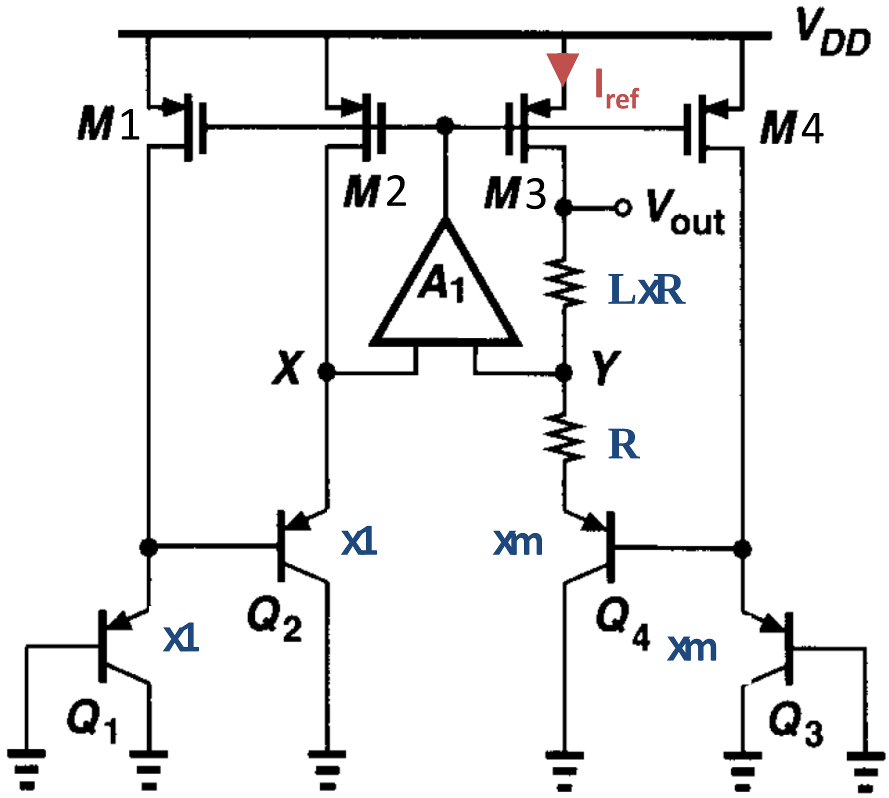
Bandgap reference



<u>**Neglect the channel modulation of the MOSFETS and the base currents of the BJTs. The OpAmp is supposed ideal. Q4 and Q3 are composed on m bipolars in parallel.**</u>

1- **Show the inverting and non-inverting node of the OpAmp on the schematic and justify your choice.**

Without loop V_Y is higher than V_X, due to the resistor R. the negative feedback at Y set lower V_Y and set it equal to V_X. Since the OpAmp drives an inverting stage (i.e. common source amp.), negative feedback at Y means non-inverting node is Y.

2- **Give the expression of I_{ref} versus temperature. Is-it PTAT or CTAT?**

$I_{ref} = 2\ nU_T\ln(m) / (R) = 2\ nkT\ \ln(m) / (qR)$, PTAT if TCR is negative.

3- **Give the expression of V_{out} and $\partial V_{out}/\partial T$.**

$V_{out} = 2n\ (L+1)U_T\ln(m) + V_{eb4} + V_{eb3} \approx 2n\ (L+1)U_T\ln(m) + 2V_D$
$\partial V_{out}/\partial T = (85\ \mu V/^\circ C)\ 2n\ (L+1)\ \ln(m) + 2(-1.6\ mV/^\circ C))$

4- **Determine the value of L in order to have a bandgap reference (i.e. Temperature independent reference).** (2pts)

$L = 3{,}2\ 10^3 / (170\ n\ln(m)) - 1$

5- **Numerical application: For m = 8. T = 300K and n = 1**

a. **Determine: L, and V_{out}.** (2pts)

$L = 3{,}2\ 10^3 / (170 \ln(8)) - 1 = 8$

$V_{out} = 2n\,(L+1)U_T\ln(m) + V_{eb4} + V_{eb3} = 2n\,(L+1)U_T\ln(m) + 2nU_T\ln(I_{ref}/mI_s)$

We cannot calculate precisely V_{out} if we don't know the values of I_{ref}, m and I_s. We can only estimate its value by using the approximation:

$V_{eb} = nU_T\ln(I_{ref}/mI_s) \approx 0.7V$ and thus:

$V_{out} \approx 2\,(8+1)\,26\ 10^{-3}\ln(8) + 2\text{x}\ 0.7 \approx 2.37\ V$

6- **Assume that bipolar transistors have a finite current gain β (i.e. we consider their base currents). Calculate the error in the output voltage V_{out}.**

$V^*_{out} = 2\,n(L+1)U_T\ln(m) + V_{eb4} + V_{eb3}$

$= 2n\,(L+1)U_T\ln(m) + nU_T\ln(I_{ref}/I_s) + nU_T\ln((I_{ref} + I_b)/I_s)$ avec $I_b = I_{ref}/\beta$

$= 2n\,(L+1)U_T\ln(m) + 2nU_T\ln(I_{ref}/I_s) + nU_T\ln(1 + \beta^{-1})$

$= V_{out} + nU_T\ln(1 + \beta^{-1})$

The error due to finite current gain β is $nU_T\ln(1 + \beta^{-1})$

7- **Suppose that OpAmp has an offset voltage V_{os} (i.e. Voltage difference at the input of the OpAmp $V_+ - V_-$ is not zero but V_{os}). Calculate the error in the output voltage V_{out}.** (2pts)

Consider that $V_{os} = V_Y - V_X$

In this case $I_{ref} = 2n\,U_T\ln(m) / (R) + Vos/R$

And

$V^*_{out} = 2n\,(L+1)U_T\ln(m) + V_{eb4} + V_{eb3} + (L+1)\,Vos$

The error due Vos is $(L+1)$ Vos

8- Comment on the effect of the two BJT branches compared to the topology with only one BJT branch. (2pts)

Band gap with two BJTs allows for a higher Vout for while the effect of Vos remains the same.

9- Is this topology useful for a sub-1V bandgap?

No the minimum value of V_{out} is about 1,4 V due to the stack of the two BJTs.