Measurements and modeling of a BJT differential pair in IF amplifier of FM receiver.

#BJT, #diffpair, #differential pair, #python, #fsolve, #IF Amplifier, #FM Receiver

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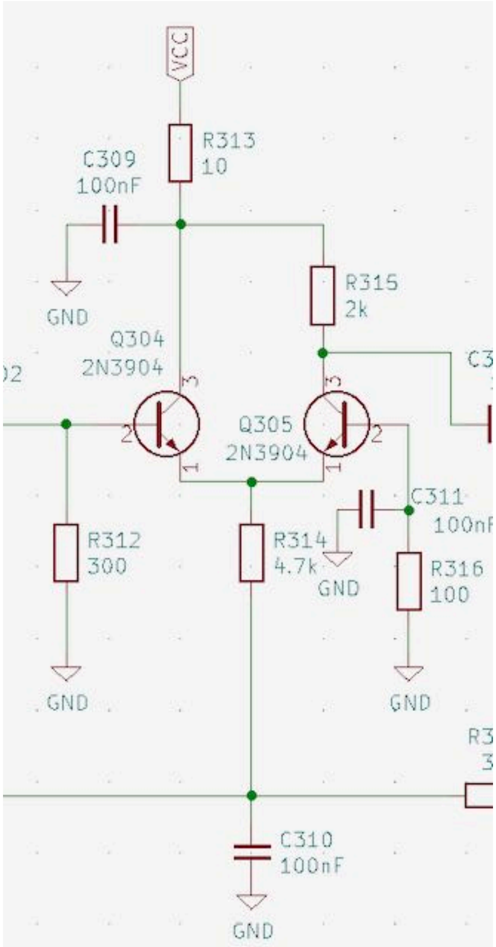
BJT differential pair amplifiers provide a well defined amplification, as well as a nice limiting action. Both of these are very useful in the IF amplifier for an FM receiver.

In the IF amplifier of my homebrew FM Receiver there is a chain of differential pairs. I did detailed scoping in one of these pairs, and found that the shared emitter voltage is not completely stable. At first this surprised me. To completely understand this I described the circuit's behaviour in a few expressions, and coded these expressions in a small Python script. With the output of the script it is easy to show the amplification of the differential pair, but also the limiting action and the unexpected voltage fluctuations on the shared emitter.

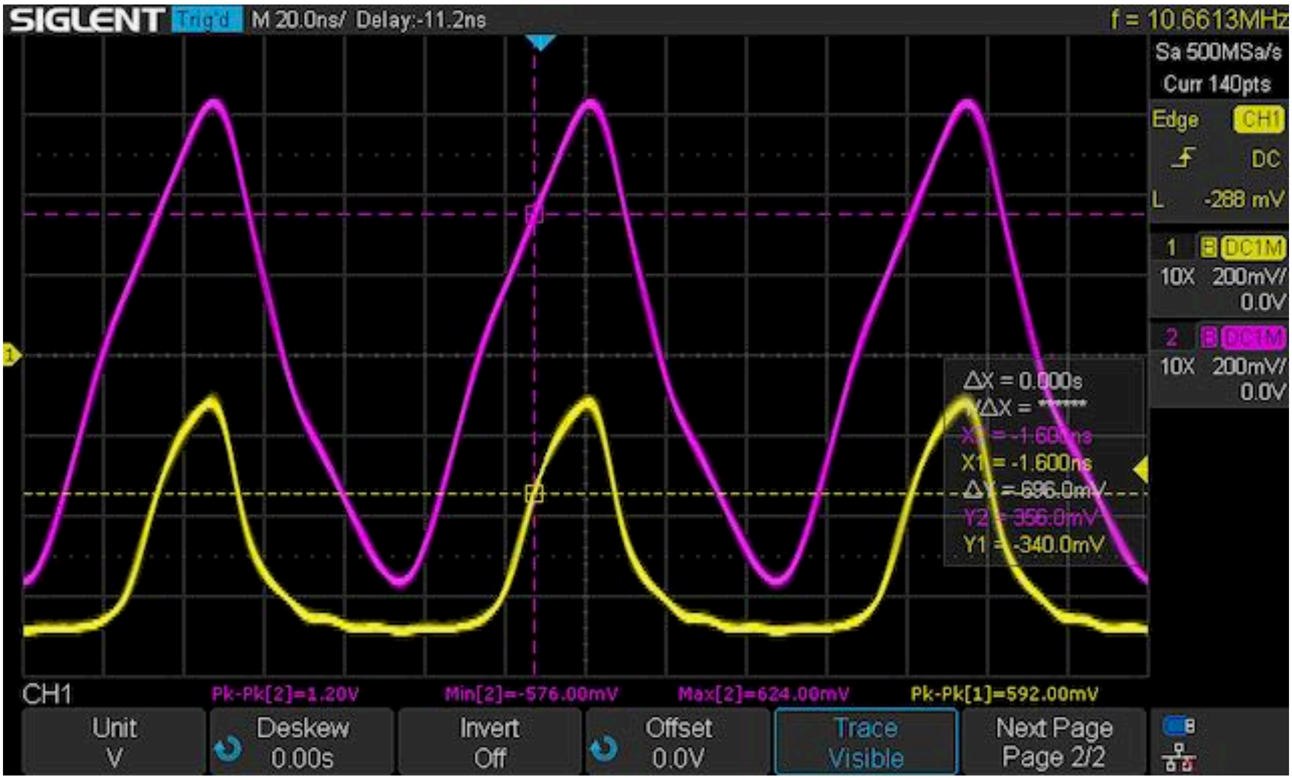
I will show the script, the scripts output, and finally I will also give an intuitive explanation of what's going on in the diffpair.

To show you the context of the diffpair, this is part of the IF amplifier.



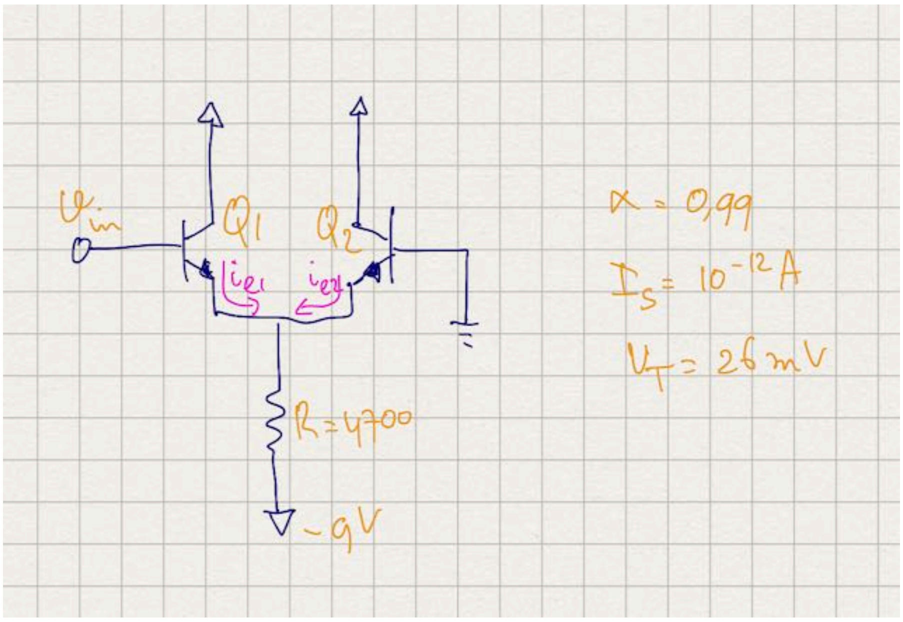
As a sidenote, since I created this circuit diagram, the actual implementation has changed somewhat. The base of the second transistor, which in this diagram is Q305 is tied to ground directly. There is no need to use R316 and C311. For the story which follows, it is not important.

What I saw at the shared emitter is this:



In purple you see the input voltage at the base of Q304, in yellow the shared emitter voltage at its emitter. What surprised me at first is that the emitter voltage is not constant, and not by a small amount. It rises with the input voltage, but only when the input voltage is positive. For negative input voltages, the emitter voltage is constant.

To understand this I modeled the diffpair as such:



The model only consists of the two transistors, a common tail resistor, the input signal at the base of Q1. The base of Q2 is tied to ground, and both collectors are put connected to the positive voltage supply. The actual voltage of the positive supply is not important as the current is dictated by both transistors.

The model can de described by the following equations:

$$(1') \quad i_{e1} - \frac{I_S}{\alpha}\left[e^{\frac{v_{in} - v_e}{V_T}} - 1\right] = 0$$

$$(2') \quad i_{e2} - \frac{I_S}{\alpha}\left[e^{\frac{v_{b2} - v_e}{V_T}} - 1\right] = 0$$

$$(3') \quad i - i_{e1} - i_{e2} = 0$$

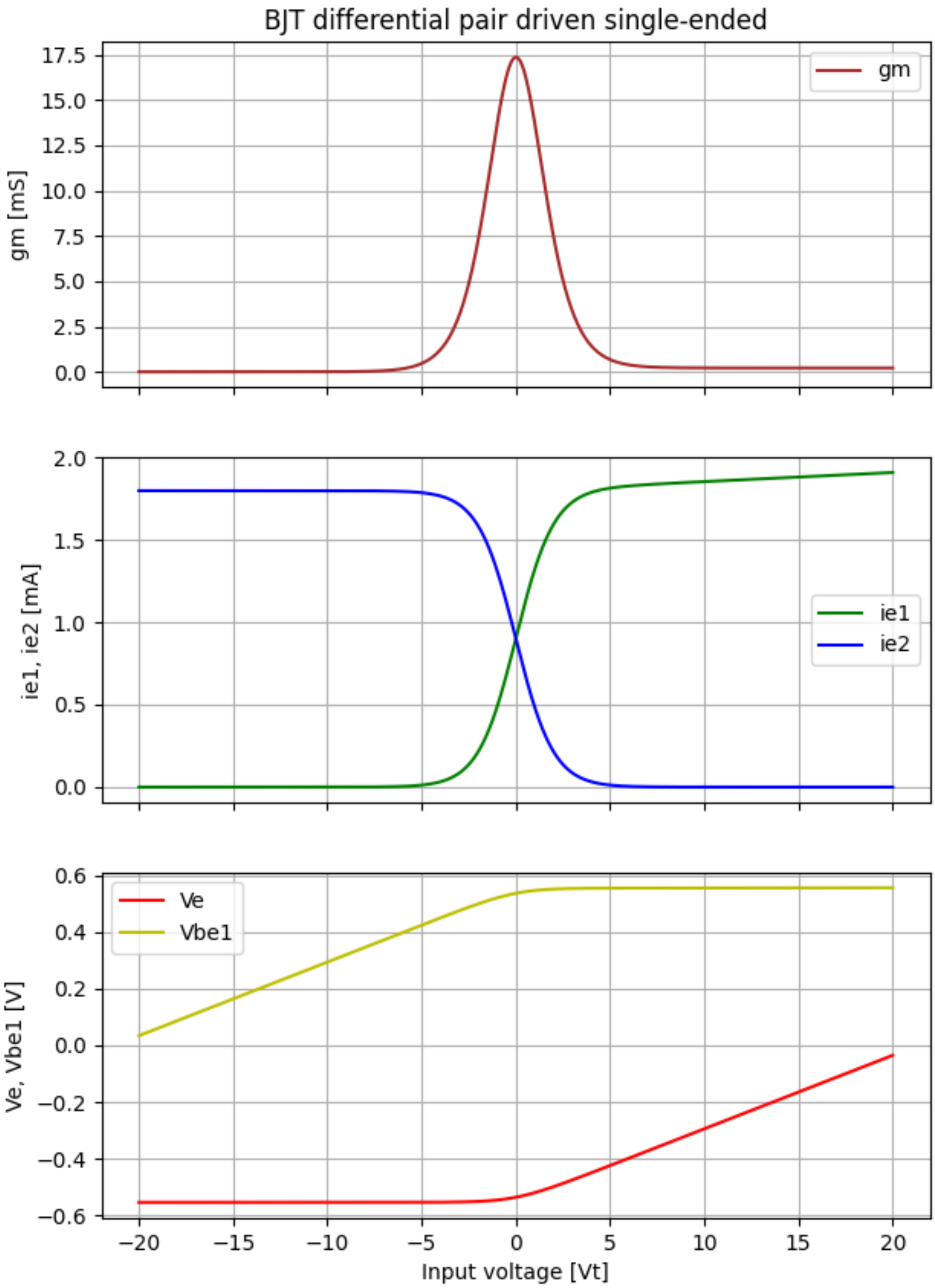
$$(4') \quad v_e - V_{EE} - i \cdot R_{EE} = 0$$

Equations 1 and 2 are the Shockley diode equations, extended with the transistor amplification. Equation 3 is the Kirchhoff current law at the shared emitter node. Equation 4 is Ohm's law over the tail resistor.

i_{e1} is the current through the input transistor Q_1 and i_{e2} is the current through the output transistor Q_2.

These equations form a nonlinear set of equations which cannot be solved algebraically. With Python's scipy.optimize.fsolve function approximated solutions for these equations can be found quite easily. I wrote a script to find solutions for these equations and plot these solutions for varying input voltages.

The output of the script are these two plots:



The middle plot shows the currents through the transistors. The bottom plot shows the shared emitter voltage V_e in red, and the base-emitter voltage drop V_{be1} for the first transistor in yellow. The top plot shows the transconductance as calculated from the middle plot. This is essentially the slope of i_{e2} in the middle plot. Note that the x-axis is in units of 26 millivolts, the thermal voltage.

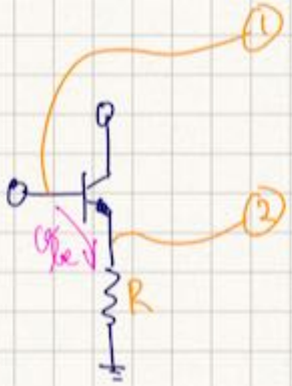
Several observations can be made from these plots.

1. Within an input range of +/- 2 times the thermal voltage, current through the output transistor depends linearly on the input voltage. The diffpair makes a good amplifier within this input range.
2. Above about 3 times the thermal voltage, the output current starts to level off. This is the before-mentioned limiting action. For input signals larger than about 5 times the thermal voltage, output current does not increase anymore.
3. For large positive input voltages, the shared emitter voltage raises linearly with the input voltage.
4. The emitter voltage remains constant for negative input voltages.
5. The base-emitter voltage drop for Q_1 is nearly 0.6 volts for positive input voltages.
6. The small signal gain g_m nicely follows $g_m = I / 2V_T$ (blue dot in top plot), where I is the total tail current.

Observations 3 and 4 explain the signals seen before in the oscilloscope plot. For positive input signals, the emitter voltage follows the input voltage, being a diode drop lower. For negative input voltages the emitter voltage remains constant for all input voltages less than zero.

The base-emitter voltage drop of nearly 0.6 volts is nearly completely dictated by the reverse saturation current I_S. I did some simple measurements on a 2N3904 to determine the reverse saturation current. It turned out to be about 1pA. This value of 1pA was used in the Python script.

These are my notes for the measurement of the reverse saturation current:



$R = 998\,\Omega$

$$i_e = \frac{V_2}{R}$$

$$v_{be} = V_1 - V_2$$

$$i_e = I_S\left(e^{\frac{v_{be}}{V_T}} - 1\right) \Longrightarrow I_S = \frac{i_e}{e^{\frac{v_{be}}{V_T}} - 1}$$

V_1 (mV)	V_2 (mV)
103	0,0
200	0,0
300	0,0
409	0,0
514	0,6
613	15,8
714	68,2
765	104,8
814	142,9
860	180,6
911	223,2
961	267,3
1009	309,1

Note that in these formules the α factor is missing. But this is not important, as it is close to one, and the measurements are not very accurate anyway. The measurements were taken with two multimeters. The measured values for V1 and V2 are entered into this sheet to calculate the reverse saturation current I_S:

Tabel 1

V1 (mV)	V2 (mV	Vbe (mV)	ie (mA)	Is (A)
103	0	103	0.00E+00	0.000E+00
200	0	200	0.00E+00	0.000E+00
306	0	306	0.00E+00	0.000E+00
409	0	409	0.00E+00	0.000E+00
514	0.6	513.4	6.01E-04	1.597E-12
613	15.8	597.2	1.58E-02	1.675E-12
714	68.2	645.8	6.83E-02	1.115E-12
765	104.8	660.2	1.05E-01	9.851E-13
814	142.9	671.1	1.43E-01	8.833E-13
860	180.6	679.4	1.81E-01	8.112E-13
911	223.2	687.8	2.24E-01	7.258E-13
961	267.3	693.7	2.68E-01	6.927E-13
1009	309.1	699.9	3.10E-01	6.311E-13

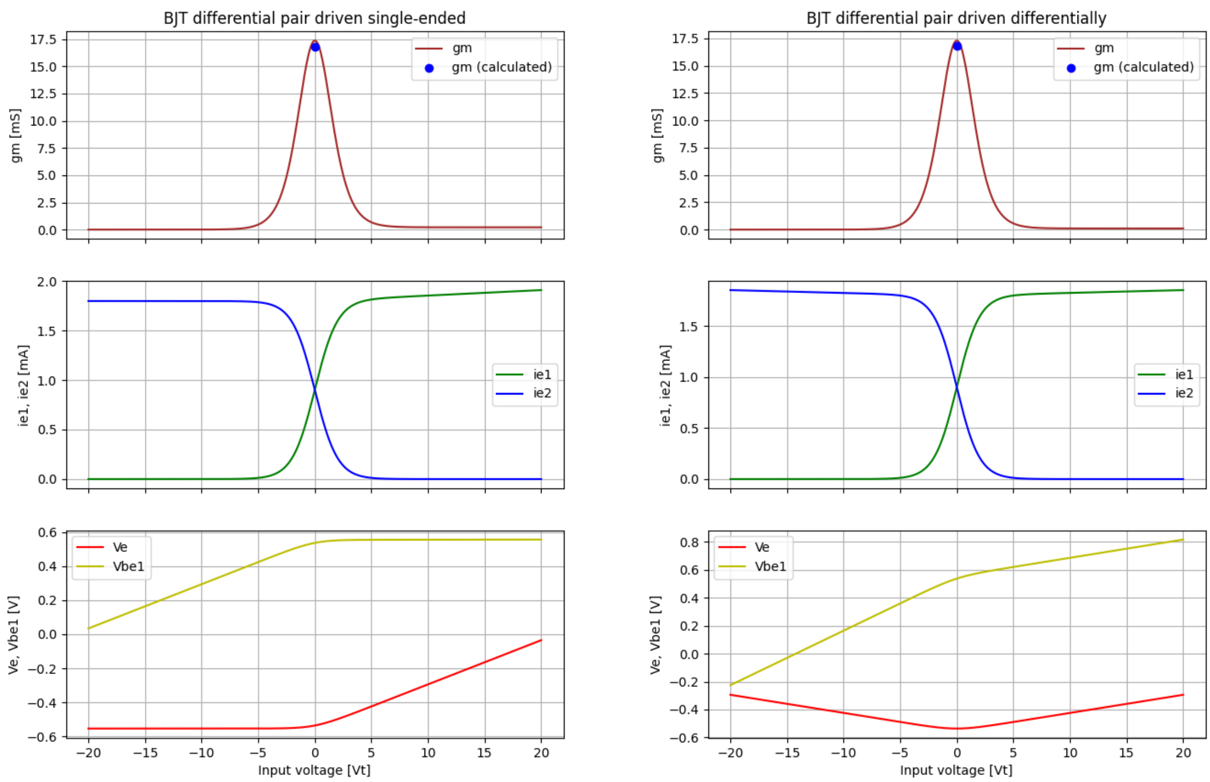
Tabel 2

R =	998	Ω
Vt =	26	mV

Apart from the zero values for I_S, the calculated values hover around 1pA.

The behaviour of the emitter voltage can also be explained intuitively quite easily. Below a certain negative input voltage, Q1 gets into cutoff. It is not able to regulate the voltage at the shared emitter anymore. The emitter voltage is completely dictated by Q2. As the base of Q2 is tied to ground, there is nothing to let the emitter fluctuate, and as such it will remain constant at about a diode drop below the base of Q2. For positive input voltages, Q1 will be in its active region. When the input voltage rises above a certain level, it will cause Q2 to get into cutoff as Q1 will conduct all the current. The shared emitter voltage is dictated by Q1. At this moment we have a simple emitter follower circuit. The emitter voltage will follow the input voltage minus one diode drop.

To get the story complete, I changed the Python script somewhat to model the circuit when it is driven differentially. That is, the base of Q2 gets the same input voltage as Q1, but opposite in phase. This is the output of the script. Compare it with the output of the script when it is driven non-differentially, only on Q1. I leave it as an exercise to understand the difference between the two.


BJT differential pair driven single-ended
gm [mS]
gm
gm (calculated)
ie1, ie2 [mA]
ie1
ie2
Ve, Vbe1 [V]
Ve
Vbe1
Input voltage [Vt]
BJT differential pair driven differentially
gm [mS]
gm
gm (calculated)
ie1, ie2 [mA]
ie1
ie2
Ve, Vbe1 [V]
Ve
Vbe1
Input voltage [Vt]