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A Compact Substrate Coupled Inductor for Interleaved Multiphase DC-DC Converters

Y.Rama Krishna[1] | B.Santosh Kumar[2] | T.Srinivasa Rao[3]

[1,2,3] Department of EEE, , Avanthi Institute of Engineering & Technology, Visakhapatnam ,Andhra Pradesh, India.

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ABSTRACT

A compact Substrate coupled inductor structure is proposed for interleaved multiphase synchronous buck converters used to power computer processors and memories that require high current and fast current flew rate. Here the error regarding load current and the reference value will be driven to PI controller which guides them in to the pulse generator. As the result distortions and harmonics will be mitigated when compared to compact coupled inductor. As we all know that the new coupled inductor structure reduces the winding resistor power loss and makes it possible to utilize Ferrite magnetic material with low core loss. In the letter, several proposed converter implementations to achieve inverse inductor coupling are illustrated, and inductance and coupling coefficient variations are studied through a simplified reluctance model and Maxwell magnetic simulation. All the results are acquired from the MATLAB simulations and various graphs are plotted.

KEYWORDS: *compact substrate coupled inductor, buck converter, PI controller.*

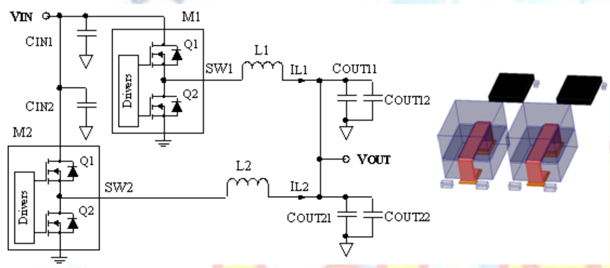
I. INTRODUCTION

In an integrated circuit, a signal can couple from one node to another via the substrate. This phenomenon is referred to as substrate coupling or substrate noise coupling.

II. SUBSTRATE COUPLING

The push for reduced cost, more compact circuit boards, and added customer features has provided incentives for the inclusion of analog functions on primarily digital MOS integrated circuits (ICs) forming mixed-signal ICs. In these systems, the speed of digital circuits is constantly increasing, chips are becoming more densely packed, interconnect layers are added, and analog resolution is increased. In addition, recent increase in wireless applications and its growing market are introducing a new set of aggressive design goals for realizing mixed-signal systems. Here, the designer integrates radio frequency (RF) analog and base band digital circuitry on a single chip. The goal is to make single-chip radio frequency integrated circuits (RFICs) on silicon, where all the blocks are fabricated on the same chip. One of the advantages of this integration is low power dissipation for portability due to a reduction in the number of package pins and associated bond wire capacitance. Another reason that an integrated solution offers lower power consumption is that routing high-frequency signals off-chip often requires a 50Ω impedance match, which can result in higher power dissipation. Other advantages include improved high-frequency performance due to reduced package interconnect parasitics, higher system reliability, smaller package count, and higher integration of RF components with VLSI-compatible digital circuits. In fact, the single-chip transceiver is now a reality.

Interleaved multiphase synchronous buck converters have been popular in applications that require high current, fast load transient response, high efficiency, and reduced space [1]. Fig. 1 (a) shows a circuit of two-phase interleaved synchronous buck converter, which can be extended to multiple phases for higher current applications. The power stage in each phase, which consists of two MOSFETs and their driver, can be co-packaged in a multi-chip module (*M1* or *M2*) to save space and reduce parasitic inductance and resistance. The inductors dominate the size in high-current multiphase converters due to much slower development in magnetic materials than in semiconductors, as shown in Fig. 1 (b). Therefore, it is the highest priority to reduce inductor size in the converters.



(a) (b)

Figure 1. A two-phase interleaved buck converter (a) Circuit (b) Layout.

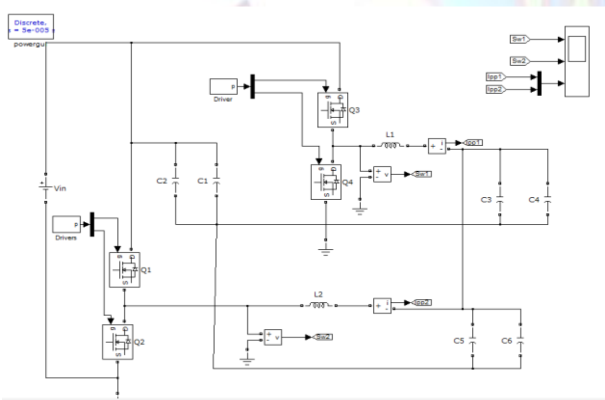


Figure 2. Simulation 1

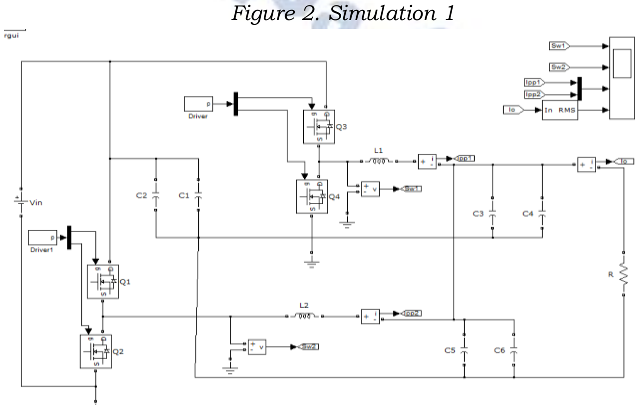


Figure 3.Simulation with feedback.

III. A COMPACT LATERAL COUPLED INDUCTOR STRUCTURE

In this section, a compact lateral inductor structure with very low winding resistance is proposed. The structure is for both multiphase and single-phase converters and can be embedded in PCB layers of motherboards or POL modules.

A. Two-Phase Lateral Coupled Inductor

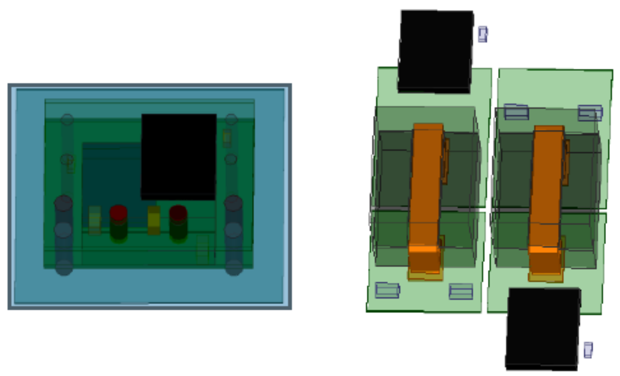
In the low-voltage, high-current applications, the *Rds(on)* of low-side MOSFETs, *Q2* of *M1* and *M2* modules in Fig. 1, is usually in *mΩ*range due to the high efficiency requirement. Any inductor winding resistance higher than a few *mΩ*contributes to significant power loss increase and therefore large efficiency reduction. For POL modules with small volume and limited thermal capacity, the extra power loss means reduced current capability and lower power density.

In high-current, low-voltage dc-dc converters, the length of inductor windings has to be reduced to lower the winding power loss. Reducing number of turns by using high permeability core material is most effective, and the winding length can be further reduced by changing the inductor structure from vertical to lateral [8].

Fig. 3 shows the lateral coupled inductor for an embedded two-phase dc-dc converter module shown in Fig. 4 (a), which is actually an extension to 3-dimension (3-D) coupled-inductor converter from the 2-dimension (2-D) converter with inverse coupling proposed in Fig. 15 of [13]. As a comparison, the layout of the 2-D converter is shown in Fig. 4 (b). The 3-D converter in Fig. 4 (a) reduces inductor power loss by replacing long inductor windings by short ones without the copper traces in Fig. 2(e). The Ferrite core material used has higher permeability than the LTCC and alloy flake composite materials, which makes it possible to further lower the winding loss by reducing number of turns from two or three to only one. The air gap, *g*, next to the windings in Fig. 3 (a) is used to adjust the inductance. The lateral inductor in Fig. 4 (a) is placed next to the power stages to save space and at the same time eliminate power loss of the extra PCB traces in Fig. 4 (b).

The relative current direction in Windings 1 and 2 in Fig. 3 (a) determines the inductor coupling. Fig. 3 (b) shows direct coupling since the currents in two windings are in the same direction [2]. Fig. 3 (c) shows inverse coupling since the currents are in reverse directions. As demonstrated in [2], [14], the inverse coupling is required for improvement of transient response and converter efficiency in applications that require fast current slew rate and low power loss. To achieve inverse coupling in the proposed inductor structure, several implementations of a two-phase converter are created. Fig. 5 shows front and top views of two proposed implementations of the inversely-coupled inductor in a two-phase converter, where dashed lines represent components on the bottom side.

The inversely-coupled inductor implementation for a POL module is shown in Fig. 5 (a), where the inductor is sandwiched by two PCB layers with one pair of MOSFETs on top side of the module and another pair on bottom side. The input voltage, output voltage and control signals of the module are connected to a motherboard, as shown in Fig. 5 (a) with the 3-D layout shown in Fig. 4 (a). To eliminate power loss of connectors between the module and the motherboard, the coupled inductor can be embedded between motherboard PCB layers, which is similar to Fig. 7(b), with one pair of MOSFETs on the top side of the motherboard and the second pair on the bottom side. Therefore, the efficiency and thermal performance are improved at the expense of motherboard area and extra cost associated with inductor embedding process in motherboard.



(a) (b)

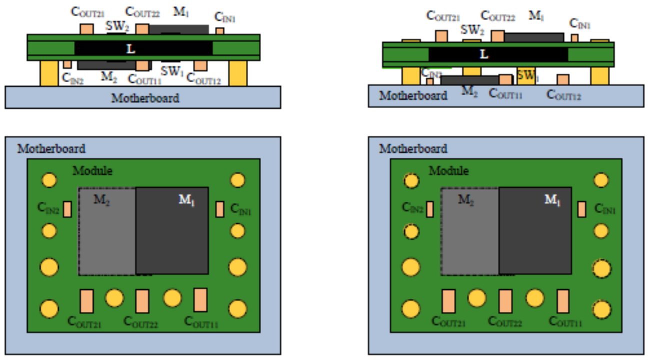
Figure 4. PCB Layout of converters with inversely coupled inductor (a) A 3-D converter with lateral inductor (b) A 2-D converter with discrete inductors.

Fig. 5 (b) shows a module with co-packaged coupled inductor and one pair of MOSFETs, *M1*, which can be placed onto a motherboard as *one* component. The second pair of MOSFETs, *M2*, can be either placed on top of the motherboard, as shown in Fig. 5 (b), or embedded inside the motherboard PCB layers.

B. Extensions of the Two-Phase Coupled Inductor

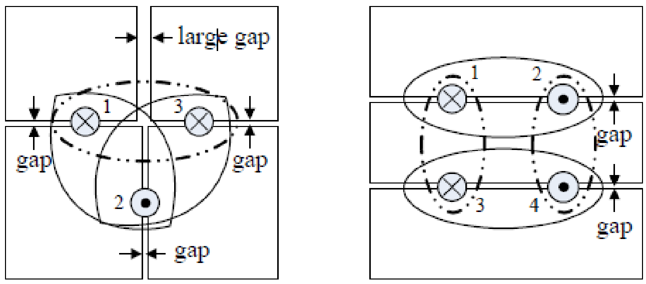
The two-phase coupled inductor structure can be extended to multiple phases including odd and even phase numbers. Fig. 6 (a) shows a proposed three-phase coupled inductor. The three small gaps control the inductance, while a large gap between Windings 1 and 3 is added to eliminate direct coupling between these two phases.

Fig. 6 (b) shows a four-phase coupled inductor. There is strong inverse coupling between Windings 1 and 2 as well as between Windings 3 and 4, as shown by the solid ellipses. However, the direct couplings between Windings 1 and 3 as well as Windings 2 and 4 are weaker due to the two extra air gaps along the coupling paths, as shown by the dashed ellipses.



(a) (b)

Figure 5. Front and top views of the two-phase embedded coupled inductor implementations (a) In a module (b) In a module and on a motherboard.



(a) (b)

Figure 6. Top view of multiphase coupled inductors (a) Three-phase (b) Four-phase.

With this arrangement, the inverse coupling is achieved while the direct coupling is minimized.

IV. EXPERIMENTAL RESULTS

Several two-phase coupled inductor samples are built to verify feasibility and applications in the two-phase synchronous buck converter. it shows two different sizes of coupled inductors. For quick prototyping and proof of concept, magnetic core pieces from off-the-shelf inductor cores have been selected to build the inductors at lab (by hand drilling the holes and filing/sanding the core pieces in the low-cost ferritecores).

The inductor dimensions are not optimized especially length *L* and thickness *h*. Therefore, this proof of concept experiment would not have optimal efficiency, inductance, etc., making total performance comparisons with [8], [12] lacking. However, the experiments that the winding resistance decreases with one turn instead of two turns and that operating current levels can be achieved similar to prior literature.

The two-phase converter is run under the conditions of 12V input voltage, 1.2 *V* or 1.8 *V* output voltage, 1 *MHz* switching frequency, and 0 *A* to 50 *A* loads.

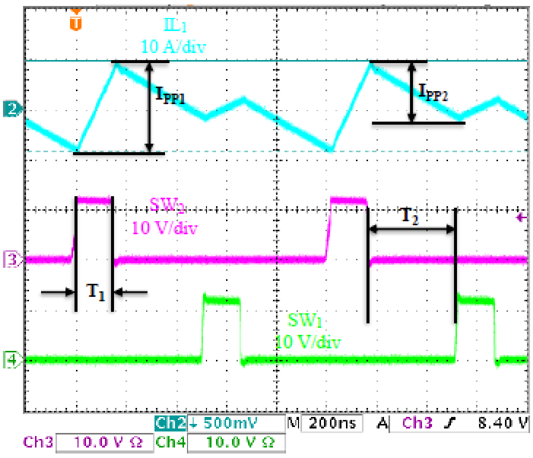
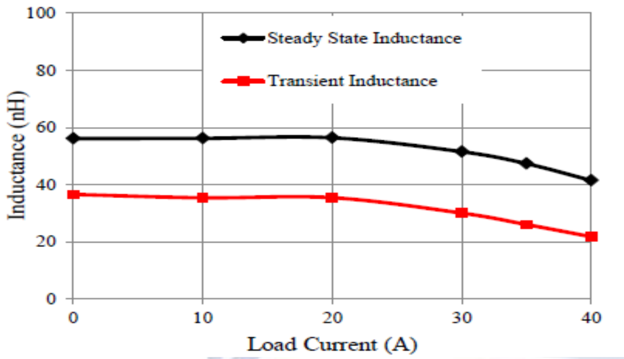
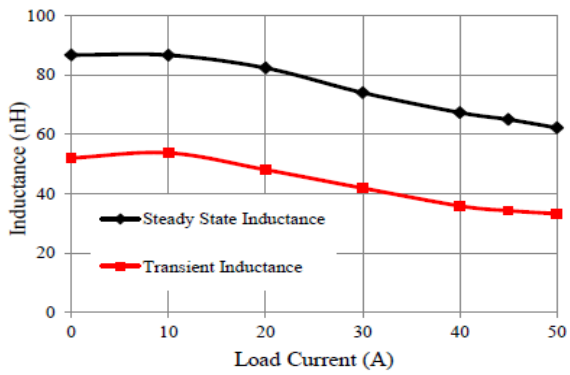


Figure 7. Two-phase inversely-coupled inductor waveform at 10 Aload, Inductor LB, 1.8V output.



(a)



(b)

Figure 8. Measured steady-state and transient inductances (a) Inductor LA (b) Inductor LB.

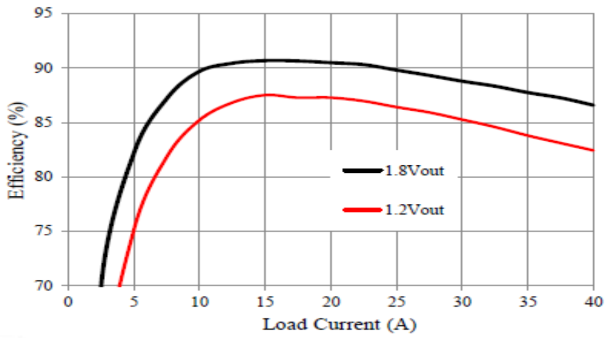


Figure 9. Efficiency of the two-phase converter with inductor LB

waveform, *SW1* and *SW2*, and inductor ripple current of one phase, *IL1*, of inductor *LB*. The inverse coupling effect is shown on the inductor waveform, which helps enhance converter transient response while keeping the same efficiency or improve efficiency while keeping the same transient response.

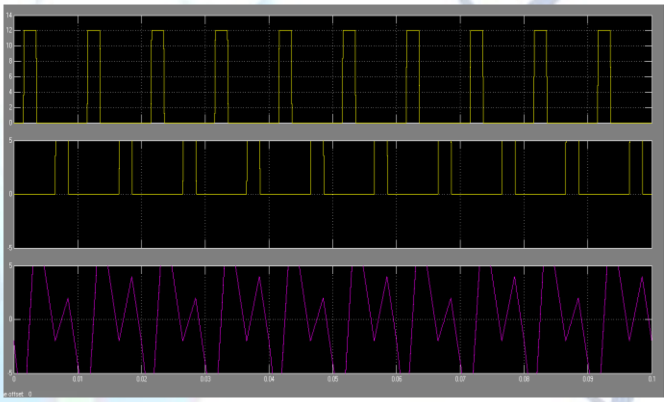


Figure 10. System without feedback

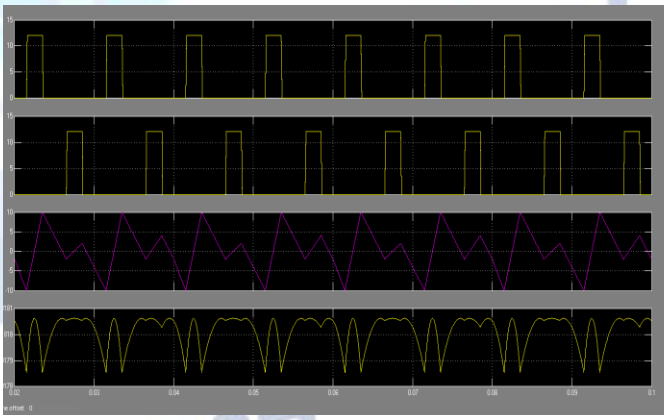


Figure 11. System with Feedback

V. Conclusion

This letter proposes a compact coupled inductor structure that has low inductor winding loss and core loss and is suitable for high frequency operation. Different implementations with two-phase inverse coupling are presented along with extensions of the inductor structure to single and multiple phases. Based on the simplified model (1)–(5) and 3-D simulation of the Maxwell magnetic software, the inductance value can be adjusted by air gap in the inductor core independently, while the coupling coefficient can be controlled by the distance between windings. The experiment of a two-phase prototype converter verifies the new coupled inductor concept and its application in high current converters.

Coming to the proposed theory of substrate coupled inductors. Here the error regarding load current and the reference value will be driven to PI controller which guides them in to the pulse generator. As the result distortions and harmonics will be mitigated

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