INVESTIGATION ON EMI EFFECTS IN BANDGAP VOLTAGE REFERENCES

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Abstract - In this paper the susceptibility of integrated bandgap voltage references to Electromagnetic Interference (EMI) is investigated by on-chip measurements carried out on Kuijk and Tsividis bandgap circuits. These measurements highlight the offset in the reference voltage induced by continuous wave (CW) EMI and the complete failures which may be experienced by bandgap circuits. The role of the susceptibility of the startup circuit and of the operational amplifier which are included in such circuits is also focused.

1. INTRODUCTION

Present day low voltage, high performance analog, digital, RF and power integrated systems require very stable and accurate voltage references for proper operation. To this purpose, many bandgap refence circuits have been developed in the last years in order to provide very accurate, temperature-independent voltages and/or currents [1-3].

However, all the efforts oriented to improve the accuracy of these reference circuits can be vanished by the presence of EMI, which is very often superimposed onto the bandgap power supply voltage, especially in present day System on a Chip (SoC) applications, in which voltage reference circuits are located on the same chip where RF amplifiers, power supplies and digital subsystems are integrated.

The nonlinear effects of EMI on the active devices [4-7] which are included in bandgap circuits, in fact, induce an offset in the reference voltage which can be orders of magnitude higher than the error due to the residual temperature dependence and, depending on the amplitude and on the frequency of EMI, it can also induce a complete failure in the voltage reference operation. For these reasons, the immunity to EMI is a critical issue in bandgap voltage references.

In this paper, the susceptibility of bandgap voltage references to EMI superimposed onto the power supply voltage is investigated through on-chip measurements. These measurements have been carried out with reference to two bandgap topologies which are well known in the literature [1-2]. On the basis of the experimental results, the contribution of each subcircuit to the susceptibility of the overall bandgap circuit is pointed out. The role played by

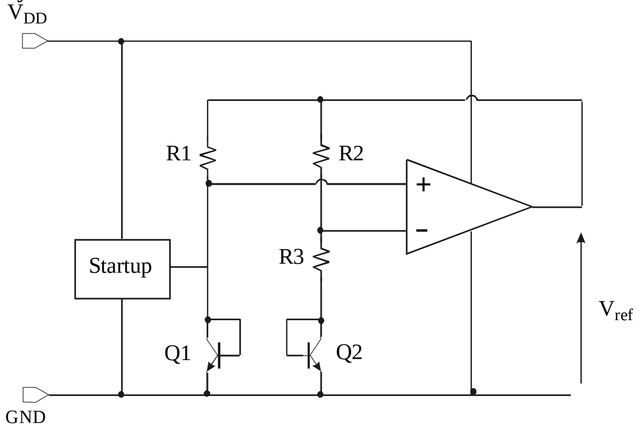

Figure 1: Kuijk Bandgap Circuit

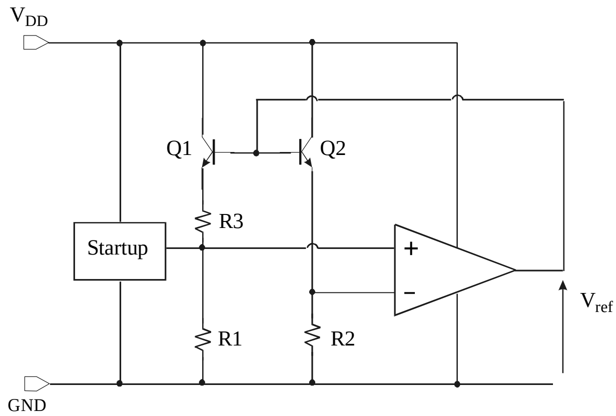

Figure 2: Tsividis Bandgap Circuit

the startup circuit and by the operational amplifier (opamp), in particular, is highlighted.

The paper has the following structure: in Section 2, the circuits which are used as devices under test (DUTs) are briefly described and in Section 3, the experimental setup which has been employed to perform the measurements is presented. In Section 4 the experimental results are shown while in Section 5, some considerations on the immunity of these circuits are exposed. Finally, in Section 6 some concluding remarks are drawn.

2. THE DEVICES UNDER TEST

The measurements which are described in this paper have been carried out on the Kuijk bandgap circuit [1] shown in Fig. 1 and on the Tsividis bandgap circuit [2] shown in Fig. 2, which are two widely employed opamp-based first-order temperature compensated bandgap circuits. In particular, both these circuits provide a reference voltage of about 1.3V which shows a temperature variation which is less than 3mV in the temperature range –20 °C - +100°C.

In both these circuits, the pMOS-input Miller opamp shown in Fig. 3 is employed. This opamp has a DC voltage gain of about 70dB, a cutoff frequency of 6MHz and a common mode input swing from 0.6V to 4V.

Furthermore, in both the bandgap circuits, the startup shown in Fig. 4 is employed in order to assure that the bandgap circuit turns on when the power supply is applied. This startup circuit is designed to force the terminal OUT to Vdd thruogh a nMOS switch for a time of about 1us after the power supply voltage is turned on. After this time has elapsed, the nMOS switch is turned off and the OUT terminal goes to high impedance. In order to highlight the susceptibility of the startup circuit, both the bandgap circuits have been tested with and without the startup circuit.

The above mentioned bandgap circuits have been designed and fabricated referring to the 1 μm BCD3s technology process [8].

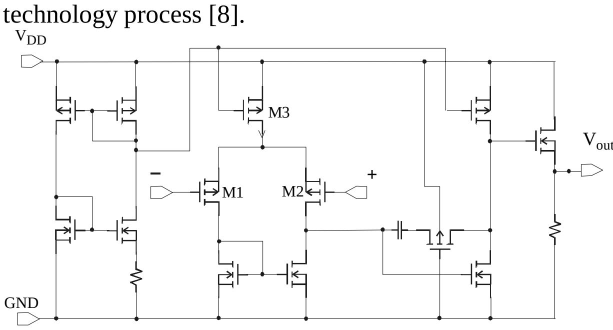

Figure 3:pMOS input two-stage Miller opamp

3. EXPERIMENTAL SETUP

The susceptibility of the above described bandgap circuits has been evaluated by using the test bench shown in Fig. 5. In this bench, the power supply *ground-signal-ground* (GSG) pads of the bandgap circuit are contacted by an RF probe [9], which is connected to a bias tee: the DC input of the bias tee is connected to a constant voltage source V_{DD}, while its RF input is connected to an RF source with

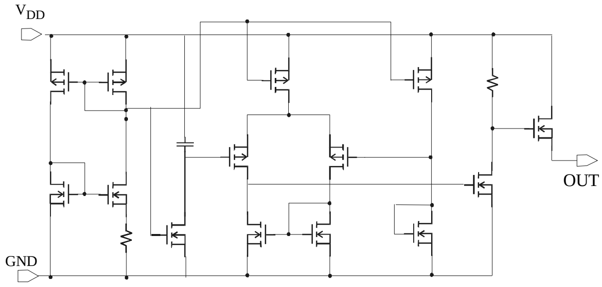

Figure 4: Startup circuit

impedance $R_g = 50\Omega$, in order to add continuous wave (CW) RF signals of peak amplitude V_{RF} to the nominal DC power supply voltage $V_{DD} = 5V$.

The bandgap output GSG pads are contacted by an RF probe which is connected to a bias tee as well: its DC port is connected to a DC voltmeter in order to measure the DC component of the reference voltage V_{REF} while the RF port is connected to the load $R_L = 50\Omega$.

The susceptibility measurements have been performed as follows: the reference voltage provided by the bandgap circuit V_{REF} when the RF voltage source is turned off is compared with the reference voltage provided by the bandgap circuit when an RF signal is injected. The difference between these voltages, which is the RFI induced offset in the reference voltage, has been measured for different amplitudes and frequencies of the RF CW interference.

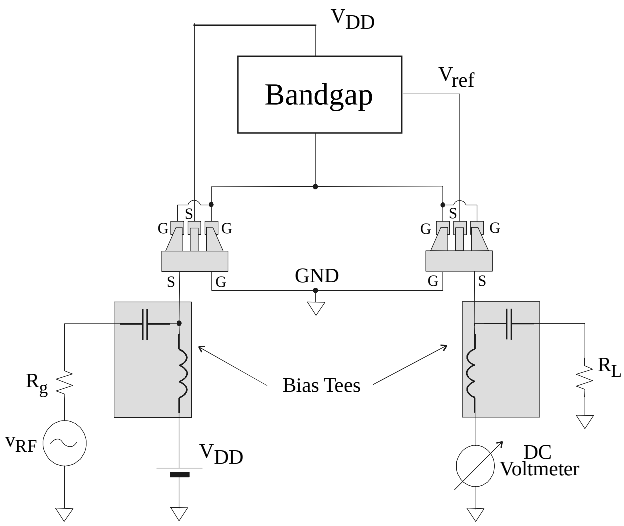

Figure 5: Experimental test setup

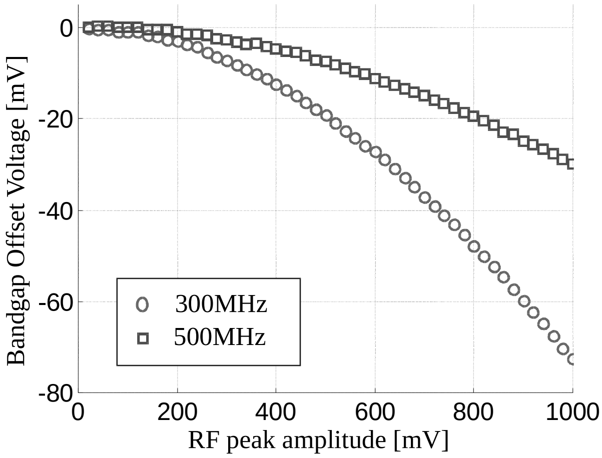

Figure 6 Bandgap offset voltage vs. CW RFI peak amplitude in the Kuijk bandgap circuit without startup

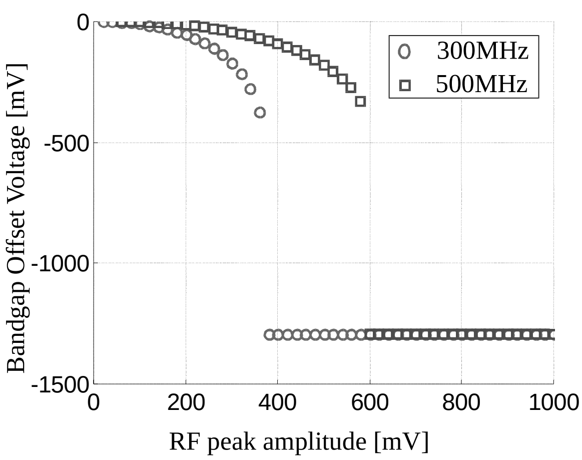

Figure 7. Bandgap offset voltage vs. CW RFI peak amplitude in the Kuijk bandgap circuit with startup

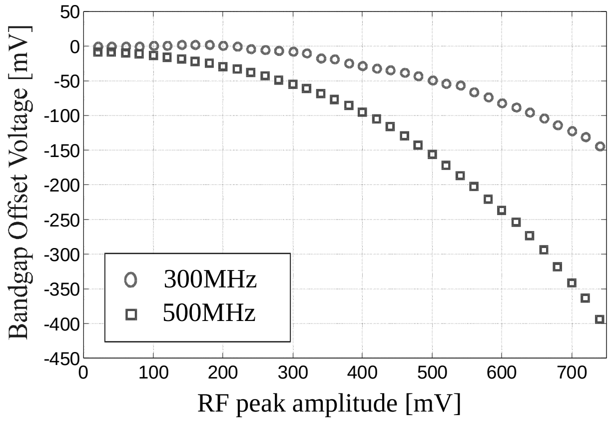

Figure 8. Bandgap offset voltage vs. CW RFI peak amplitude in the Tsividis bandgap circuit without startup

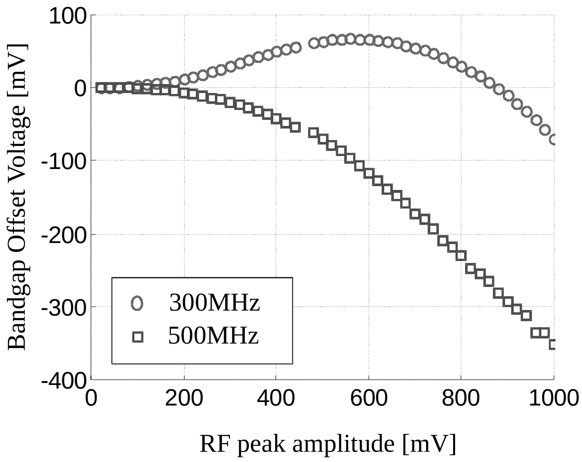

Figure 9. Bandgap offset voltage vs. CW RFI peak amplitude in the Tsividis bandgap circuit with startup

4. EXPERIMENTAL RESULTS

The offset in the reference voltage induced by RFI in the bandgap circuits has been measured as a function of the peak amplitude of the CW RFI superimposed on the bandgap power supply voltage. The results of these measurements are shown in Figs. 6-9. In particular, Fig. 6 refers to the Kuijk bandgap circuit without startup, Fig. 7 refers to the Kuijk circuit with startup, Fig. 8 refers to the Tsividis circuit without startup and Fig. 9 refers to the Tsividis circuit with startup. In all these plots, two different frequencies have been considered: the circles refers to a frequency of 300MHz, while the squares refers to a frequency of 500MHz. In Fig. 10 the RFI-induced bandgap voltage reference offset in the Kuijk bandgap circuit without startup is plotted for a 500mV peak amplitude superimposed on the power supply.

From Figs. 6-10 it can be observed that the RFI induced shift in the regulated voltage is much higher than the temperature variations of this voltage even for relatively small peak amplitudes of the CW RFI.

From the comparison of Fig. 6 with Fig. 8 it can be observed that the Kuijk bandgap circuit is more immune to RFI than the Tsividis circuit, as the RFI-induced offset voltage in the second circuit is about five times greater that the offset voltage induced in the second circuit, for a similar amplitude of the RF signal.

Furthermore, from the comparison of Fig. 6 with Fig. 7 and of Fig. 8 with Fig. 9, it can be noticed that the startup circuit shown in Fig. 4 deeply influences the behaviour of the circuit in the presence of RFI: in particular, it can be observed from Fig. 7 that the presence of RFI induce a complete failure in the bandgap operation.

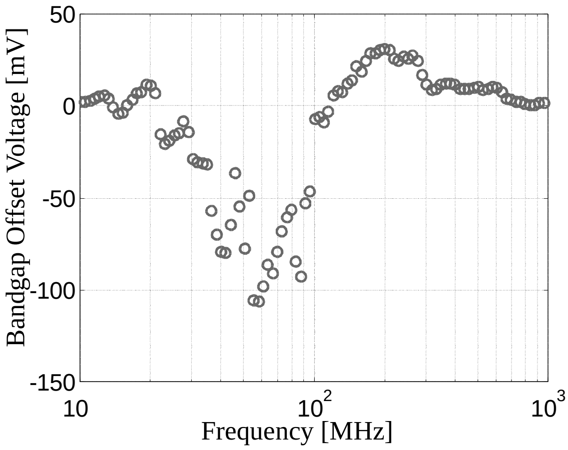

Figure 10. Frequency dependence of the offset voltage induced by RFI in the Kuijk bandgap circuit without startup

5. BANDGAP SUSCEPTIBILITY TO EMI

Based on the experimental results presented in the previous section, some considerations on the bandgap voltage reference susceptibility can be derived.

It can be observed that the RFI induced offset voltage shows an almost quadratic dependence on the peak amplitude on the RF interference superimposed onto the power supply.

This behaviour is similar to the one of an operational amplifier subjected to RF interference superimposed on its input terminals and on its power supply rails. In particular, it has been shown that the simultaneous presence of RFI superimposed onto the opamp input differential voltage and onto its common mode input voltage or its power supply voltage induce an offset in the output voltage because of a mixer effect in the opamp input differential pair [7].

In the immunity test that has been described in this paper, the opamp circuit which is included in both the bandgap circuits is subjected to RFI superimposed both onto its power supply voltage and, indirectly, onto it input terminals. Based on these considerations, the experimental results which have been shown above agree with the general reasoning depicted in [6].

The frequency behaviour of the offset voltage which is depicted in Fig. 10 is rather complex. This can be ascribed to the complex frequency dependent phase relationship between the RF signal superimposed on the power supply, and the RF signal superimposed on the opamp input terminals.

The complete failure experienced in the bandgap circuits with the startup network are due to the fact that RFI superimposed on the startup power supply can unbalance the differential pair included in it and, as a consequence, the startup circuit can be turned on by RFI during normal circuit operation.

6. CONCLUSIONS

In this work, the susceptibility of bandgap voltage reference circuits to RFI has been investigated by an experimental approach. In particular, on-chip measurements have been carried out referring to two common opamp circuits, i.e. Kuijk's bandgap circuit and Tsividis' bandgap circuit, which have been compared.

Furthermore, the results of the measurements which have been performed point out that the RFI induced offset in the regulated voltage is closely connected to the nonlinear operation of the operational amplifier included in the bandgap circuits.

Finally it has been highlighted how the bandgap startup network can deeply affect the susceptibility of bandgap circuits, up to cause complete failures.

7. ACKNOWLEDGEMENTS

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