Laboratory Report

Activity No. 5

Bandgap Voltage Reference

In partial fulfilment for the course

ECE 126 (Introduction to Analog IC Design)

Submitted by

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Submitted to

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Introduction

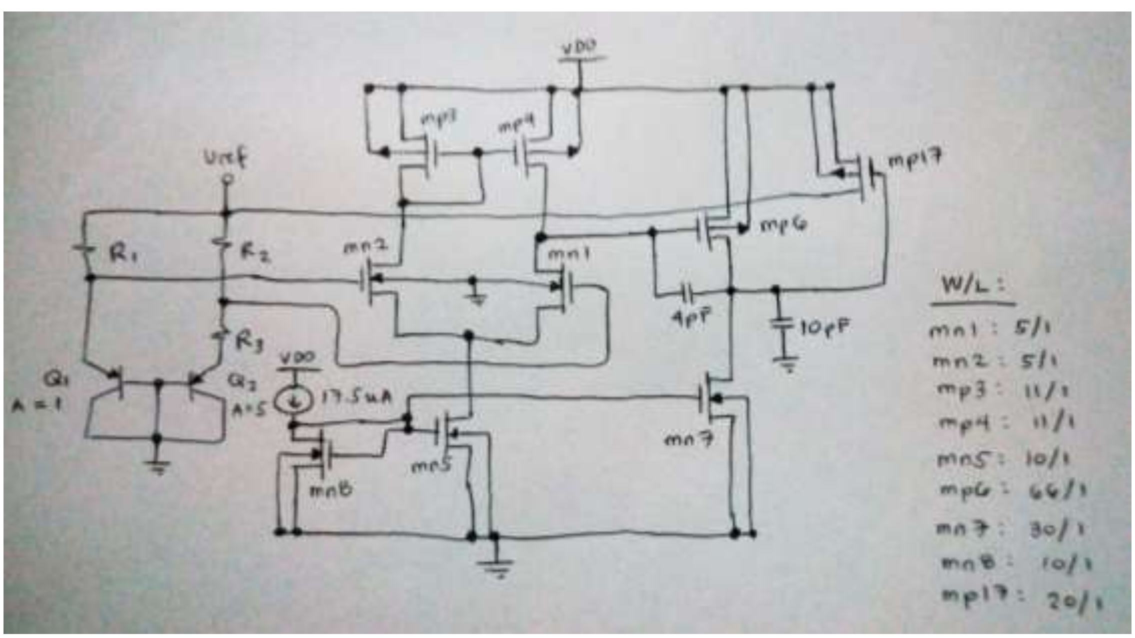
Voltage references are electronic devices that can produce a constant amount of voltage. Ideally, its constant voltage output does not vary with respect to the loading, the changes in supply voltage, the changes in temperature, and varying manufacturing process. Commonly, voltage references are called voltage sources; but technically, voltage references are used to create voltage sources.

Objective

This laboratory activity aims to produce a design of voltage reference using the operational amplifier previously constructed in activity no. 4. Changes of the output voltage with respect to the changes in temperature, voltage supply, and process corners are to be observed in this activity.

Procedure

Construct the bandgap voltage reference circuit diagram below and set equal initial values for resistances R1, R2, and R3.



Set R1 = R2 = R3 = 7 kΩ and simulate (TT process corner only).

opamp_bandgap - Notepad

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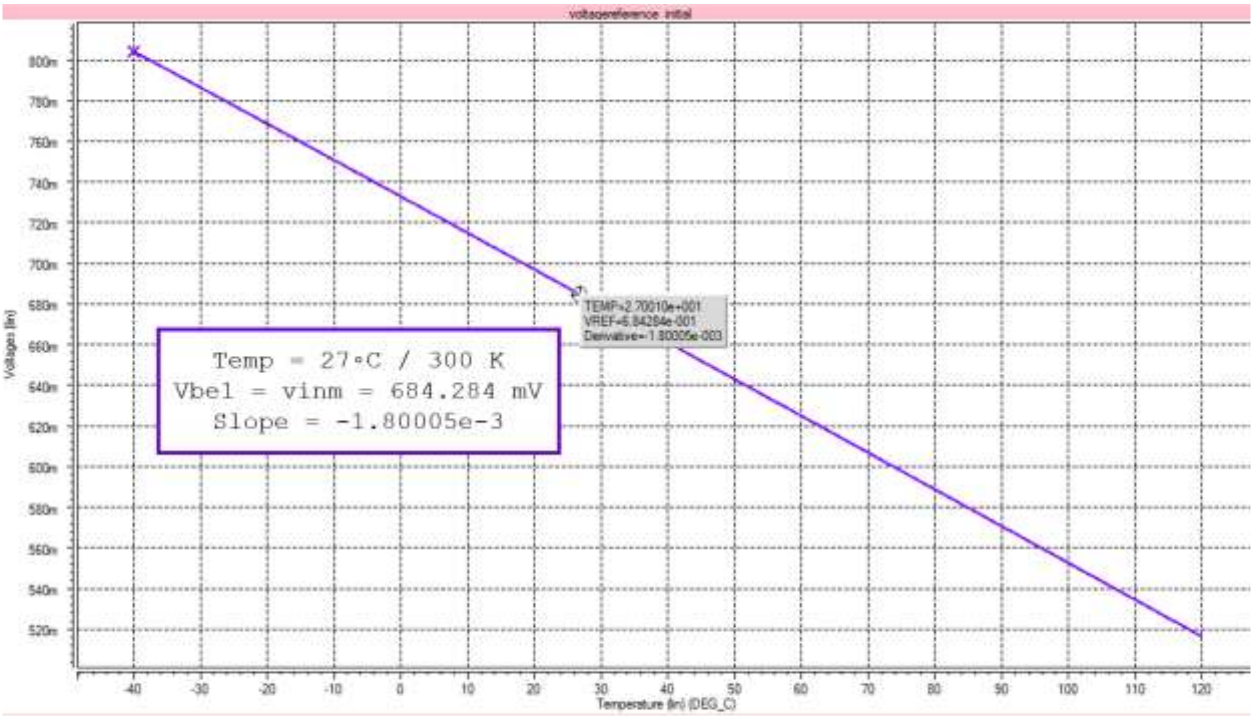
```
VoltageReference_Initial

.lib 'mm018.l' tt
.lib 'mm018.l' tt_bip
.subckt opamp vinm vinp vout
vdd vdd gnd 1.8v
mp4 vx vg1 vdd vdd pch w=11u l=1u
mp3 vg1 vg1 vdd vdd pch w=11u l=1u
mn2 vg1 vinm vs1 gnd nch w=5u l=1u
mn1 vx vinp vs1 gnd nch w=5u l=1u
mn5 vs1 vg2 gnd gnd nch w=10u l=1u
mn8 vg2 vg2 gnd gnd nch w=10u l=1u
mp6 vout vx vdd vdd pch w=30u l=1u
mn7 vout vg2 gnd gnd nch w=30u l=1u

Iref vdd vg2 17.5u
cc vx vout 4p
cload vout gnd 10p
.ends

vdd vdd gnd 1.8v
xopamp vinm vinp vout opamp
q1 gnd gnd vinm pnp10 area=1
q2 gnd gnd ve2 pnp10 area=5
mp17 vref vout vdd vdd pch w=20u l=1u
r1 vref vinm 7k
r2 vref vinp 7k
r3 vinp ve2 7k

.option post probe
.dc temp -40 120 0.1
.dc vdd 1.62 1.98 0.1
.op
.probe v(vref), v(vinm), v(vinp,ve2)

.end
```

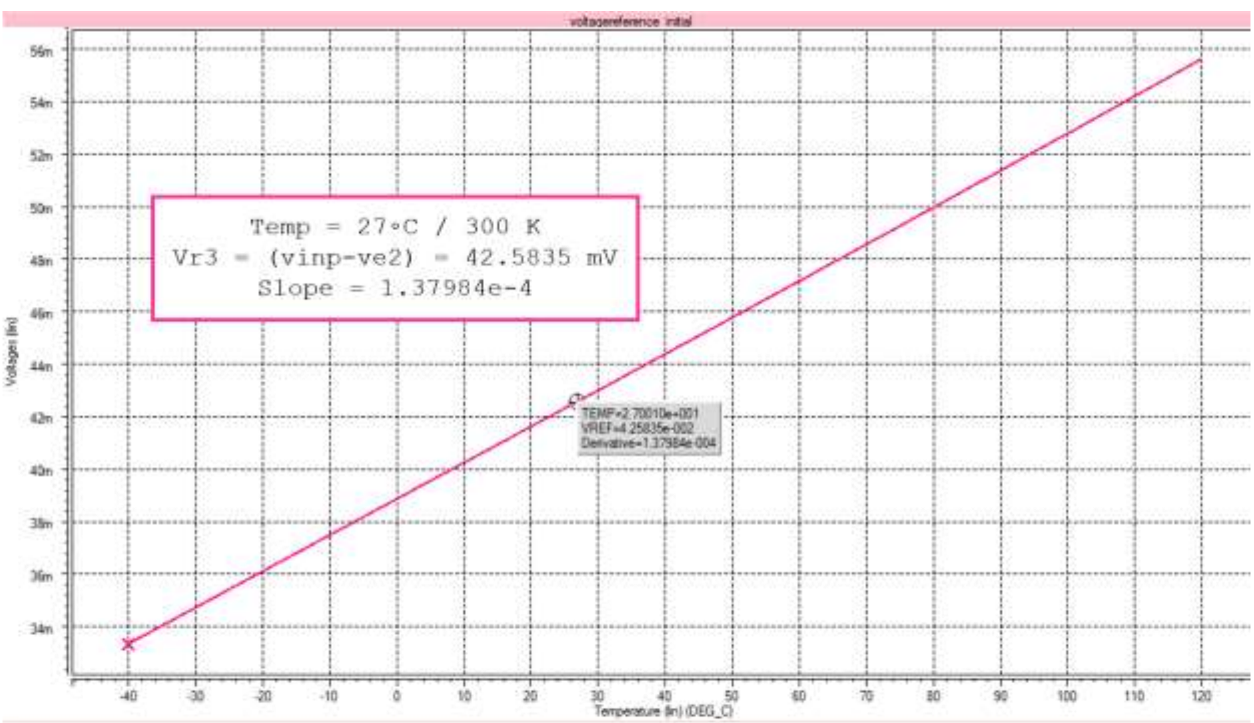
**** mosfets

subckt		xopamp	xopamp	xopamp	xopamp	xopamp	xopamp	xopamp	xopamp
element	0:mp17	1:mp4	1:mp3	1:mn2	1:mn1	1:mn5	1:mn8	1:mp6	1:mn7
model	0:pch.2	0:pch.2	0:pch.2	0:nch.5	0:nch.5	0:nch.5	0:nch.5	0:pch.2	0:nch.2
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	-12.1856u	-8.0374u	-7.9933u	7.9933u	8.0374u	16.0307u	17.5000u	-54.9422u	54.9421u
ibs	1.2553a	8.412e-19	8.366e-19	-188.1248a	-188.1248a	-3.108e-20	-3.393e-20	5.6227a	-1.041e-19
ibd	37.0889f	20.5417f	20.5417f	-3.6043p	-813.6146f	-363.5461a	-366.9388a	54.7791f	-122.1078p
vgs	-572.5568m	-588.7123m	-588.7123m	562.4238m	563.1080m	533.8898m	533.8898m	-690.5417m	533.8898m
vds	-1.0691	-690.5417m	-588.7123m	1.0858	983.9968m	125.4615m	533.8898m	-572.5568m	1.2274
vbs	0.	0.	0.	-125.4615m	-125.4615m	0.	0.	0.	0.
vth	-458.5495m	-458.6383m	-458.6618m	518.1284m	518.1526m	483.4028m	483.3087m	-458.6638m	482.7150m
vdsat	-133.6906m	-144.3100m	-144.2936m	109.5749m	109.9857m	113.1262m	113.1857m	-220.3299m	113.5311m
vod	-114.0073m	-130.0739m	-130.0504m	44.2954m	44.9554m	50.4871m	50.5812m	-231.8779m	51.1748m
beta	1.4300m	794.7320u	794.7277u	2.0543m	2.0541m	4.1930m	4.1930m	2.0833m	12.6231m
gam eff	487.0362m	496.0994m	496.0994m	516.6628m	516.6628m	511.7809m	511.7809m	483.3501m	531.0444m
gm	149.0823u	91.7464u	91.3281u	125.8040u	126.3507u	235.9377u	269.6497u	408.0533u	837.4950u
gds	594.1761n	420.4814n	447.2459n	409.6834n	419.5245n	24.7889u	1.1261u	2.8911u	2.6583u
gmb	48.8054u	30.1251u	29.9862u	33.8988u	34.0454u	67.6364u	77.1915u	134.5298u	243.3598u
cdtot	23.0385f	13.5456f	13.8124f	5.2485f	5.3131f	12.6577f	11.4717f	37.5308f	30.8087f
cgtot	123.1419f	69.0659f	69.0659f	24.6075f	24.7227f	51.3471f	51.3470f	195.9453f	154.8115f
cstot	156.4698f	88.4316f	88.4316f	26.8314f	27.0233f	57.7516f	57.7515f	254.3388f	174.4806f
cbtot	83.7827f	47.4705f	47.7373f	17.7127f	17.7866f	39.0557f	37.8697f	128.9203f	110.7538f
cgs	100.5458f	56.8615f	56.8615f	17.3158f	17.4615f	36.8747f	36.8746f	165.9628f	111.1670f
cgd	6.5502f	3.5982f	3.5982f	1.8252f	1.8252f	3.6577f	3.6577f	9.8302f	10.9877f

Observe the changes in the base-emitter voltage of Q1 with respect to varying temperature and also indicate the resulting voltage at room temperature (300 K).



Observe the changes in the voltage across R3 and do the same as the previous instruction.



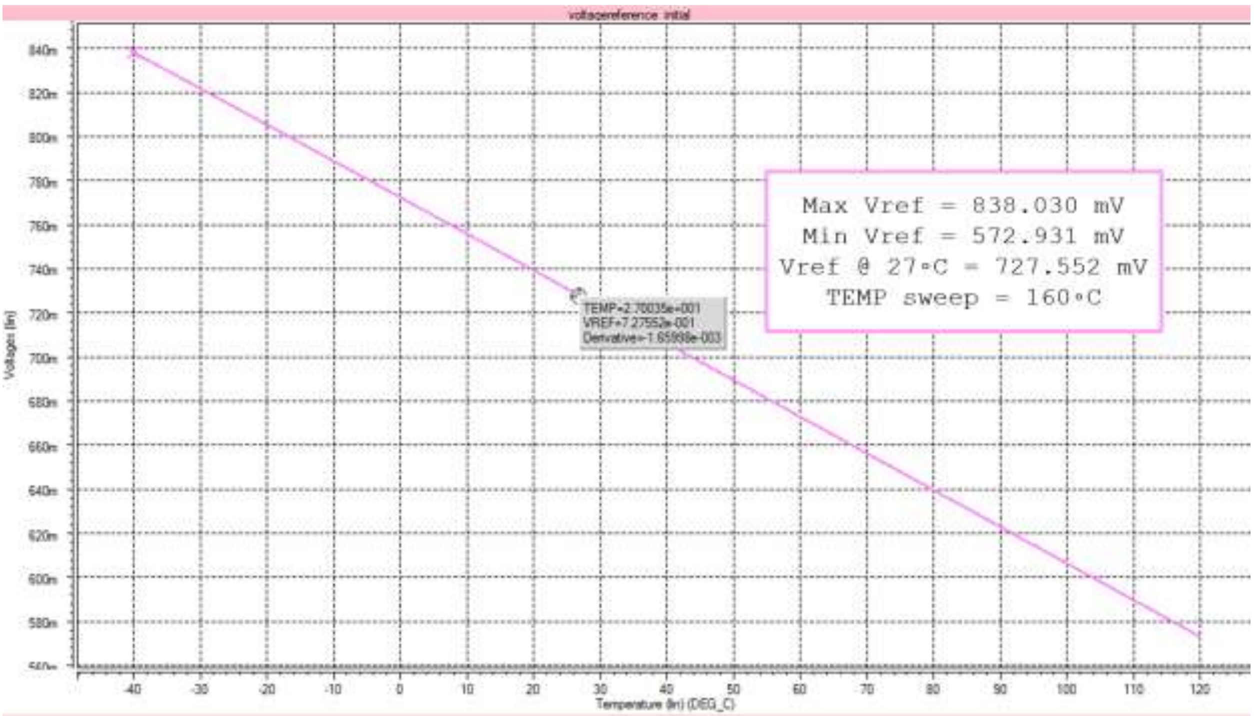
TEMPERATURE COEFFICIENT

$$TC = \frac{V_{ref\,max} - V_{ref\,min}}{\text{TEMP sweep} \times V_{ref} \text{ at } 27°C}$$

SENSITIVITY TO VOLTAGE SUPPLY CHANGE

$$S\left(\frac{V_{ref}}{V_{dd}}\right) = \frac{V_{dd}}{V_{ref}}\left(\frac{dV_{ref}}{dV_{dd}}\right) \times 100\%$$

Observe the changes in the value of Vref with respect to the changing temperature.



Solve for the Temperature Coefficient (changes in voltage value per degree Celsius) using the formula indicated.

INITIAL :

$$TC = \frac{0.838030 - 0.572931}{160\,(0.727552)} = 2277.32 \text{ ppm}/°C$$

For optimal performance, solve for the values of R1 and R2 with respect to R3 by using the idea that Vref = Vbe1 + (R1/R3) ln(n) Vr3.

FROM THE RELATION

$$\frac{\partial V_{ref}}{\partial T} = \alpha_1 \frac{\partial V_{be1}}{\partial T} + \alpha_2 \frac{\partial V_{r3}}{\partial T} \; ;$$

$$\frac{\partial V_{ref}}{\partial T} = 0 = -1.80005\,(10^{-3}) + 1.37984\,(10^{-4})\left(\frac{R_1}{R_3}\right)$$

$$R_1 = 13 R_3 = R_2$$

$$\boxed{\begin{array}{l} \therefore\; R_1 = R_2 = 91\ k\Omega \\ R_3 = 7k\Omega \end{array}}$$

Using the new values for R1 and R2, simulate again the bandgap reference voltage but now in three (3) different process corners (TT, FF, SS).

opamp_bandgap_design - Notepad

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```
VoltageReference_Design

.lib 'mm018.l' tt
.lib 'mm018.l' tt_bip
.subckt opamp vinm vinp vout
vdd vdd gnd 1.8v
mp4 vx vg1 vdd vdd pch w=11u l=1u
mp3 vg1 vg1 vdd vdd pch w=11u l=1u
mn2 vg1 vinm vs1 gnd nch w=5u l=1u
mn1 vx vinp vs1 gnd nch w=5u l=1u
mn5 vs1 vg2 gnd gnd nch w=10u l=1u
mn8 vg2 vg2 gnd gnd nch w=10u l=1u
mp6 vout vx vdd vdd pch w=30u l=1u
mn7 vout vg2 gnd gnd nch w=30u l=1u

Iref vdd vg2 17.5u
cc vx vout 4p
cload vout gnd 10p
.ends
```

```
vdd vdd gnd 1.8v
xopamp vinm vinp vout opamp
q1 gnd gnd vinm pnp10 area=1
q2 gnd gnd ve2 pnp10 area=5
mp17 vref vout vdd vdd pch w=20u l=1u
r1 vref vinm 91k
r2 vref vinp 91k
r3 vinp ve2 7k

.option post probe
.dc temp -40 120 0.1
.dc vdd 1.62 1.98 0.1
.op
.probe v(vref)

.end
```

TT:

**** mosfets

subckt		xopamp	xopamp	xopamp	xopamp	xopamp	xopamp	xopamp	xopamp
element	0:mp17	1:mp4	1:mp3	1:mn2	1:mn1	1:mn5	1:mn8	1:mp6	1:mn7
model	0:pch.2	0:pch.2	0:pch.2	0:nch.5	0:nch.5	0:nch.5	0:nch.5	0:pch.2	0:nch.2
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	-11.9868u	-8.0318u	-7.9878u	7.9877u	8.0318u	16.0195u	17.5000u	-54.9401u	54.9400u
ibs	1.2348a	8.406e-19	8.360e-19	-188.0997a	-188.0997a	-3.106e-20	-3.393e-20	5.6225a	-1.040e-19
ibd	36.7594f	20.5417f	20.5417f	-3.6273p	-819.4961f	-363.4976a	-366.9388a	54.7791f	-121.1182p
vgs	-573.3493m	-588.6518m	-588.6518m	562.2580m	562.9425m	533.8898m	533.8898m	-690.5309m	533.8898m
vds	-566.9834m	-690.5309m	-588.6518m	1.0863	984.4528m	125.0163m	533.8898m	-573.3493m	1.2267
vbs	0.	0.	0.	-125.0163m	-125.0163m	0.	0.	0.	0.
vth	-458.6652m	-458.6383m	-458.6618m	518.0090m	518.0332m	483.4029m	483.3087m	-458.6636m	482.7152m
vdsat	-134.1559m	-144.2675m	-144.2510m	109.5444m	109.9553m	113.1261m	113.1857m	-220.3219m	113.5310m
vod	-114.6841m	-130.0134m	-129.9899m	44.2490m	44.9093m	50.4870m	50.5812m	-231.8673m	51.1746m
beta	1.4297m	794.7413u	794.7370u	2.0543m	2.0542m	4.1930m	4.1930m	2.0834m	12.6231m
gam eff	487.0362m	496.0994m	496.0994m	516.6653m	516.6653m	511.7809m	511.7809m	483.3501m	531.0444m
gm	146.9223u	91.7083u	91.2900u	125.7362u	126.2831u	235.6293u	269.6497u	408.0546u	837.4720u
gds	698.2952n	420.2479n	447.0027n	409.4365n	419.2650n	25.1026u	1.1261u	2.8870u	2.6585u
gmb	48.0859u	30.1125u	29.9736u	33.8878u	34.0345u	67.5491u	77.1915u	134.5301u	243.3531u
cdtot	25.0991f	13.5456f	13.8126f	5.2485f	5.3131f	12.6594f	11.4717f	37.5249f	30.8115f
cgtot	123.2728f	69.0619f	69.0619f	24.6000f	24.7153f	51.3471f	51.3470f	195.9451f	154.8115f
cstot	156.6992f	88.4245f	88.4245f	26.8193f	27.0115f	57.7516f	57.7515f	254.3384f	174.4806f
cbtot	85.8549f	47.4701f	47.7371f	17.7147f	17.7887f	39.0574f	37.8697f	128.9144f	110.7566f
cgs	100.7168f	56.8562f	56.8562f	17.3050f	17.4509f	36.8747f	36.8746f	165.9624f	111.1670f
cgd	6.5502f	3.5982f	3.5982f	1.8252f	1.8252f	3.6577f	3.6577f	9.8302f	10.9877f

FF:

**** mosfets

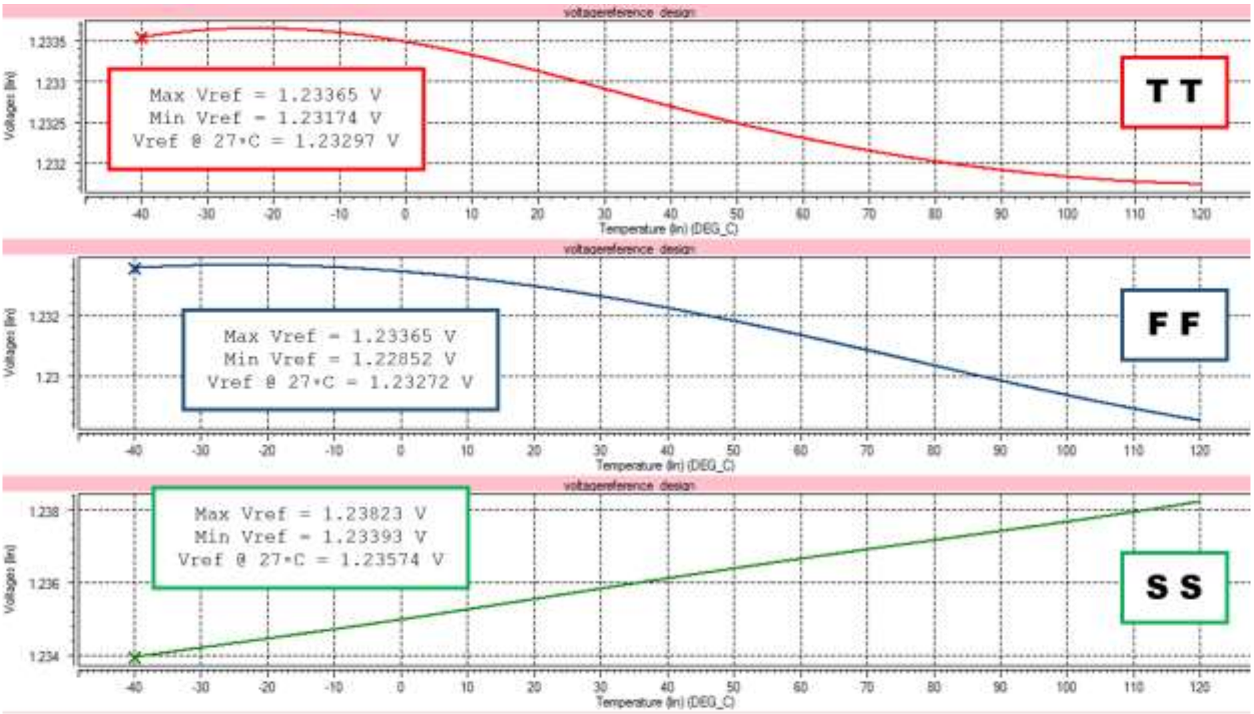
subckt		xopamp	xopamp	xopamp	xopamp	xopamp	xopamp	xopamp	xopamp
element	0:mp17	1:mp4	1:mp3	1:mn2	1:mn1	1:mn5	1:mn8	1:mp6	1:mn7
model	0:pch.2	0:pch.2	0:pch.2	0:nch.5	0:nch.5	0:nch.5	0:nch.5	0:pch.2	0:nch.2
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	-11.9821u	-8.5303u	-8.4828u	8.4828u	8.5303u	17.0131u	17.5000u	-55.9701u	55.9698u
ibs	1.2343a	8.928e-19	8.878e-19	-190.2707a	-190.2707a	-3.299e-20	-3.393e-20	5.7278a	-1.060e-19
ibd	36.7990f	20.5813f	20.5813f	-3.3472p	-799.9261f	-366.9687a	-367.0984a	54.8187f	-257.1579p
vgs	-500.9453m	-521.2865m	-521.2865m	482.9710m	483.6405m	430.6076m	430.6076m	-617.5623m	430.6076m
vds	-567.2135m	-617.5623m	-521.2865m	1.0744	978.1448m	204.2929m	430.6076m	-500.9453m	1.2991
vbs	0.	0.	0.	-204.2929m	-204.2929m	0.	0.	0.	0.
vth	-391.7983m	-391.7605m	-391.7827m	438.9203m	438.9436m	383.4417m	383.3894m	-391.8249m	382.8454m
vdsat	-130.2488m	-143.8107m	-143.7951m	109.2582m	109.6608m	110.5584m	110.5909m	-215.5912m	110.9623m
vod	-109.1470m	-129.5260m	-129.5038m	44.0507m	44.6968m	47.1659m	47.2182m	-225.7374m	47.7622m
beta	1.5342m	852.6267u	852.6224u	2.2027m	2.2026m	4.4820m	4.4820m	2.2342m	13.5959m
gam eff	487.2530m	496.3698m	496.3698m	516.1361m	516.1361m	511.6158m	511.6158m	483.5404m	531.1462m
gm	150.9120u	97.8154u	97.3463u	134.6599u	135.2541u	266.1914u	275.1161u	425.1762u	868.4627u
gds	716.2573n	474.3051n	515.0396n	440.8704n	451.0247n	4.5175u	1.3337u	3.4519u	2.7483u
gmb	49.3880u	32.1106u	31.9552u	34.7885u	34.9415u	75.7184u	78.2412u	140.2008u	250.9518u
cdtot	24.5249f	13.4339f	13.6903f	5.1524f	5.2078f	12.1457f	11.5192f	37.1953f	30.1530f
cgtot	125.2503f	70.7455f	70.7455f	25.2185f	25.3346f	51.6380f	51.6379f	200.3777f	155.4363f
cstot	156.8654f	89.5254f	89.5254f	26.9711f	27.1612f	56.6520f	56.6520f	257.2007f	170.8510f
cbtot	84.6916f	47.1152f	47.3716f	17.0765f	17.1406f	38.2418f	37.6154f	127.8162f	109.1150f
cgs	101.7246f	58.1543f	58.1543f	17.8725f	18.0183f	36.4442f	36.4442f	169.4140f	109.6465f
cgd	6.8852f	3.7856f	3.7856f	1.9249f	1.9249f	3.8490f	3.8490f	10.3292f	11.5455f

SS:

**** mosfets

subckt		xopamp	xopamp	xopamp	xopamp	xopamp	xopamp	xopamp	xopamp
element	0:mp17	1:mp4	1:mp3	1:mn2	1:mn1	1:mn5	1:mn8	1:mp6	1:mn7
model	0:pch.2	0:pch.2	0:pch.2	0:nch.5	0:nch.5	0:nch.5	0:nch.5	0:pch.2	0:nch.2
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	-12.0408u	-5.7530u	-5.7124u	5.7124u	5.7530u	11.4654u	17.5000u	-54.0705u	54.0704u
ibs	1.2404a	6.022e-19	5.979e-19	-170.3000a	-170.3000a	-2.223e-20	-3.394e-20	5.5335a	-1.024e-19
ibd	36.7197f	20.5020f	20.5020f	-3.7755p	-594.4694f	-329.7504a	-509.4995a	54.7394f	-51.3523p
vgs	-646.0858m	-633.0563m	-633.0563m	627.6929m	628.5514m	637.7840m	637.7840m	-763.7534m	637.7840m
vds	-564.3189m	-763.7534m	-633.0563m	1.1072	976.5459m	59.7007m	637.7840m	-646.0858m	1.1539
vbs	0.	0.	0.	-59.7007m	-59.7007m	0.	0.	0.	0.
vth	-525.5363m	-525.5193m	-525.5493m	600.1551m	600.1855m	583.3622m	583.2295m	-525.5064m	582.5891m
vdsat	-138.3207m	-128.8766m	-128.8564m	99.8446m	100.3153m	116.1533m	116.2386m	-225.2429m	116.5509m
vod	-120.5494m	-107.5370m	-107.5070m	27.5379m	28.3659m	54.4218m	54.5545m	-238.2470m	55.1949m
beta	1.3354m	745.5245u	745.5192u	1.9125m	1.9123m	3.8941m	3.8942m	1.9473m	11.6540m
gam eff	486.8255m	495.8370m	495.8370m	517.1270m	517.1270m	511.9413m	511.9413m	483.1651m	530.9453m
gm	143.4602u	72.6300u	72.2151u	94.6522u	95.2170u	137.9611u	263.7658u	392.3584u	808.2221u
gds	685.5166n	303.0593n	318.8846n	309.1585n	318.0396n	124.2963u	1.0047u	2.5203u	2.5767u
gmb	46.9521u	23.8288u	23.6909u	26.5079u	26.6649u	40.0480u	75.9261u	129.3226u	235.9114u
cdtot	25.6851f	13.6497f	13.9903f	5.3344f	5.4250f	13.1785f	11.4267f	37.8347f	31.5096f
cgtot	121.3480f	65.5903f	65.5903f	20.6945f	20.8912f	51.1728f	51.1726f	191.7189f	154.5173f
cstot	156.5370f	84.1214f	84.1214f	21.0843f	21.4175f	59.0067f	59.0062f	251.7097f	178.5592f
cbtot	87.0750f	47.6817f	48.0223f	18.0224f	18.1305f	39.9072f	38.1554f	130.0741f	112.5284f
cgs	99.7141f	53.1760f	53.1760f	12.5614f	12.8118f	37.4235f	37.4231f	162.6856f	113.0237f
cgd	6.2158f	3.4114f	3.4114f	1.7263f	1.7263f	3.4671f	3.4671f	9.3318f	10.4306f

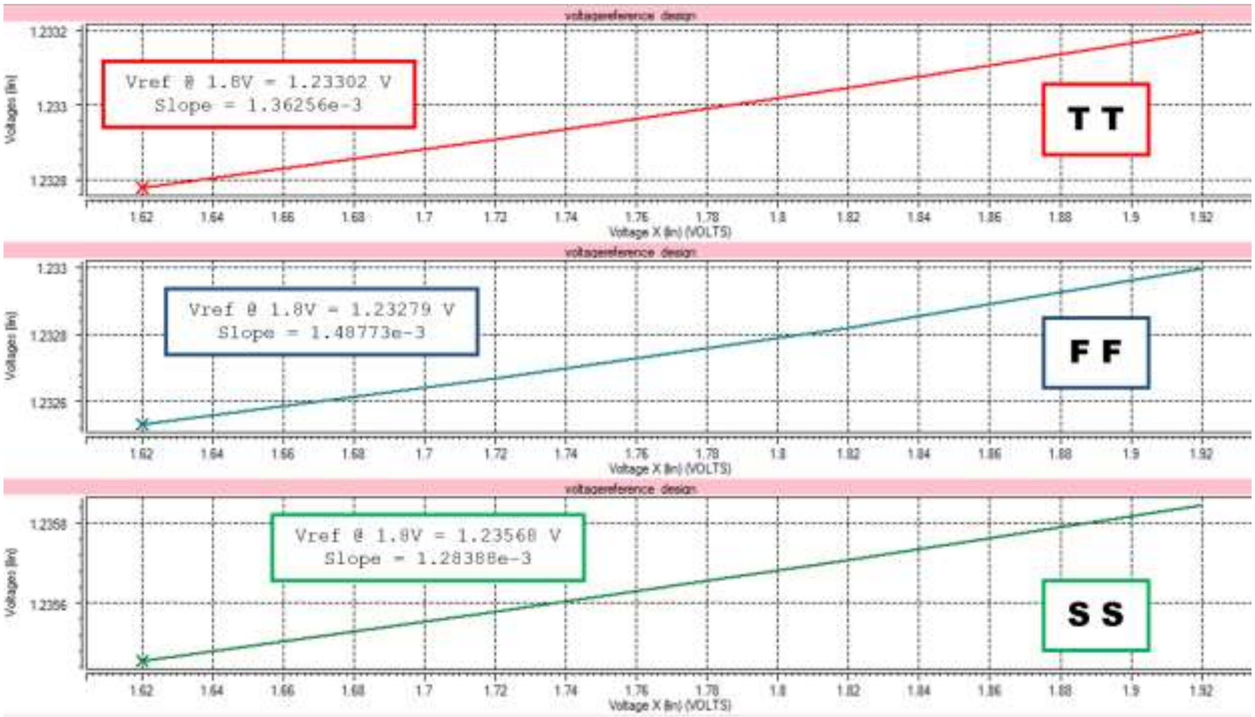
Observe the changes in the values of Vref with respect to the changes in temperature in three (3) different process corners.



PROCESS CORNERS	TEMPERATURE COEFFICIENT (ppm/∘C)
TT	9.68191
FF	26.00956
SS	21.74810

Calculations:

Observe the changes in the values of Vref with respect to the changes in the voltage supply (±10%) in three (3) different process corners.



PROCESS CORNERS	SENSITIVITY TO VDD CHANGE
TT	0.19891%
FF	0.21722%
SS	0.18702%

Calculations:

Discussion of Results

The initial circuit having R1 = R2 = R3 = 7 kΩ has a temperature coefficient of 2227.32 ppm/◦C which is relatively high. To improve the performance of this voltage reference with respect to its dependence on temperature variation, R1 and R2 were both set to 91 kΩ according to the relation specified earlier in this activity.

After the changes in the values of the resistors, the new voltage reference was simulated in three different process corners. The results are much better as compared to the initial design: from 2227.32 ppm/◦C to less than 30 ppm/◦C.

The results on the variation of the supply voltage (VDD±10%) show that the new design has less than 1% sensitivity to sudden changes in supply voltage in all three process corners.

Looking at the results with respect to the different process corners, there are apparent differences among the processes especially in temperature variation. The supply voltage variation has somehow the same results in the three processes but looking closely to their values, there are differences in the millivolts scale.

Conclusion

The designed bandgap voltage reference in this activity is considerably good in terms of its independence on the changes in temperature and changes in supply voltage. The different process corners, however, impact the way the output of the reference voltage should behave. Overall, this design performs as it should be but no way near ideal voltage references where there is complete independence on the varying parameters.