AN IMPROVED BANDGAP REFERENCE WITH HIGH POWER SUPPLY REJECTION

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ABSTRACT

An improved bandgap reference with high power supply rejection (PSR) is presented. The proposed circuit consists of a simple voltage subtractor circuit incorporated into the conventional Brokaw bandgap reference. Essentially, the subtractor feeds the supply noise directly into the feedback loop of the bandgap circuit which could help to suppress supply noise. The simulation results have been shown to conform well with the theoretical evaluation. The proposed circuit has also shown robust performance across temperature and process variations.

1. INTRODUCTION

Many analog-digital systems utilize bandgap reference to provide precise and stable voltage reference across wide temperature range. There is an increasing demand to have high rejection of power supply noise in analog-digital systems, particularly in wireless communication circuits. The performance of measure is known as power-supply rejection (PSR). The supply noise coupled to the reference node of the integrated bandgap circuit can pose as a significant noise source to the remaining systems. Thus, a high PSR bandgap reference is desired for high performance analog-digital systems[1][2][3].

A widely used bandgap reference[3] is illustrated in Fig.1. The DC value of V_{BG} can be expressed as

$$V_{BG} = V_{BE2} + (R_2/R_1)V_t \ln N \qquad (1)$$

where N is the emitter ratio of Q2 over Q1 and $V_t \approx$ 25mV. The small signal variation of V_{BG} (v_{bg}) due to supply noise (v_{dd}) is given by

$$v_{bg} = A_{dd2}v_{dd} + v_{c1}(-g_{m2}/g_{o2}) \qquad (2)$$

where A_{dd2} is the power gain = v_{c1}/v_{dd}, and v_{c1} is the small signal variation at the gate terminal of PMOS current mirror. Using the methodology as in [4], the PSR can be shown as

$$PSR = \frac{v_{bg}}{v_{dd}} \approx \frac{1}{1-\frac{\beta_2}{\beta_1}}\left[\frac{1}{A_1} + \frac{g_{o2}}{g_{m2}}\frac{1}{A_1} - \frac{1}{PSRR_1}\right]\frac{1}{\beta_1} \qquad (3)$$

where $PSRR_1$ is the power supply rejection ratio of op-amp and is given by $PSRR_1 = A_1/A_{dd1}$. Also, $\beta_1 = \frac{g_{mQ1}+R_1}{g_{mQ1}+R_1+R_2}$, $\beta_2 = \frac{g_{mQ2}}{g_{mQ2}+R_3}$, and A_1 and A_{dd1} are the open-loop differential gain and power gain of amplifier respectively.

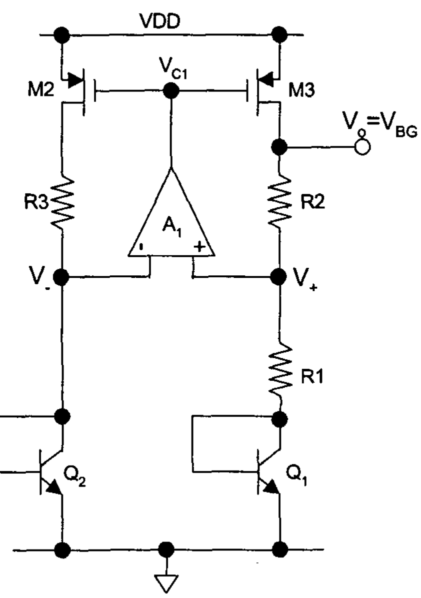

Figure 1. Conventional bandgap reference

From (1), the PSR is dominated by the first term, i.e. $\frac{1}{1-\frac{\beta_2}{\beta_1}}\left[\frac{1}{A_1\beta_1}\right]$. Thus, with an amplifier open-loop DC gain of 98dB and a resistor ratio R2/R1 of 10, the PSR yields approximately -78dB. Thus, an easy technique to improve PSR is to increase the loop gain[5] (loop formed by the amplifier and the PMOS current mirror). By increasing the amplifier's open-loop gain (A_1), the PSR would further increase. However, a high loop gain system generally poses risk to stability. Another technique is to employ a voltage regulator to provide pre-regulation and used its output as the supply node for the bandgap reference[3]. However, this technique can cost "headroom" for low voltage operation and consume significant power consumption.

In this paper, a simple circuit is proposed which can be easily integrated into the existing bandgap reference circuit and improve the PSR performance.

2. IMPROVED BANDGAP REFERENCE

The basic idea is to have a voltage-subtractor integrated as shown in Fig.2, which feed the supply noise directly into the feedback loop and modulate the gate with respect to the source terminals of PMOS current mirror. This would reduce the drain current variation from the PMOS and allow the reference node to be less sensitive to the supply noise. Note that the input terminals to the op-amp need to be reversed as compared with the conventional configuration since the subtractor also would produce a phase inversion in the loop.

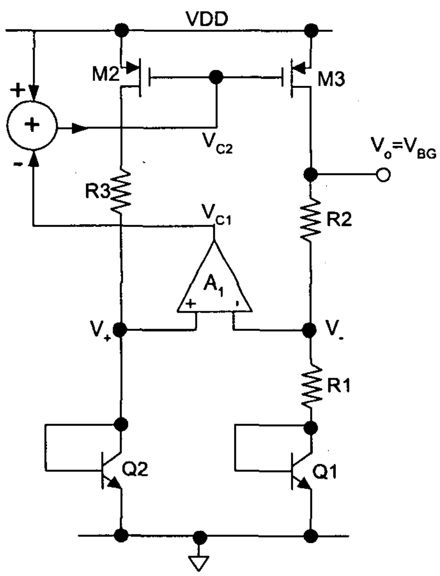

Figure 2. Improved bandgap reference.

The subtractor can be easily implemented using two NMOS transistors[6] which is illustrated in Fig.3. It can be shown that the PSR of the modified bandgap reference circuit is given by

$$PSR=\frac{v_{bg}}{v_{dd}}=$$

$$\frac{1}{1-\frac{\beta_2}{\beta_1}}\left[\frac{g_{o42}-g_{o41}}{g_{m42}}\frac{1}{A_1}+\frac{g_{m41}+g_{o42}}{g_{m42}}\frac{g_{o2}}{g_{m2}}\frac{1}{A_1}+\frac{1}{PSRR_1}\right]\frac{1}{\beta_1} \quad (4)$$

By comparing between (3) and (4), it is shown that the dominant term $\frac{1}{1-\frac{\beta_2}{\beta_1}}\left(\frac{1}{A_1\beta_1}\right)$ is eliminated . The dominant term in (4) is now $\frac{1}{1-\frac{\beta_2}{\beta_1}}\left(\frac{1}{PSRR_1}\right)$. Thus, a good design of the op-amp with high PSRR would generally have high PSR for the bandgap reference.

Similar results can also be observed if MN1 is replaced by a PMOS with gate and drain terminals tied in a 'diode' connection as in Fig.3.

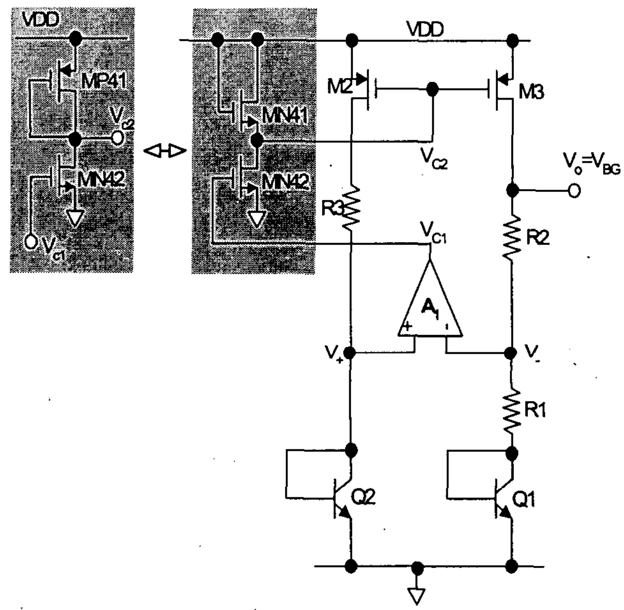

Figure 3. Implementation of the improved bandgap reference.

The op-amp used in the bandgap circuit is a simple two stage operational transconductance amplifier as illustrated in Fig.4. The component sizes and values of the bandgap circuit are listed in Table 1. The open-loop gain is 98dB.

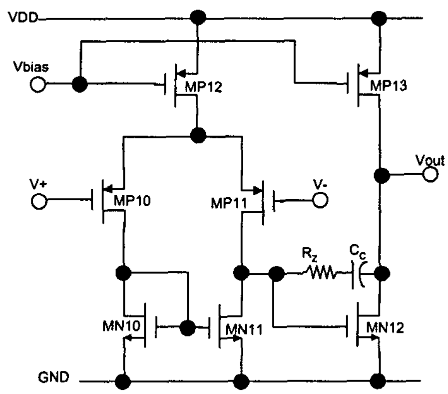

Figure 4. Op-amp used in the bandgap reference.

Table 1. Circuit components

Components	Value/Size M(W/L)
M2, M3	16(6um/6um)
R2,R3	103k ohms
R1	10k ohms
MP10, MP11	2(20um/2um)
MP12	8(2um/2um)
MP13	32(2um/2um)
MN10,MN11	4(2um/2um)
MN12	40(2um/2um)
R_Z, C_C	1k ohms , 2pF
MN41, MN42	2um/2um

3. SIMULATION RESULTS

3.1. Nominal performance

Simulation has been carried out using a 0.8um BiCMOS technology. The temperature dependency for both the conventional and proposed bandgap reference is shown in Fig.5. Both waveforms exhibit comparable temperature coefficients over the range from –40°C to 125°C. For simplicity, the aspect ratios for MN41 and MN42 are the same. This gives a unity DC gain for that branch which still maintains the same loop-gain as in the conventional circuit. The current consumption of the branch is only 2uA. The PSR performances at room temperature between the two circuits are compared in Fig.6. The proposed circuit is shown to have improved the PSR at low frequency by approximately 30dB. Using equation (3) and (4), the PSRs are calculated as 77.1dB and 107.4dB respectively while the simulated values are 77.4dB and 110.3dB. The simulation results are closed to that of the theoretical evaluated values. The simulation results are summarized in Table 2.

Table 2. Nominal simulation results

	Conventional	Improved
Mean I_{DD}	33uA	35uA
Mean V_{BG}	1.208	1.207
Temperature Drift	3.1mV in –40degC to 125degC	2.8mV in –40degC to 125degC
PSR at DC	77.4dB	110.3dB
PSR at 1kHz	47.3dB	98.4dB

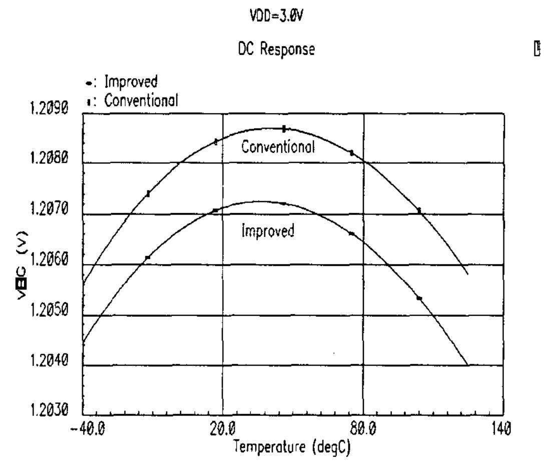

Figure 5. Temperature dependence of reference voltage.

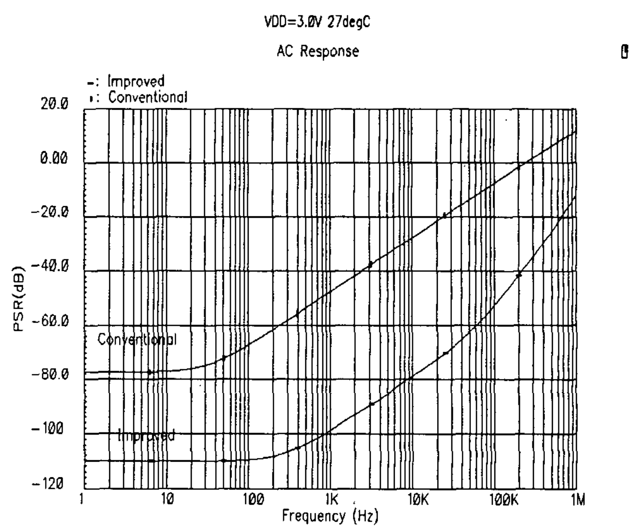

Figure 6. PSR of bandgap reference between conventional and improved reference circuits.

3.2. Temperature and process variation

To verify the robustness of the improved bandgap reference, the circuit has been simulated under different temperature and process conditions. The performance is summarized in Table 3. It is shown that over a wide temperature range, the improved bandgap reference has a higher PSR at low and medium frequency. Simulation has also been carried using two extreme process models i.e., "weak" and "strong" models which correspond to a deviation of about 20% of Idrive characteristics (drain current measured when transistor biased in triode region) from the nominal model. The results are compared in Figure 7. It is shown the improved bandgap reference yields a reasonably good PSR performance across the process variations.

Table 3. Simulation results of bandgap reference with temperature variation.

	Conventional	Improved
	DC, 1kHz	DC, 1kHz
-40 degC	77.2dB, 48.4dB	108.6dB, 103.8dB
25degC	77.4dB, 47.5dB	110.0dB, 98.5dB
125degC	78.0dB, 46.5dB	101.0dB, 93.1dB

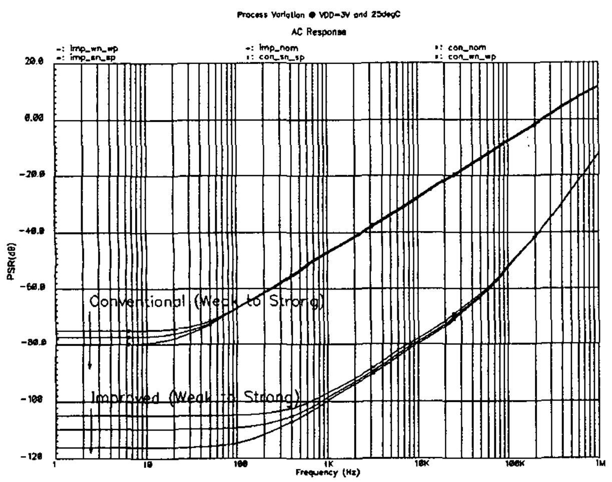

Figure 7. PSR of bandgap reference between conventional and improved reference circuits over process corners.

4. CONCLUSION

By incorporating a simple voltage subtractor circuit, the PSR of a conventional bandgap reference could achieve significant improvement. The proposed circuit does not add much complexity to the original bandgap reference. It also consumes little silicon space and power, and is suitable for low voltage operation. The theoretical calculation of PSR matches closely with the simulated value. The improved bandgap reference is shown to have good PSR performance across temperature and process variation as compared to the conventional implementation.

5. REFERENCES

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