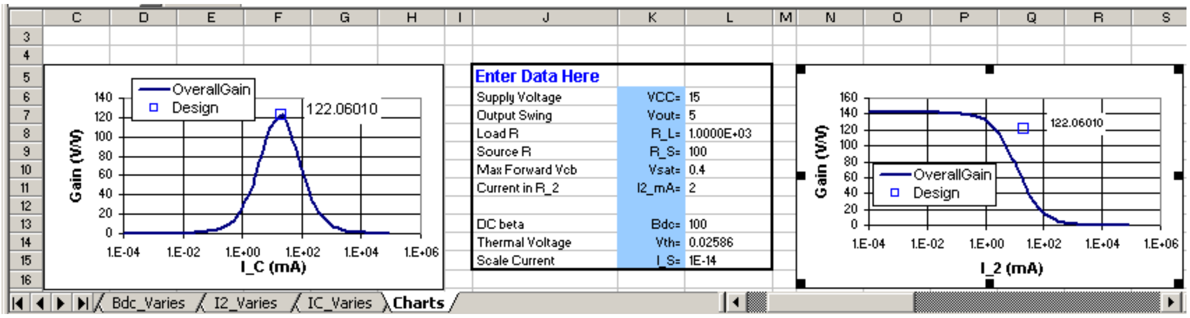


FIGURE 39

The chart on the right now reports the Gain data from worksheet "I2_Varies"

ADDING A DESIGN MARKER

The square data point DESIGN still refers to the chart on the left in Figure 39, instead of the new worksheet. To fix this, we need to construct a new DESIGN REPORT column on worksheet "Charts", as described in Appendix 1. The modified DESIGN REPORT section of "Charts" is shown in Figure 40.

AH26 = =IF(AG26=I2_mA,'I2_Varies '!AB26,0)

	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
2	Design Report from Other Worksheets										I_2 worksheet			
3			Gain	Max								Gain		
4	IC_mA	Gain	Design	UpSwing	R_C3	R_1	R_2	OutDivider2	InDivider		I2_mA	Design	UpSwing	InDivider
5	0	2.59E-03	0	0	0	0	0	0	0		0.00E+00	0	0	0
6	0	5.25E-03	0	0	0	0	0	0	0		0.00E+00	0	0	0
7	0	7.93E-03	0	0	0	0	0	0	0		0.00E+00	0	0	0
25	0	2.58E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
26	0	4.61E+01	0	0	0	0	0	0	0		2.00E+00	122.0601	3.347508	0.484998
27	0	6.22E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
28	0	8.52E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
29	0	1.05E+02	0	0	0	0	0	0	0		0.00E+00	0	0	0
30	0	1.13E+02	0	0	0	0	0	0	0		0.00E+00	0	0	0
31	20	1.22E+02	122.0600957	3.347508	482.3835	6485.244	366.2315	0.674588646	0.484998		0.00E+00	0	0	0
32	0	1.15E+02	0	0	0	0	0	0	0		0.00E+00	0	0	0
33	0	9.71E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
34	0	7.59E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
35	0	6.59E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
36	0	3.93E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
37	0	2.79E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
38	0	1.76E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
39	0	1.13E+01	0	0	0	0	0	0	0		0.00E+00	0	0	0
40	0	9.15E+00	0	0	0	0	0	0	0		0.00E+00	0	0	0
41	0	4.66E+00	0	0	0	0	0	0	0		0.00E+00	0	0	0
42	0	3.13E+00	0	0	0	0	0	0	0		0.00E+00	0	0	0
43	0	1.88E+00	0	0	0	0	0	0	0		0.00E+00	0	0	0
44	0	1.18E+00	0	0	0	0	0	0	0		0.00E+00	0	0	0
45	0	9.44E-01	0	0	0	0	0	0	0		0.00E+00	0	0	0
46	0	4.72E-01	0	0	0	0	0	0	0		0.00E+00	0	0	0
47	0	3.14E-01	0	0	0	0	0	0	0		0.00E+00	0	0	0
48	0	1.89E-01	0	0	0	0	0	0	0		0.00E+00	0	0	0
49	0	1.18E-01	0	0	0	0	0	0	0		0.00E+00	0	0	0
50	20		122.0600957	3.347508	482.3835	6485.244	366.2315	0.674588646	0.484998		2	122.0601	3.347508	0.484998
51	Maximum	1.22E+02	Gain	Swing	RC	R1	R2	OutDivider(rev)	InDivider		I_2	Gain	Upswing	InDivider

Charts

FIGURE 40

Design report updated to include report from worksheet I2_Varies

The design marker with x-value AG50 and y-value AH 50 then is added to the chart to replace the old design marker, as shown in Figure 41 below.

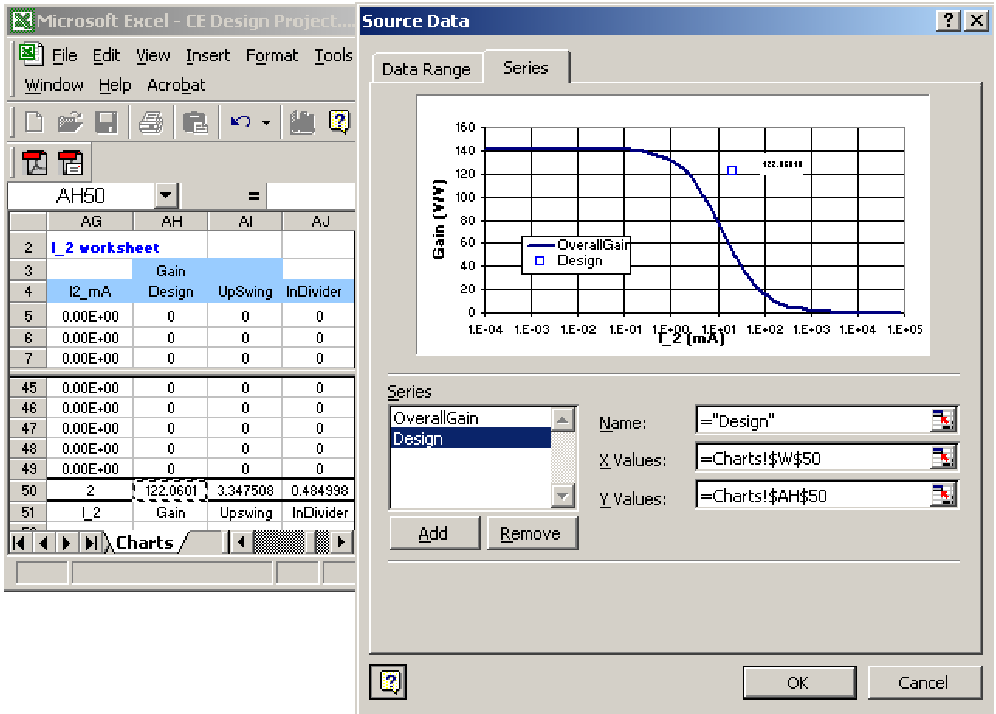


FIGURE 41

Inserting the DESIGN boxed point on the Gain chart : Cell AH50 from Row 50 is selected from the DESIGN REPORT section of "Charts"

Following the addition of the design marker, the chart is now as we want it, as shown in Figure 42.

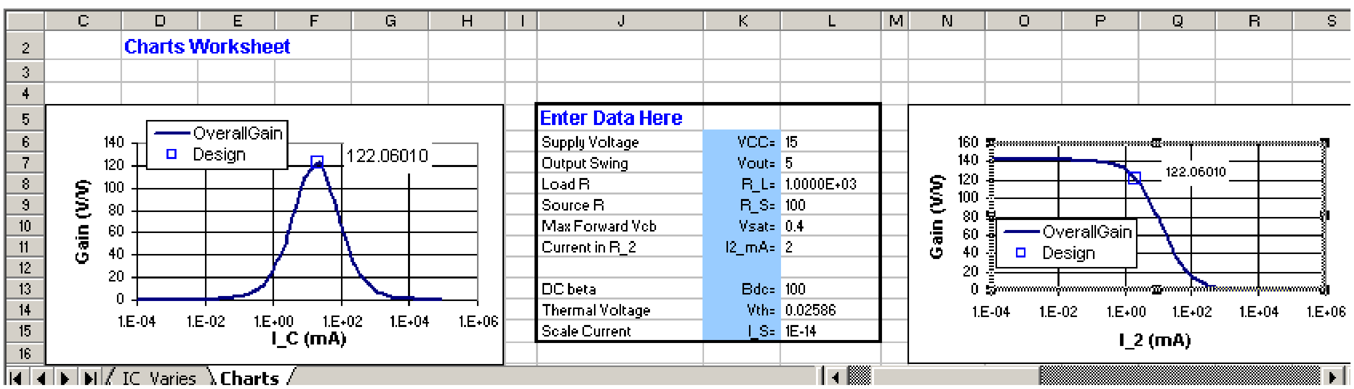


FIGURE 42

Final version of "I2_Varies" gain plot with design marker