Substrate-embedded, magnetic core inductors for Integrated Voltage Regulators

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Outline

- Goals & Objectives
- Prior Work
- Technical Approach
- Results & Key Accomplishments
- Comparison with Prior Art
- Schedule
- Summary
Goals and Objectives

Design and demonstrate embedded inductors to yield a low power module with:

- Power density: 2 A/mm²
- Miniaturized modules:
  - Inductor thickness < 300 µm
  - Added thickness due to passives ~100 µm
- Single-stage power conversion close to load
- Short PDN path
- Losses (interconnects and passives): < 5%

Metrics

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Objectives</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance (nH/mm²)</td>
<td>10-20 at 1 - 10 MHz 6 at 100 – 140 MHz</td>
<td>- Model and design magnetic-core inductors with target specifications</td>
</tr>
<tr>
<td>Current handling (A/mm²)</td>
<td>2</td>
<td>- Develop new process to fabricate and characterize substrate-integrated inductors</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.3 – 0.5</td>
<td>- Develop an innovative process to embed LC into substrates</td>
</tr>
</tbody>
</table>
Prior Work

- New magnetic materials with high permeability but high loss:
  - Loss analysis indicated high permeability was critical in energy saving
- Measured electrical parameters and established mechanical performance of the composite:
  - Low-frequency permeability: 140 at 10 MHz, High-frequency permeability: 25 at 140 MHz
  - Good adhesion of composite to ABF (952 g/cm)
  - The magnetic composites were tested for their endurance to different via drilling processes: UV, IR, CO₂
- Modeled different inductor topologies for high permeability cores meeting target objectives

Embedding process was developed to integrate inductors into the substrate

Modeled and fabricated spiral (2D) inductors for low-frequency IVRs:

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Inductance (nH/mm²)</th>
<th>DC Resistance (mΩ)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objectives</td>
<td>10</td>
<td>&lt; 10</td>
<td>0.5</td>
</tr>
<tr>
<td>Fabricated Performance</td>
<td>12.43</td>
<td>15.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Inductor Packaging Evolution

- **Discrete inductors**
  - SMT Discrete
    - Large Height
    - Large foot-print

- **Substrate embedded passives**
  - Smaller Height
  - Small foot-print

- **Substrate embedded inductor**
  - Improved power density with advanced materials and designs
  - Miniatrurized modules
  - Higher efficiency
  - Short PDN path: Reduce the need for decoupling
  - Reduced impedance
Current Approach for Inductor Fabrication

**Sumida PSI2: Inductor in package**

- 2.8% increase in efficiency with 3-5 Amp current

*Ref: Wang et al. ECTC 2016*

**Virginia Tech: Inductor in PCB Substrate**

- PCB-embedded ferrite and metal flake composites

*Ref: Su et al. IEEE 2013*

**Tyndall: On-chip inductors**

- Thin magnetic films; coupled inductor designs

*Ref: Wang et al. IEEE 2010*
Embedding Challenges

- Low volumetric density
- Thicker component
- Self-assembled
- Low stability

Inductors:
- Low current
- Higher cost
- Low power handling
### Substrate Material Selection

<table>
<thead>
<tr>
<th>Material</th>
<th>Ferrite</th>
<th>Sputtered thin-films</th>
<th>Metal-polymer composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq. stability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scalability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current handling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate compatibility</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Ferrite, metal-polymer composites and sputtered thin-films are considered as the candidate for magnetic substrate.
- Metal-polymer composites provide the best trade-off for density and power-handling.

Current focus:

- Metal-polymer composites
Unique Approach at PRC

Innovative Inductor Designs

Unique inductor designs:
- Spiral inductors (2D)
- Novel toroidal inductors (3D)

Advanced Materials

Magnetic composites for high inductance density
- High permeability
- Trade-off high current handling, DC resistance, and inductance density

Advanced Integration Process

- Substrate-compatible process to integrate inductor into substrates
- Reliability testing - Thermal cycling and warpage

Spiral

Polymer insulation
Magnetic core

Substrate
Copper winding

Solenoid

Polymer insulation
Magnetic cores

Substrate
Copper winding

Characterization set-up

Electrical characterization
- L vs Frequency
- L vs Current
- DC resistance
Electrical Characterization of Composites

Courtesy: Panasonic

Required material properties for 96% efficiency:

- The permeability is somewhere in between 50 and 150
- Loss tangent must be less than 0.033
- Magnetic saturation field must be greater than 0.6 Tesla

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low frequency</th>
<th>High frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability (H/m)</td>
<td>150 at 10 MHz</td>
<td>25 at 140 MHz</td>
</tr>
<tr>
<td>Loss tangent</td>
<td>0.146</td>
<td>0.230</td>
</tr>
</tbody>
</table>

\[ \mu' = 76 \]

\[ \tan \delta = 0.034 \]

\[ \mu'' = 2.6 \]

\[ I = 3.5A \]
Modeling of Inductor Topologies using Composites

- Planar inductors show lower current handling, but are easier to fabricate
- Solenoid inductors have a comparable inductance but higher current handling

Low-Frequency Material Designed Parameters:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{DC}$ [A]</td>
<td>&lt;1.25</td>
<td>&lt;1.25</td>
<td>&lt;1.00</td>
<td>&lt;1.00</td>
</tr>
<tr>
<td>$L$ [nH]</td>
<td>23.8</td>
<td>44.1</td>
<td>66.6</td>
<td>116.9</td>
</tr>
<tr>
<td>Inductance Density [nH/mm$^3$]</td>
<td>88.0</td>
<td>101.0</td>
<td>151.6</td>
<td>164.6</td>
</tr>
<tr>
<td>$R_{DC}$ [mΩ]</td>
<td>5.5</td>
<td>8.5</td>
<td>9.8</td>
<td>15.7</td>
</tr>
<tr>
<td>$R_{AC}$ [mΩ]</td>
<td>227</td>
<td>426</td>
<td>635</td>
<td>1102</td>
</tr>
<tr>
<td>$R_{AC}$ [mΩ/nH]</td>
<td>9.6</td>
<td>9.7</td>
<td>9.5</td>
<td>9.4</td>
</tr>
</tbody>
</table>

- Toroidal inductors show highest inductance because of closed magnetic loops
Fabrication Process Flow

1. Magnetic sheet substrate
   - 300 um

2. Laser drill slot with a fempto-laser

3. Laminate the polymer and fill the slots.

4. Laser drill the vias in slots

5. Deposit an electroless layer of copper

6. Laminate a negative photoresist

7. Place a positive mask and expose to UV light

8. Remove the photoresist that was not exposed.

9. Electroplate with thick copper

10. Etch out the photoresist and seed copper
# Fabrication of Inductor Topologies

Demonstration of substrate-embedded 2D and 3D inductors for low and high-frequency IVRs

## Metrics

<table>
<thead>
<tr>
<th>Metrics</th>
<th>2D Low Frequency Objectives</th>
<th>2D Low Frequency Fabricated Values</th>
<th>2D High Frequency Objectives</th>
<th>2D High Frequency Fabricated Values</th>
<th>Solenoid Low Frequency Objectives</th>
<th>Solenoid Low Frequency Fabricated Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance Density (nH/mm²)</td>
<td>10-20</td>
<td>12.38</td>
<td>6</td>
<td>8.21</td>
<td>10-20</td>
<td>To be Measured</td>
</tr>
<tr>
<td>DC Resistance (mΩ)</td>
<td>5 - 10</td>
<td>9.83</td>
<td>&lt; 10</td>
<td>7.72</td>
<td>5 - 10</td>
<td></td>
</tr>
<tr>
<td>Thickness (µm)</td>
<td>500</td>
<td>435</td>
<td>200 - 300</td>
<td>315</td>
<td>200 - 300</td>
<td></td>
</tr>
</tbody>
</table>

## Optical View

- Top view of spiral inductors
- X-section view
- Optical view of planar inductor

## Images

- The top view of spiral inductors
- Optical view of planar inductor
- X-section view of substrate-embedded inductors
Comparison with Prior Art

- Discrete inductors can accommodate higher thickness which leads to high inductance density with lower resistance.
- Low loss tangent materials with moderate permeability have been simulated to show high efficiency embedded inductors with low DC resistance.
- There is a trade-off between inductance density and DC resistance.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Targets</th>
<th>GT-PRC</th>
<th>On-chip inductor</th>
<th>Discrete inductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/R (nH/mΩ)</td>
<td>~ 20</td>
<td>~ 9.6</td>
<td>0.18</td>
<td>23</td>
</tr>
<tr>
<td>Current handling (A/mm²)</td>
<td>2</td>
<td>2</td>
<td>3-4</td>
<td>0.6</td>
</tr>
<tr>
<td>DC resistance (mΩ)</td>
<td>&lt; 10</td>
<td>7.72</td>
<td>1200</td>
<td>5.2</td>
</tr>
</tbody>
</table>
Schedule

- Toroidal single inductor is already designed
- Optimization of fabrication process ongoing
- A single inductor based 4-phase buck converter is in design step
- A Journal paper will be prepared with the analysis results to date
- Next step will be preparing a measurement setup to measure the inductor under DC current bias and with triangular current waveform
- Next iteration will be the design of a tapped inductor-based converter
Summary

- Modeled and designed spiral inductors for target specifications as below.
  - Low-Frequency: L - 10 nH/mm², R – 5 mΩ, thickness – 0.5 mm
  - High-Frequency: L – 6 nH/mm², R – < 10 mΩ, thickness – 0.3 mm
- Developed and optimized process flow for fabricating substrate integrated inductors.
- Fabricated and characterized planar inductors for low and high-frequency applications:
  - Low-Frequency: L – 12.38 nH/mm², R – 9.83 mΩ
  - High-Frequency: L – 8.21 nH/mm², R – 7.72 mΩ
- Fabricated solenoid inductors for low and high-frequency applications
- Modeled novel toroid inductors and currently optimizing the fabrication process

Next Milestones:
- Fabricate toroid inductors and measure the inductance
- Establish effect of undercut on the inductance density
- Lower losses with high L/R_{dc} with filled vias
- Model and fabricate inductors for 48V-1V applications using very low loss materials