Integrating Power Inductors onto the IC – SOC Implementation of Inductor Multipliers for DC–DC Converters

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Abstract—**This paper introduces the technique of active inductor multiplier, whereby a small inductor is effectively multiplied to generate the effects of a large power inductor. Medium/High power dc-dc converters, which are essential power supply circuits in almost all portable applications, require off-chip inductors, which take-up significant PCB real estate, add cost, and impede SOC implementation. The inductor multiplier technique developed here makes it possible for large inductors to be integrated onto the IC, thus meeting the demands of mobile battery-powered applications and approaching SOC solutions. A 1.8 V, 2.5 A buck-converter for 2-cell Ni-Cd/NiMH (3.2-1.8 V) battery applications was simulated with and without the inductor-multiplier. An inductance of 150 nH was effectively multiplied to 1.5 µH, giving the same ripple performance. Efficiency, however, was lower throughout the load current range with a 5 to 19 % difference in the range from 5 to 1.5 A (efficiency was 74 % at 2.5 A), but still better than what a linear regulator would have yielded (less than 70 %).**

Index Terms—**Inductor-multiplier, SOC, dc-dc converter, integrated inductor, fully integrated power-supply circuit.**

I. INTRODUCTION

POWER SUPPLIES are ubiquitous in electronic systems. The trend towards low power, low voltage, and high accuracy in portable equipment has been driving technology, as well as the parametric requirements of integrated power supplies.
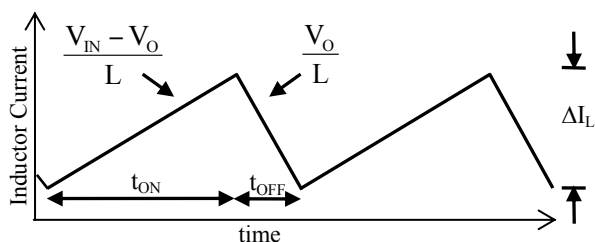

Fig. 1. Inductor Current Waveform in a Buck Converter.

Magnetic theory is at the heart of any switching regulator, with the use of an inductor to transfer energy from input to output in a lossless fashion and to filter the output from switching signals. The size of inductor also determines the magnitude and shape of the output ripple current (equation (1)), the ripple voltage (equation (2)), and bandwidth requirements (equation (3)) of the circuit. (Fig.1),

$$\Delta I_L = \left(\frac{V_{IN} - V_O}{L} \right) t_{on} , \qquad (1)$$

$$\Delta V_O = \left(\frac{V_{IN} - V_O}{L} \right) t_{on} R_{ESR\_C} , \qquad (2)$$

$$\text{and } f_1, f_2 = \frac{1}{2\pi\sqrt{LC}} , \qquad (3)$$

where f_1 and f_2 are complex conjugate poles. The requirements for high efficiency and accuracy (i.e., low ΔI_L and low ΔV_O) make the size of the inductor prohibitively large for SOC solutions, where the inductor is embedded in the chip.

Inductors can be realized in present-day integrated circuit technologies but the low inductance values [2] of on-chip inductors are only suitable for RF applications. Furthermore, the inherent substrate losses tend to degrade the performance by essentially increasing the equivalent series resistance (ESR), which consequently reduces the quality factor (Q).

Because of the inherent limitations of integrated inductors, one of the main directions of the power electronics industry in the last decade has been towards the development of switching-mode power converters without using inductors and transformers. The Inductorless options that are available are linear regulators and switched-capacitor circuits (charge pumps). On one hand linear regulators are characterized by poor efficiency and their use is limited in relatively low current applications [3]. Switched capacitor implementations [4]-[10] use off-chip capacitors in place of an inductor, but they suffer from degraded efficiency and low output current handling capacity. Developments and ingenuity in fabrication technologies have also facilitated the integration of high performance magnetic elements using Micro-electro-mechanical-systems (MEMS) [12]-[13], but their effectiveness in power supply circuits is yet to be realized.

This paper introduces the concept of active inductor multiplier to maximize the use of integrated inductors and to allow the complete integration of dc-dc converters, which is especially important in portable power applications. Section II reviews the relevant state-of-the-art in the field. The novel concept of active inductor multiplication is then presented in

Section III. The simulation results obtained on a 1.8 V, 2 A buck-converter are then shown and discussed in Sections IV and V, which are subsequently followed by conclusions.

II. STATE-OF-THE-ART

A. Inductorless Options

A.1 Switched Capacitor Circuits (Charge Pumps)

Switched capacitor dc-dc converters (also called charge pumps) are power converters that consist of switches and energy-transferring capacitors in the power stage. The switches are periodically turned on and off so that the converter cycles through a number of switched networks. Fig. 2. shows an ideal switched-capacitor voltage doubler in which the voltage conversion ratio (V_O/V_{DD}) is uniquely determined by the converter topology.
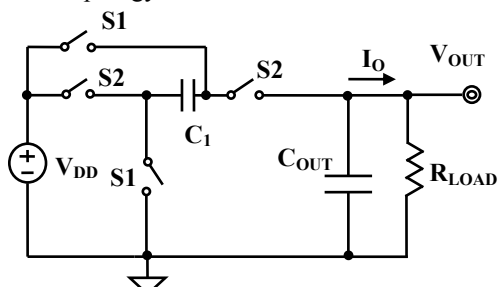

Fig. 2. Ideal switched-capacitor voltage doubler. Switches "S1" and "S2" are oppositely phased.

The topology described in Fig. 2 has many practical advantages like ease in implementation, but it also suffers from several drawbacks: (1) the input current is pulsating, (2) the regulation capability is weak since the output voltage varies with the input voltage accordingly, and (3) the dc voltage conversion ratio is usually predetermined by circuit structure.
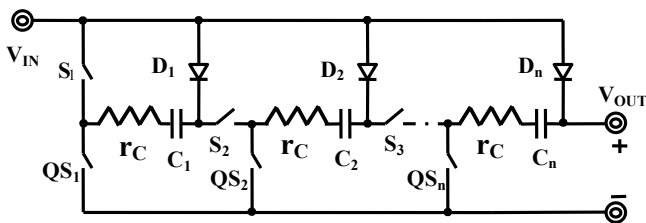

Fig. 3. Basic structure of the n-stage step-up dc-dc converter.

An n-stage step-up dc-dc converter [5] as shown in Fig. 3 addresses the problems of input current and output voltage regulation. The two types of switches (i.e., QS_1 to QS_n and S_1 to S_n) are oppositely phased. In one clock phase, C_1 to C_n are linearly charged by a constant current and in the other phase, all capacitors are connected in series with the input source and connected to the output load. To regulate the output, the output voltage is sensed and fed through the feedback network to control the charging current

The complete implementation has two such cells connected in parallel. This realization has the advantage of continuous input current during alternate switching cycles, thereby reducing EMI. This can also provide high output current but at

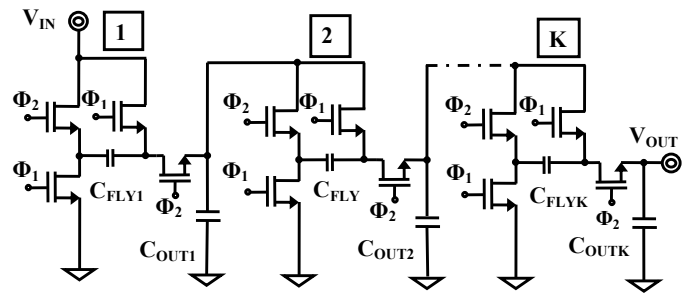the cost of large capacitors ($C_1 = C_2 = ...C_n = 47$ µF), which prohibits its on-chip implementation.

Fig. 4. Cascaded Converter.

One of the main disadvantages of the standard switched-capacitor topology is that, for a given conversion ratio, its efficiency is dependent on the ratio V_{OUT} to V_{IN}, which is especially important in single battery cell (V_{IN}=1.8 to 0.9 V) to 3.3 V applications, where a voltage conversion ratio of four is needed at $V_{IN} = 0.9$ V, as compared to three at $V_{IN} = 1.8$ V. Modifications to the standard topology was made in [6], which cascades charge pumps in series (shown in Fig. 4). Due to the cascaded structure, it is possible to choose the supply voltage of any of the charge pump stages from their respective previous stages. This means that the flying capacitor of stage K can be charged from the output of the (K-1) stage, and discharged independently with any of the (K-1), (K-2)… stages.

This scheme provides an enhancement in the overall efficiency but the output current is still limited by the capacitors. The efficiency of a switched-capacitor converter can also be enhanced by selecting the conversion ratio according to the input voltage and loading conditions [14]. Commercially, there are many switched-capacitor implementations [9 [10].

Switched-Capacitor circuits do provide a viable solution in eliminating inductors but they are limited by their output current capacity. To deliver large currents, large capacitors are required, which again, prohibits on-chip implementation.
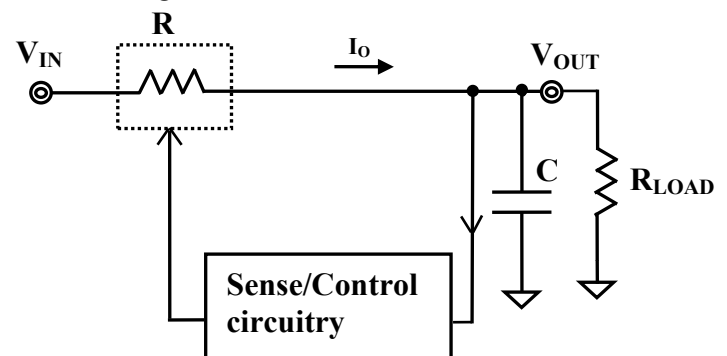
A.2 Linear Regulators

Fig. 5. Typical Linear Regulator.

Linear Regulators (also called series regulators) use a pass switch (resistor) between the input supply and the regulated output. The value of the resistance is modulated through the feedback control of the output voltage. This is a strong candidate for SOC implementation, since it does not

incorporate any bulky inductors. The output current capacity of linear regulators, however is limited to less than 1 Amp, not to mention their inherently poor efficiency [3].

$$\eta_{Lin-Reg} = \frac{I_{LOAD}V_{OUT}}{(I_{LOAD} + I_q)V_{IN}} \le \frac{V_{OUT}}{V_{IN}}. \quad (4)$$

B. Integrated Inductor - MEMS Approach

Micro-Electro-Mechanical Systems (MEMS) technology has been very productive in the recent past, especially in the implementation of on-chip passive elements.   DC-DC converters using micro-machined inductors have been reported in [12], [13]. One of the major problems in this realization is the issue of process compatibility with current main-stream fabrication processes (e.g. interfacing with active CMOS/BJT devices), and their consequent increase in product cost. The size of the fabricated device and low Q factor at high inductance values is also a major concern. The use of MEMS inductors for power supply circuits is yet to be effective and requires further research.

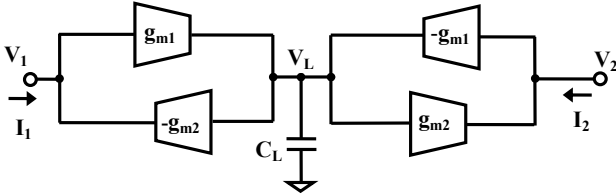### C. Virtual Inductor - Op-Amp Realization

Fig. 6. Virtual Inductor using a gyrator.

Integrated filters can be implemented by emulating an inductor through the use of active circuits. Fig. 6. shows a floating active inductor realized by a gyrator. The effective inductance L_{EFF} is dependent on the value of capacitor C_L and the transconductances g_{m1} and g_{m2},

$$sC_L V_L + g_{m_1} V_1 - g_{m_1} V_2 = 0 \implies V_L = \frac{g_{m_1}(V_2 - V_1)}{sC_L}, \quad (5)$$

$$I_1 = -g_{m_2}\frac{g_{m_1}(V_2 - V_1)}{sC_L} \implies I_2 = g_{m_2}\frac{g_{m_1}(V_2 - V_1)}{sC_L}, \quad (6)$$

thus , $$L_{EFF} = \frac{C_L}{g_{m_1}g_{m_2}}. \quad (7)$$

Since the whole output current flows through the inductor, replacing it with the one shown above would result in large losses in g_{m1} and g_{m2}. This technique still looks attractive in terms of replacing the inductor; but, in terms of practical implementations of dc-dc converters, it requires further investigation.

III. NOVEL APPROACH - ACTIVE INDUCTOR MULTIPLIERS

The concept of active inductor multiplication is to maximize the use of integrated inductors by using active circuit techniques to effectively multiply the   inductance of an otherwise small integrated inductor. The multiplication can be accomplished in voltage and/or current mode.

Recently, a capacitor multiplier technique was proposed [11]

to facilitate the realization of larger on-chip capacitors. The theory behind the proposed method is to sense the current through a small capacitor and amplify it, thereby magnifying the total capacitor current. Fig. 7 illustrates this technique, where the equivalent capacitance seen at the input is a multiplied factor of capacitor C_C. An interesting approach could be to extend this idea to inductors and investigate the possibility of inductor multipliers. The nano-henry (nH) inductors that are now available in present-day integrated circuit technologies can be multiplied to micro-henrys (µH), advancing toward SOC solutions, especially when considering switching regulators.
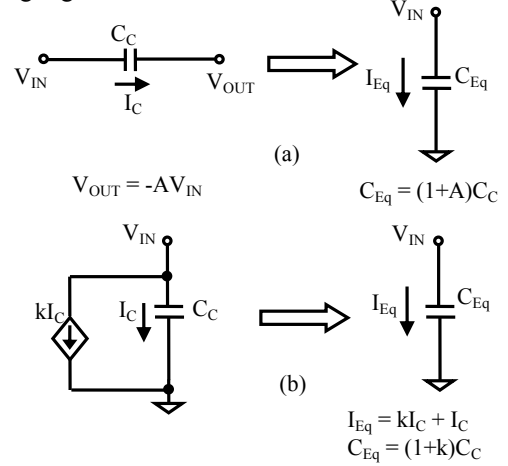

Fig. 7. Voltage-mode and current mode capacitor multipliers.

A. Inductor Multiplier - Voltage Mode

The current-voltage relationship in an inductor (given by equation (8)) shows that, for a constant current ripple, the effective inductance can be increased K times by decreasing the voltage impressed across the inductor by the same factor,

$$\frac{di}{dt} = \frac{V}{L} \implies \frac{V/K}{L} = \frac{V}{L_{eff}} \quad \therefore \quad L_{eff} = K \times L \quad (8)$$

Fig. 8. shows the realization of the concept, with A and B scaling the voltage (e.g., resistor ladders can do the job).
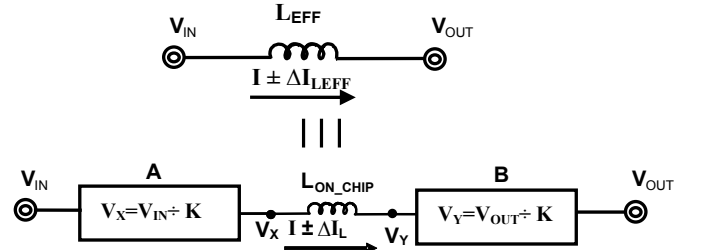

Fig. 8. Voltage-mode inductor multiplier.

The disadvantage lies in the power losses incurred by A and B, which conduct the full ripple current. Also, the direction of current conflicts with the voltage across B, which consequently demands negative resistance.

B. Inductor Multiplier - Current Mode

A similar approach can also be applied in current-mode. In this realization, the voltage across the inductor is kept constant but the current ripple is multiplied,

$$V = L\frac{di}{dt} \implies L(K\frac{di}{dt}) = L_{eff}\frac{di}{dt} \quad \therefore \quad L_{eff} = K \times L$$

(9)

As seen in equation (9), the effective inductance between two points can be increased by allowing the current ripple in the inductor to increase. The ac magnitude of the inductor current is therefore sensed, amplified, and fed back. Implementation of this approach is done by a current-controlled-current-source (cccs) connected in parallel with the passive inductor to be multiplied, as shown in Fig. 9.
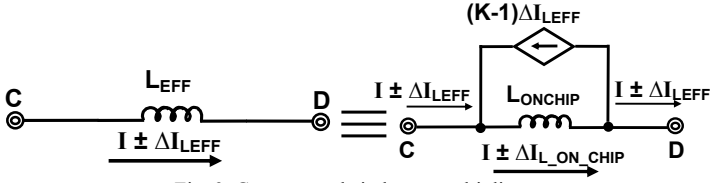

Fig. 9. Current-mode inductor multiplier.

The topology described above presents a challenge. The direction of current from node C to D, implies that the voltage at C be greater than D, which is not always the case in dc-dc converters. The modified circuit shown in Fig. 10 circumvents this problem by connecting one of the ends of cccs to ground, which can be done as C is a low impedance node. This configuration leads to increased power dissipation, and its effect on the efficiency of a dc-dc converter is discussed later.
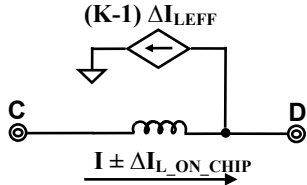

Fig. 10. Modified Current-mode inductor multiplier

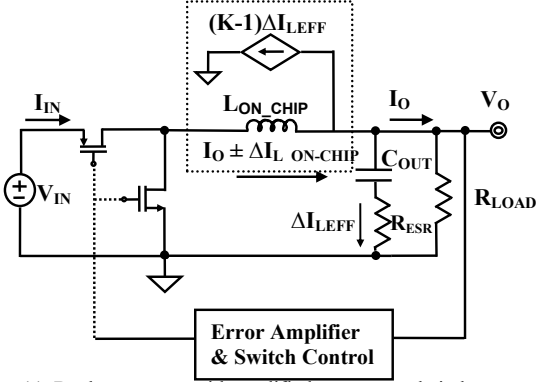### IV. BUCK-CONVERTER WITH ACTIVE INDUCTOR MULTIPLIER

Fig. 11. Buck-converter with modified current-mode inductor multiplier.

A buck-converter was designed and simulated employing the current-mode multiplier, with the input voltage as 2.5 V, midway between the fully charged and discharged values of a typical 2-cell Ni-Cd/NiMH (3.2 - 1.8 V) battery application with a fixed output voltage of 1.8 V, in accordance with the junction breakdown voltage considerations of current 0.18 μm CMOS technologies.

In the case of buck-converter, (referring to Fig. 9), C is a low impedance node, which allows the use of the modified current-mode inductor multiplier shown in Fig. 10, as shown in Fig. 11. Since the ripple inductor current is the same as the

capacitor current in a buck-converter, the capacitor current ripple is sensed and amplified. This allows only the ac part of the current to be sensed, thereby minimizing power losses.

V. SIMULATION RESULTS AND DISCUSSION

The sensed and amplified inductor current ripple waveforms are shown in Fig. 12. The output voltage ripple and hence the accuracy is inversely proportional to the value of the inductor used (equation (2)). The use of an active inductor multiplier allows the converter to use a smaller inductor, yet maintain the characteristics of a larger inductor accuracy. The simulated results of the buck-converter with a 150 nH inductor, with and without the multiplier, are shown in Fig. 13. As seen from the figure, the output ripple voltage is reduced K times with the use of an inductor multiplier (in this case K = 10).
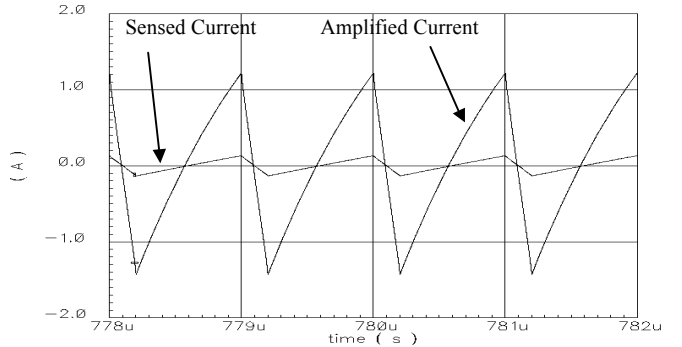

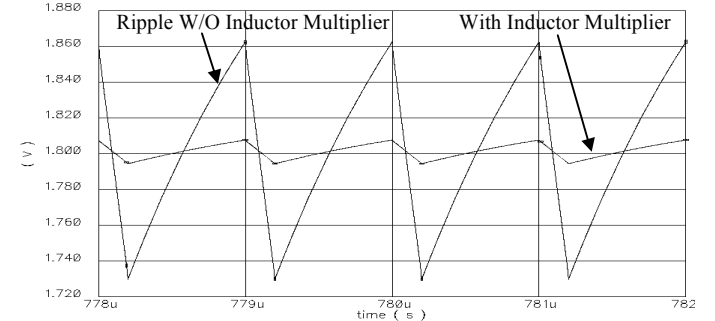Fig. 12. Sensed and amplified inductor ripple current..

Fig. 13. Output ripple voltage, with and without inductor-multiplier.

Power losses in a switching regulator reduce to switching and conduction losses, with the latter consisting of dc as well as rms losses. Since the rms losses are proportional to the current ripple, the use of modified inductor-multiplier topology leads to increased conduction losses in the switches,

$$P_{Rms} = \frac{(K-1)^2 \Delta I_L^{\ 2}}{12} \times (R_{SWITCH} + R_{ESR\_L}), \qquad (10)$$

and in the device sourcing the amplified ripple current. Power losses associated with the inductor multiplier can be calculated by observing its current waveform (Fig. 14). During times t1 and t3, inductor-multiplier sources amplified ripple current to the output and, during time t2, it sinks the ripple current to ground.
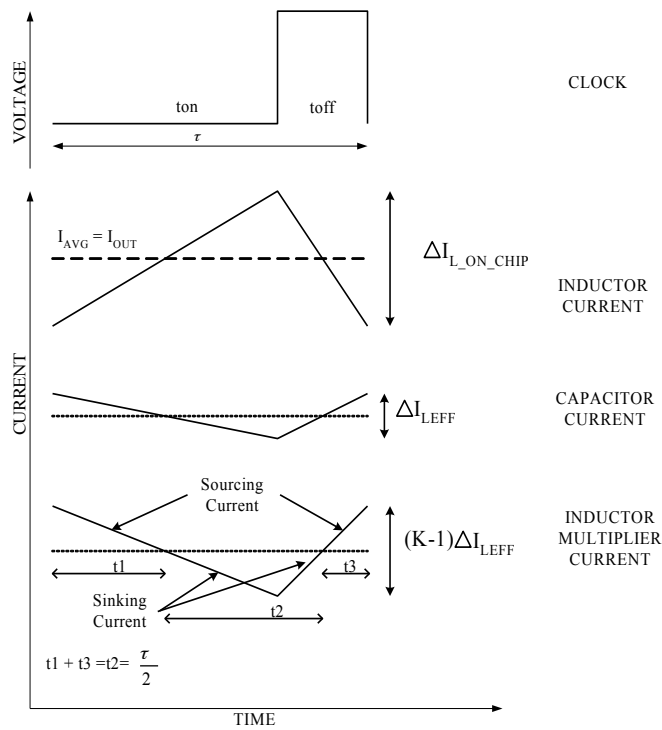
Fig. 14. Current waveforms of an inductor multiplier in a buck-converter

The power losses during times t1 and t3 (when the inductor multiplier is sourcing current to the load), is given by,

$$P_{t1\&t3} = (V_{IN} - V_{OUT})I_{avg\_source} = (V_{IN} - V_{OUT})\left(\frac{\Delta I_{L\text{-}PEAK}}{8}\right), \quad (11)$$

while in time t2 (when the inductor multiplier is sinking current) is given by,

$$P_{t2} = V_{OUT}I_{avg\_sink} = (V_{OUT})\left(\frac{\Delta I_{L\text{-}PEAK}}{8}\right), \quad (12)$$

assuming V_{OUT} to be roughly constant. The simulation results of the losses in a buck converter, with and without the inductor multiplier, are tabulated in Table I. The efficiency of the designed converter with the inductor multiplier was 74 % with a 2.5 A load current as compared to 86.6 % without the inductor multiplier. The overall degradation in efficiency results from an increase in the ripple current (a consequence of a smaller inductor), which is not delivered to the output. At high output currents, conduction losses dominate and the overall efficiency is reduced for both the inductor multiplier and non-inductor multiplier cases (Fig. 15). At light loading conditions, there is a significant difference in the efficiency performance of the circuits. In the case of the inductor multiplier, the ripple current is K times larger; therefore, the onset of negative inductor currents occur at a higher output current (as shown with points P and Q on the plot for 0.2 and 1.5 A respectively). Since the output current is fixed, the negative current is supplied from the inductor multiplier, leading to reduced power efficiency. One of the ways of circumventing this problem could be to operate in asynchronous mode rather than in synchronous rectification. The effect of this on the design and operation of the inductor

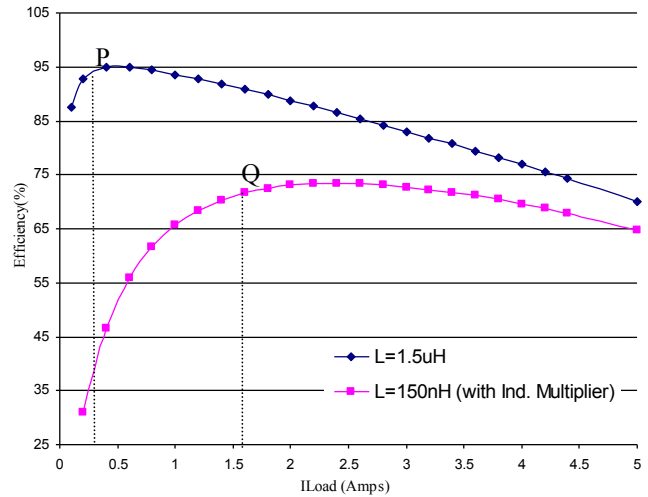multiplier is being researched.

Fig. 15. Efficiency variation with changing load current

TABLE I
POWER LOSSES

Table II summarizes all the plausible alternatives discussed and compares their characteristics with the inductor multiplier. The inductor multiplier is conducive toward SOC power-management solutions for portable power applications. Charge pumps and regulators using external inductors require large passive components, preventing complete integration. While linear regulators and converters using MEMS inductors are options for SOC implementation, their efficiency and output power handling capacity is always an issue. Implementation using a virtual inductor is also an option, but replacing the

$V_{IN} = 2.5V$ $V_{OUT} = 1.7V$ $I_{OUT} = 2.5A$		Buck Converter L=Lo(1.5uH)	Buck Converter L=Lo/K (150nH) K=10	Linear Regulator	Buck Converter L=Lo/K (150nH) Inductor Multiplier
DC Losses (mW)	Switch R_{HS}=75mohms R_{LS}=17mohms	396.25	396.25		396.25
	R_{ESR_L} (10 ohms)	62.5	62.5		62.5
	Sub Total	458.75	458.75		458.75
RMS Losses (mW)	Switch R_{HS}=75mohms R_{LS}=17mohms	0.4	40.6		40.6
	R_{ESR_L} (10 ohms)	.07	6.8		6.8
	R_{ESR_C} (10 ohms)	0.42	42.5	NA	0.42
	Sub Total	1	89.9		47.75
Diode Loss (mW)			23.6	38		38
Switching Loss (mW) F=1Mhz tr=tf=15ns		174	202.5		202.5
Loss (Ind-Mx) (mW)		-	-		742
TOTAL LOSSES (mW)		657	789		1489
EFFICIENCY		**86.60 %**	**84.3 %**	**70 %**	**74.05 %**

inductor completely would result in large losses and its effectiveness is yet to be realized in power supply circuits. Inductor multiplier on the other hand satisfy the demands of SOC implementation, even at medium/high load currents,

falling back only on the efficiency, which is the topic of research in the near future.

TABLE II
COMPARATIVE EVALUATION

	Charge Pumps	External Inductor	Linear Regulator	MEMS	Virtual Inductor	Inductor Multiplier
SOC Feasibility	Worst	Worst	Better	Good	Best	Best
Output Power	Low	Highest	Low	Medium	Medium	Medium
Cost (PCB Estate)	High	Highest	Lowest	High	Low	Low
Efficiency	Good	Best	Worst	Poor	Moderate	Moderate

VI. CONCLUSION

The novel concept of active inductor multiplication to maximize the use of integrated inductors for SOC implementation of switching regulators is introduced. A buck converter designed with an inductor multiplier generates the same ripple performance as with the standard (but larger) discrete inductor. The drawback, however, is increased power dissipation and hence reduced efficiency. The efficiency is still better than linear regulators, though, which can at best be 70.5 % efficient ($\eta_{max} = V_{OUT}/V_{IN}$). The use of inductor multipliers is an enabling technique that makes it possible for integrated inductors to be used as discrete components in a very practical manner, which is conducive toward the much demanded SOC solutions of tomorrow. Furthermore, integrated inductor spares valuable PCB real estate, thus reducing the overall cost of the system and making it very attractive for mobile, battery-powered applications.

ACKNOWLEDGMENT

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