Steve Flannagan's

IC Design Journal

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Dear Friends and Colleagues,

In the last issue, I emphasized that good opportunities can be found even in rough times, for those with insight. In this issue I have for you:

1. How to Build a World-Class Business
2. Direct your Career with World-Class Quality
3. Today's Technical Feature: Understanding Temperature Independence

The theme of the next few issues is "*To be the Very Best*." I will review the key requirements for building a world-class business, and show how the careers of individuals contribute to this enterprise.

For our Technical Topic, we will return to the On-Chip regulator begun in the previous issue, and explore how temperature independence actually arises in a design.

Thank you all very much for your comments and feedback. Be assured that I read every letter and email individually, and will continue to be your partner for a bright future in Technology!

Sincerely,
Steve

Business Outlook

To Be the Very Best

Have you ever asked the question, "What does it take to be the very best in the entire world?"

Generally, it's believed that taking an enterprise to the world leadership position requires about five years. As many times as I've observed this process, and had the privilege to participate in it, the path has been different each time. But certain essential components are always present.

Define responsibilities coherently

The most important advantage is a culture that contains a good spirit of co-operation, where the individual is totally dedicated to the success of everyone involved: their co-workers, superiors, subordinates and customers. This is best achieved when responsibilities are defined coherently. Job definitions should be flexible and coordinated with the mission. Especially, they must not be in conflict with one another.

Know where you are

Intensity of effort can never be the whole story. Success also depends on timing, positioning, and wise choice of the mission. Often a specific idea will be ripe at a given time, when the market needs it and the industry has not yet exploited the best architecture for the product. Your own organization may be in a better position to excel at one particular enterprise and not others. A careful choice for the first product is very important.

For similar reasons, study carefully the existing state-of-the-art. Especially look for key difficulties for which prior designs may not have the strongest solution. Often, this is a good opportunity to gain an extremely significant advantage.

Provide for frequent communication between your designers and product engineers. Testing and evaluation of products (both your own and those from other companies) is essential for making good design improvements and breakthroughs.

Allow time for exploration

Early in the project, the team needs the flexibility to study and understand design needs. This phase of design must be adequately staffed. Its goals need to be energetic, but adaptive at the same time. The managers should protect the technical contributors from organizational distractions during this period of preparation.

Make the first product a significant winner

Growing an enterprise to world-class should begin with a significant break-through application or design for high demand. Typically this will take about a year of very careful work and background preparation.

Make every component a quality design

High-quality technical knowledge is widely available. But it's surprising how seldom all the necessary technical attributes are assembled for a successful project. Make sure that every key aspect of the project is understood and designed correctly, with good immunity to variations in parameters, and tolerance for marginality in other components.

Rework and debug cost a lot more later than earlier. Invest the effort to utilize existing knowledge as early as possible in the project.

If your process includes an approach of quick implementation followed by later improvement, that method can also be managed to better provide the results you desire. Break the enterprise down into cleanly demarcated segments, and then thoroughly debug the parts individually before assembling them. The points of interaction must then be completely defined, understood and checked. The choice of how to partition your project thus becomes a key input into the quality.

Another reason that this compartmentalization is important, is that bugs have a way of interacting with each other. When there are several problems happening at once, it's sometimes difficult to separate out the specific cause and effect relationships.

Promote co-operation

There should be synergy and exchange of information among different groups, and a certain willingness to get the best benefit from available resources.

Your team includes individuals who are highly competitive by nature. Inspire them to transcend that inclination and to co-operate. An important natural unifying force is the perception of a common adversary. Make sure that the team recognizes the opponent as your company's competitors, and not some other group across the hall. Regularly compare and benchmark your products' performance with the rest of the industry. Inspire professionalism by example; speak well of your own equals and superiors within your organization. Be consistently supportive of all the contributors on the project.

Career View
The Quality is the Key

To build a world-class business over a period of a few years, the quality must be present at the very beginning. This means that the managers must have available to them a key advantage or application that will carry them forward. One of the best things you can do for your career is to provide them with such a key advantage.

Always ask your superiors and co-workers about their significant needs. Find out what are the major problems facing their organization, and how you can assist them in achieving the world-class success that they desire.

Our seminar *Future-Oriented Career Development* explores key ideals for being the best possible in your technical career, and supporting your organization. Do you know the answers to these key career questions?

1. What is the *most important function of my supervisor?*
2. How do I find a compass *when there's no clear direction?*
3. How do I recognize if my manager is a *strong leader?*
4. How do I know when I have *enough data?*
5. What should I do, and avoid, when *entering a new organization?*
6. What is the *number one cause of delay* in technical work?
7. What are the major *sources of conflict* within an organization?

These are a few of the 15 key career issues covered in our seminar. Please see the Careers section of our web site for a more complete description.

The career seminar consists of a series of talks and discussion groups focused on methods to help professionals to maximize their potential by renewing their teamwork ideals. It begins with business goals, introduces technical priorities and management methods, and explores the dynamics of respect and integrity for individuals and groups. This seminar can be tailored to the specific needs of your department.

<u>Today's Technical Feature</u>:
Temperature Invariance for the On-Chip Regulator in CMOS

For the first part of this analysis, please see our previous issue, available at our web site.

In our previous issue, we identified the three major parts of an on-chip regulator; (1) the Bandgap Generator, (2) the Reference Generator, and (3) the Output Driver. We developed the methods to design the second and third parts with good stability and gain. Today we complete the study by looking into the "Bandgap Generator," from which temperature independence originates.

A qualitative exploration of the temperature independence of Widlar-style circuits is available in most advanced bipolar circuit design textbooks. Here I will expand the equations more extensively, giving individual terms as a function of temperature, so that we can see how they vary algebraically.

In most circuit design activities, equations are empirical rather than analytical. For this range of operation, an empirical expression taking the form of the general diode equation is applicable:

$$J = J_s\left(\exp\frac{V_{BE}}{kT} - 1\right) \qquad (1)$$

J_S is also dependent on temperature. Using the subscript "o" to denote the room-temperature value of any parameter, the saturation current density (J_S) relative to its room temperature value (J_{SO}) is

$$J_s = J_{so}\left(\frac{T}{T_o}\right)^a \exp\left(\frac{E_g}{kT_o} - \frac{E_g}{kT}\right) \qquad (2)$$

Neglecting the 'minus one' in eq. (1), and substituting eq. (2) into eq. (1), gives the forward diode current density as a function of temperature:

$$J = J_{so}\left(\frac{T}{T_o}\right)^a \exp\left(\frac{V_{BE} - E_g}{kT} + \frac{E_g}{kT_o}\right) \tag{3}$$

Rearranging gives an expression for the diode voltage as a function of temperature:

$$V_{BE} = kT\ln\left(\frac{J}{J_{so}}\right) - kTa\ln\left(\frac{T}{T_o}\right) - E_g\frac{T}{T_o} + E_g \tag{4}$$

Equations (3) and (4) can be expressed in terms of the currents (I) or current densities (J).

Now we go to the familiar bandgap circuit (Fig. 1) and apply the nodal equations at V_1. Since at equilibrium $V_1 = V_3$, we write

$$I_2 = \left(V_3 - V_2\right) / R_3 \tag{5}$$

Using eq. (4) to substitute expressions for V_2 and V_3, this becomes

$$I_2 = \frac{kT}{R_3}\ln\left(\frac{I_1 I_{SO2}}{I_2 I_{SO1}}\right) \tag{6}$$

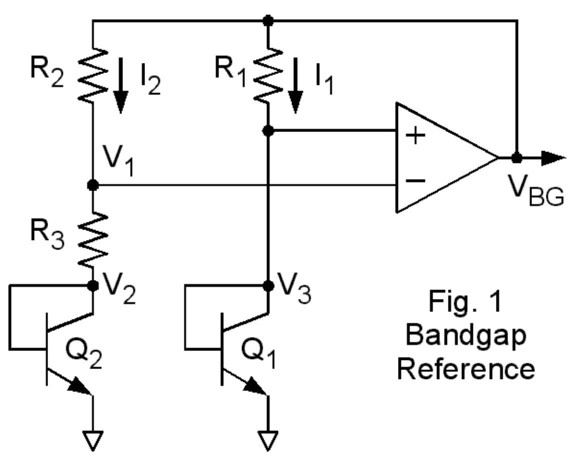


Fig. 1 Bandgap Reference

Then since we're using equal sizes for Q_1 and Q_2, we allow $I_{so1} = I_{so2}$ to cancel in eq. (6). Then substitute $I_1 / I_2 = R_2 / R_1$ into (6) and the result is

$$I_2 = \frac{kT}{R_3}\ln\left(\frac{R_2}{R_1}\right) \tag{7}$$

From the schematic we get

$$V_{BG} = I_2 R_2 + V_1 \tag{8a}$$

then substituting $V_1 = V_3$ results in

$$V_{BG} = I_2 R_2 + V_3 \tag{8b}$$

Then use eq. (4) to get an expression for V_3 in terms of I_1. Substitute that expression for V_3 into eq. (8b) and then substitute $I_1 = I_2 R_2 / R_1$. The resulting equation for V_{BG} will be:

$$V_{BG} = I_2 R_2 + kT\ln\frac{I_2 R_2}{I_{so1} R_1} - kTa\ln\frac{T}{T_o} - E_g\frac{T}{T_o} + E_g \tag{9}$$

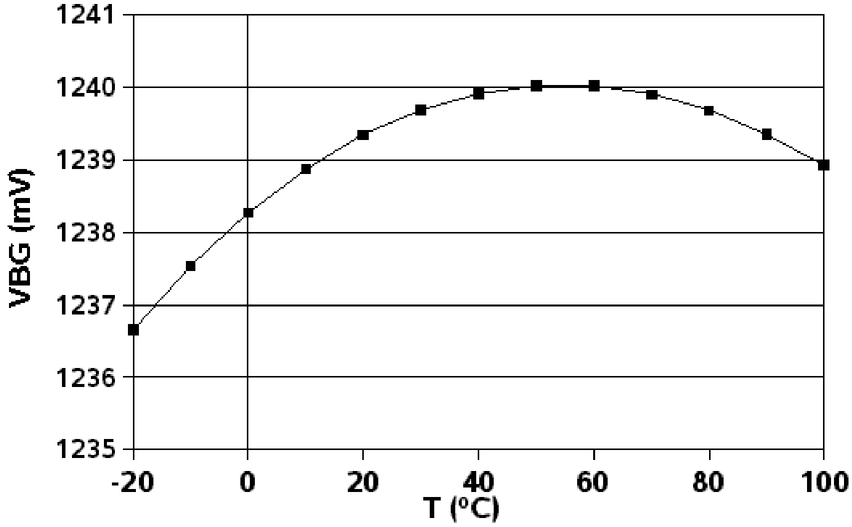
Substituting (7) into (9) gives

$$V_{BG} = kT\frac{R_2}{R_3}\ln\frac{R_2}{R_1} + kT\ln\left(\frac{kTR_2}{R_3 R_1 I_{so1}}\ln\frac{R_2}{R_1}\right) - kTa\ln\frac{T}{T_o} - E_g\frac{T}{T_o} + E_g \tag{10}$$

which provides an algebraic expression for V_{BG} in terms of temperature. Some typical parameter values might be:

kT_o	=	0.0257	V
E_g	=	1.12	V
a	=	5.25	
T_o	=	298	°K
I_{so}	=	8.5E-17	A
k	=	8.6242E-05	V/°K
R_1	=	34,900	ohm
R_2	=	14,250	ohm
R_3	=	1,000	ohm

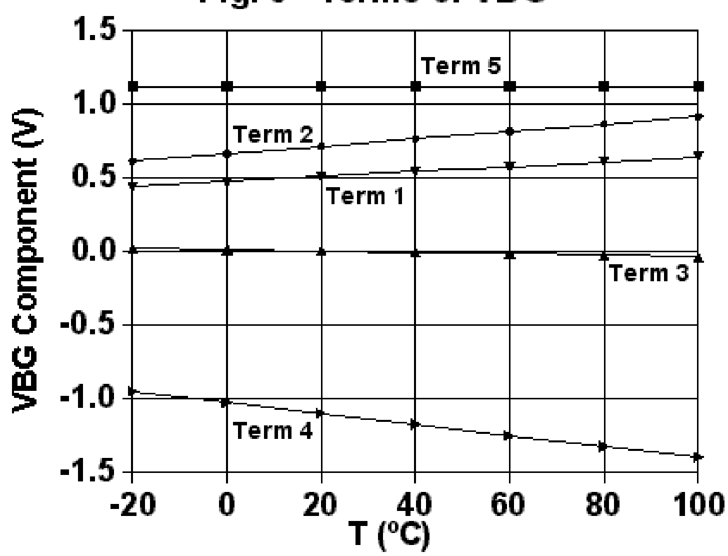
Fig. 2 VBG Variation with Temperature



In this above example, the values of R_1, R_2 and R_3 are selected to minimize the variation of V_{BG}. Because of the ratios appearing in equation (10), for a given value of one of the resistors, the optimum point is reached with an optimum ratio of the other two. Choose larger resistance values to reduce the current consumption of the circuit.

The actual value of I_s is dependent on many factors. There is some controversy about the best value of a, but small changes in the value used for E_g can be made to achieve an empirical fit. Early textbooks had used a = 1.5 and E_g = 1.2, but later empirical analyses have adjusted E_g to the value of 1.12 and compensated with larger values of a.

Fig. 3 Terms of VBG



Equation (10) details the variation of the terms of V_{BG}. Term 5 (E_g) variation is neglected in this range. The temperature independence is realized as terms 3 and 4 decrease while terms 1 and 2 increase (Fig. 3.)

Summary

Temperature independent circuits can be created using the classical double-diode technique. Empirical design techniques make it straightforward to implement these methods in a modern design. Good bus routing techniques are appropriate to ensure a quiet supply over the entire chip.

Technical References

[1] R. J. Widlar, "New developments in IC voltage regulators," *IEEE J. Solid-State Circuits*, Vol. SC-6, pp. 2-7, February 1971
[2] Gray and Meyer, *Analog Integrated Circuits*, Second Edition, Wiley, 1984, ch.4

This concludes the second edition of *Steve Flannagan's IC Design Journal*. We hope you have found this interesting and useful. Feel free to send me your comments, suggestions, or ideas for future issues. Please contact me for assistance in your technical business, electronic design, planning, training or team development.

Regards,
Steve

About the writer:

Steve Flannagan is a highly respected electronics designer and consultant, widely acclaimed for his leadership and professionalism. He is especially regarded for his teamwork and dedication to the success of individuals. Steve has designed some of the world's leading SRAM and memory circuits, is widely published in the field and holds more than 40 United States Patents in the area of circuit design and evaluation. He has worked professionally as a designer at Intel, and also at Motorola where he held the title of *Fellow*.

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Flannagan I. C.
Technical Services and Consulting, Inc.

POB 200367
Austin, Texas 78720-0367
512-346-3927

WWW.FLANIC.COM