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An Ultra-Compact Green Bio-Regulator Dedicated for Brain Cortical Implant Using a Dynamic PSR Enhancement Technique

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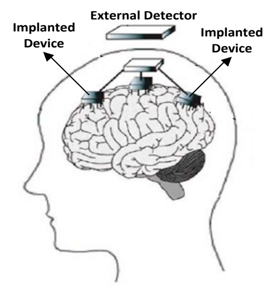
***Abstract* — This article presents an ultra-compact green Bio-regulator dedicated for brain cortical implant using a dynamic PSR enhancement technique. This novel technique enabled the regulator to achieve a very high power supply rejection (PSR) of -58dB and -78dB at 1 MHz and 10MHz respectively. The Bio-regulator achieves a very low quiescent current of 2µA coupled with an ultra-low power consumption of 1.8µW. This Bio-regulator, simulated with Global Foundries 0.18µm CMOS process, yields a stable output voltage of 0.5V with a supply voltage ranging from 0.9-1.2V. Its distinct features, ultra-low power consumption and high PSRR at 1MHz and 10MHz, make it ideally suitable for biomedical brain cortical implant.**

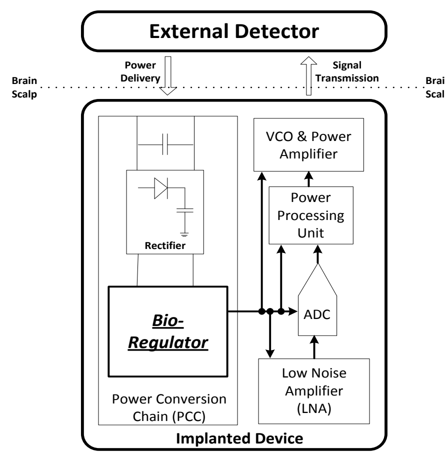
I. Introduction

For the past few years, there have been intensive research carried out on developing wireless biomedical brain cortical implant [1-5]. They are used for recording neural activities in specific areas of the brain and speed up diagnosis for any imminent brain disease. For neural classification and recognition to occur, it requires continuous monitoring with large number of passing neutrons [8]. However, safety is of paramount importance and must be uphold strictly since the device is implanted physically in the patient's brain. One important safety aspect is that the rise of temperature from brain tissues, after implanting the device, should never exceed 1°C [9]. Furthermore, the bio-compatibility and size of the implant should be considered and designed carefully to prevent any possible health hazards.

Fig. 1(a) shows the implantable system for brain cortical recording [10]. Detailed recording of the brain's neural activities are carried out in various parts of the human's brain. Fig. 1(b) illustrates the block diagram which is composed of two components, the external detector and the wireless biomedical cortical implanted device. The external detector delivers power and useful data to the implanted device. The device, in turn, records the varying neural activities of the brain and sends important neural information back to the external detector. The two way transfer of power and data are made feasible by wireless ac inductive coupling between the two respective coils.



(a)



(b)

Figure 1. (a) Implantable system for brain cortical recording [10] (b) Block diagram of wireless biomedical cortical implanted device

The implanted device has a power conversion chain (PCC) which consists of DC rectifier and a Bio-regulator. The regulator is a vital component in the PCC as it must yield excellent PSRR at high frequencies, ultra-low power consumption and stable operation at low load current [5, 11]. Furthermore, it needs to have a fast line and load transient response as its output voltage is used as a reference voltage for many of the analog blocks in the implanted biomedical device.

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Recently, there are three LDO regulators designed solely to be used in the PCC for wireless biomedical cortical implants [3-5]. However, all of them consume large quiescent current and lead to high power consumption (> 42µW). In addition, they only cater to a low load current (< 5mA) which is insufficient to drive the components in the implanted device. Furthermore, the PSRR is poor at 1MHz and 10MHz respectively. Therefore, all the recent regulators [3-5] are not ideally suitable for wireless biomedical cortical implants whereby power consumption and PSRR are of utmost importance.

Therefore, in this paper, an ultra-compact and ultra-low power Bio-regulator is designed and dedicated for wireless brain cortical implant. It demonstrates the use of a dynamic PSR enhancement technique to achieve a high PSR of -58dB and -78dB at 1MHz and 10MHz respectively. In the following section, the individual blocks of the Bio-regulator will be presented in greater details.

II. Proposed Bio-Regulator Structure

The proposed Bio-regulator for brain cortical implant is presented in Fig. 2 below.

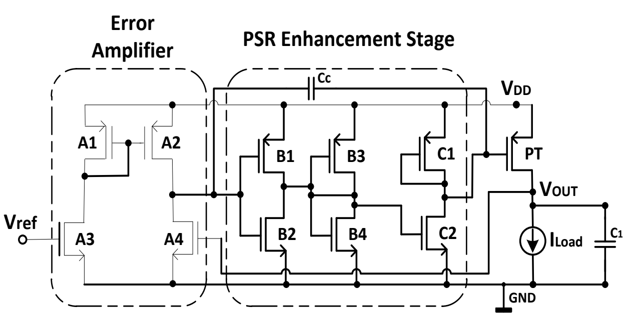

Figure 2. Proposed Bio-regulator for wireless biomedical cortical implant

It can be categorized into two simple circuit blocks:

- Error Amplifier
- PSR Enhancement Stage

The regulated voltage, V_{OUT}, is feedback to the error amplifier for comparison and amplification. After which, the output signal goes through the PSR enhancement stage whereby it forms a low-resistance load for common-mode signals. This leads to a robust controlled of the DC output level. In addition, the regulator will achieve high loop gain which ensures that it remains inherently stable for driving any load current. At the same time, it allows the Bio-regulator to achieve excellent PSR at very high frequencies. The on-chip capacitor, C_c, acts like a Miller capacitor which is required for frequency compensation. This helps to improve both the gain and phase margin.

A. Overall Loop Gain

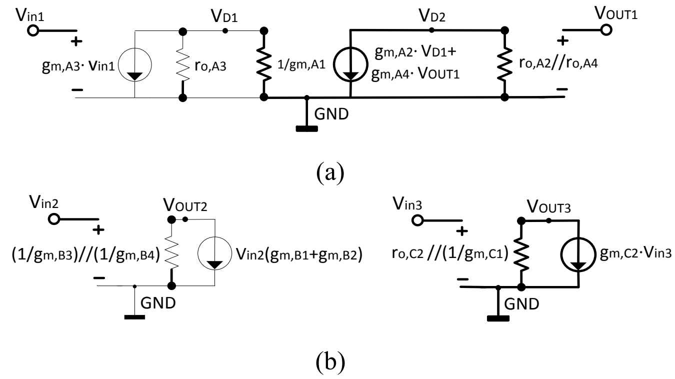

Figure 3. Small signal diagram of (a) Error Amplifier (b) PSR Enhancement Stage

The overall loop gain, A_v, is calculated to be:

$$A_v \approx -\frac{(g_{m,B1}+g_{m,B2})(g_{m,PT}\cdot g_{m,A4}\cdot g_{m,C2})}{(g_{m,B3}+g_{m,B4})(g_{m,C1})}\cdot(r_{o,A2}||r_{o,A4})\cdot(r_{o,PT}||R_L) \quad (1)$$

where g_m and r_o refer to the small signal transconductance and output resistance of the transistor respectively.

B. Power Supply Rejection (PSR)Enhancement Technique

The PSR [12] of the proposed Bio-regulator is:

$$PSR = 20\log\frac{A_{v1}}{B_{v1}} \quad (2)$$

where A_{v1} is the open loop gain of regulator and B_{v1} is the gain from V_{DD} to V_{OUT} without feedback.

$$A_{v1} = A_v\cdot\frac{(1+{}^{s}/_{\omega_{Z1}})}{(1+{}^{s}/_{\omega_{P1}})(1+{}^{s}/_{\omega_{P2}})} \quad (3)$$

$$\omega_{P1} = \frac{1}{C_1(R_L+R_{ESR})} \qquad \omega_{P2} = \frac{1}{(C_{PT}+C_c)\cdot({}^{1}/_{g_{m,C1}})}$$

$$\omega_{Z1} = \frac{1}{C_1\cdot R_{ESR}}$$

where C_1 is the off-chip capacitor, C_{PT} is the parasitic capacitance at the gate of Power Transistor (PT), C_c is the on-chip capacitor, R_L is the load resistance and R_{ESR} is the ESR value of the capacitor.

$$B_{v1} = g_{m,PT}\cdot(r_{o,PT}||R_L||Z_{FB}) \quad (4)$$

where $g_{m,PT}$ and $r_{o,PT}$ refer to the transconductance and output resistance of Power Transistor (PT) respectively. Z_{FB} is the impedance of the feedback loop.

By substituting (1), (3) & (4) into (2), the PSR of the Bio-regulator can be expressed as:

$$PSR = 20\log\left\{\frac{-(g_{m,B1}+g_{m,B2})(g_{m,PT}\cdot g_{m,A4}\cdot g_{m,C2})\cdot(r_{o,A2}||r_{o,A4})\cdot(r_{o,PT}||R_L)\cdot(1+sC_1R_{ESR})}{(g_{m,B3}+g_{m,B4})\cdot(g_{m,C1}\cdot g_{m,PT})\cdot(1+sC_1(R_L+R_{ESR}))\cdot\{1+s(C_{PT}+C_c)({}^{1}/_{g_{m,C1}})\}\cdot(r_{o,PT}||R_L||Z_{FB})}\right\} \quad (5)$$

III. SIMULATION RESULTS

The simulation of the proposed Bio-regulator is carried out with GF 0.18µm standard CMOS process. The regulator can drive up to a maximum load current of 30mA which is sufficient to drive many of the components for cortical brain implant. There is an on-chip and off-chip capacitor of 1.0pF and 1.0µF respectively.

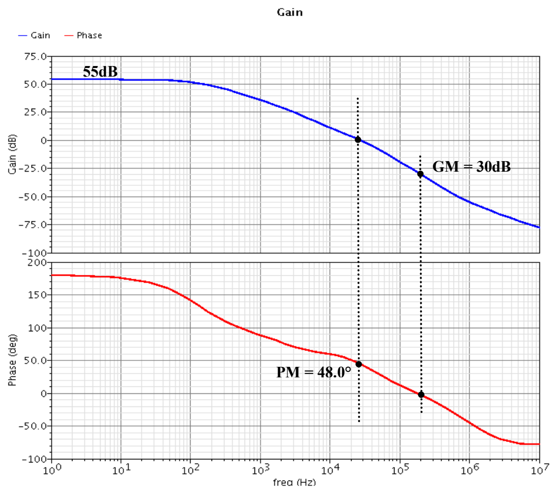

Figure 4. Loop Gain & Phase of proposed Bio-regulator

Fig. 4 shows the loop gain frequency response of the proposed regulator at 1mA load current. It exhibits a high DC gain of 55dB and proves that the regulator is stable with a high gain and phase margin of 30dB and 48.0° respectively.

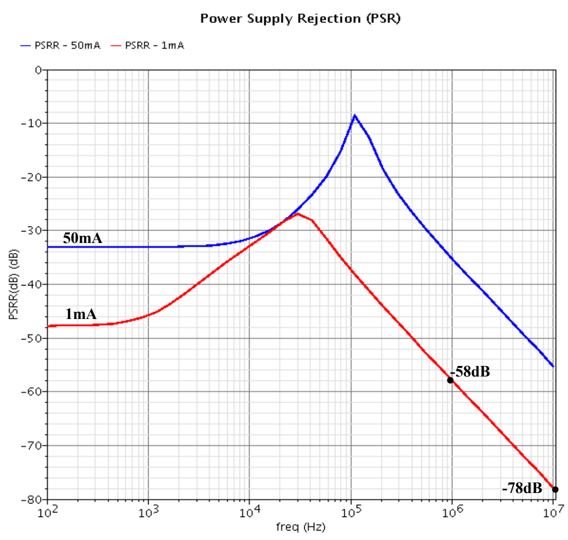

Figure 5. Power Supply Rejection (PSR) of proposed Bio-regulator

Fig. 5 shows the power supply rejection (PSR) of the proposed Bio-regulator at a load current of 1mA and 30mA. At low-load condition, it achieves a very high PSR of -58dB and -78dB at 1 MHz and 10 MHz respectively. This makes it ideally suitable for brain cortical implant as it gives a very clean and ripple-free output voltage even at high frequencies.

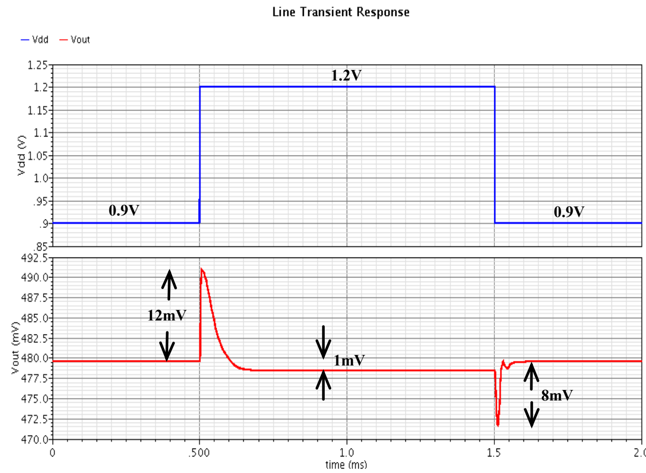

Figure 6. Line Transient Response of proposed Bio-regulator

Fig. 6 shows the line transient response of the proposed Bio-regulator during a fast supply voltage transition from 0.9V to 1.2V and vice versa. The rise and fall time is 1.0µs respectively. The largest voltage glitch is only 12mV. It achieves a good line regulation of 0.03%. This shows that our proposed Bio-regulator remains stable even during a fast transition of the supply voltage.

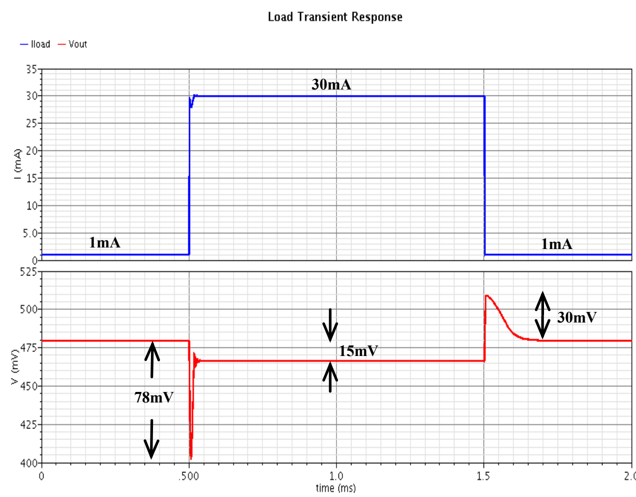

Figure 7. Load Transient Response of proposed Bio-regulator

Fig. 7 shows the load transient response of the proposed Bio-regulator during a fast load current transition from 1mA to 30mA and vice versa. The rise and fall time is 1.0µs respectively. The largest voltage glitch is only 78mV. It achieves a good load regulation of 0.5mV/mA. This shows that our proposed Bio-regulator remains stable even during a fast transition of the load current.

All the above simulation results prove that the proposed Bio-regulator is very stable when driving a maximum load current of 30mA. This certainly makes it the best available Bio-regulator for wireless biomedical brain cortical implant.

TABLE I: PERFORMANCE COMPARISION WITH RECENT BIO-REGULATOR DESIGNED FOR BRAIN CORTICAL IMPLANT

		Units	[6] ISSCC	[3] ESSCIRC	[4] TCAS II	[5] AICSP	[7] CICC	**This Work**
Year			2009	2009	2010	2010	2010	2012
Technology		μm	0.13	0.18	0.13	0.35	0.09	0.18
Supply Voltage		V	1.15	2.1	0.95	2.2	1.15	***0.9***
Output Voltage		V	1.0	1.8	0.75	1.0	1.0	***0.5***
Drop-out Voltage		V	0.15	0.3	0.2	1.2	0.15	0.4
Maximum Load		mA	25	4	2	0.5	140	30
Quiescent Current		μA	50	28	45	36	33	***2.0***
Power Consumption		μW	57.5	58.8	42.8	79.2	38.0	***1.8***
On-Chip Capacitor		pF	5.0	200.0	NA	NA	NA	1.0
Off-Chip Capacitor		μF	4.0	0.0018	NIL	0.00003	1.0	1.0
PSRR@	1 MHz	dB	-67	-37	-55	NA	-62	***-58***
	10 MHz		-56	-19	-57	-38	-56	***-78***
Current Efficiency		%	99.800	99.305	99.800	93.284	99.976	***99.993***
Line Regulation		%	NA	0.02	0.15	3.9	NA	0.03
Load Regulation		mV/mA	0.05	0.18	0.50	13.0	0.048	0.5

IV. DISCUSSION

From Table I, comparing with recent regulator designed solely for biomedical brain cortical implant [3-5], the proposed Bio-regulator achieves the lowest power consumption of 1.8μW. Furthermore, implemented with the novel dynamic PSR enhancement technique, it achieves the highest PSR of -78dB at 10MHz as compared to all previous works. It also uses a relatively larger off-chip capacitor but a smaller on-chip capacitor. The above features make our regulator ideally suitable for wireless biomedical brain cortical implant whereby power consumption and PSRR are of utmost importance.

Simulation results explicitly show that the proposed Bio-regulator is capable of driving a maximum current load of 30mA while consuming a very low quiescent current of 2.0μA. This gives rise to an excellent current efficiency of 99.993%. In addition, the Bio-regulator proves to be very stable during a fast load current or supply voltage transition.

Furthermore, as compared to the state of the art Bio-regulator published in [6, 7], our proposed regulator achieves a lower power consumption, higher PSRR at 10MHz and a better current efficiency. Overall, our proposed Bio- regulator is obviously the most suitable one dedicated for wireless biomedical brain cortical implant.

V. CONCLUSION

An ultra-compact green Bio-regulator dedicated for brain cortical implant using a dynamic PSR enhancement technique is proposed. This novel technique enabled the regulator to achieve a very high power supply rejection (PSR) of -58dB and -78dB at 1 MHz and 10MHz respectively. The Bio-regulator achieves a very low quiescent current of 2μA coupled with an ultra-low power consumption of 1.8μW. Furthermore, it yields an excellent current efficiency of 99.993% and remains inherently stable when driving a large load current of 30mA. This makes it ideally suitable for wireless biomedical brain cortical implant.

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