Planar Spiral Inductors With Multilayer Micrometer-Scale Laminated Cores for Compact-Packaging Power Converter Applications

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***Abstract*—Ultralow (0.4 mm) profile spiral inductors with multilayer micrometer-scale NiFe laminated cores were developed for compact-packaging power applications. A simple sacrificial Cu etching process was used to realize seven layers of 1.8-μm-thick laminations, forming the magnetic cores. The laminated cores were combined with a spiral coil to fabricate the spiral inductor in a hybrid fashion. The dimension of a complete device is 40 $\times$ 15 mm. *In situ* electrical characterization verified compatibility with compact-packaging applications. The inductor was implemented in a boost converter (5–10 V) operating at 2.2 MHz, which demonstrated 2-W output with overall efficiency exceeding 70%.**

***Index Terms*—Compact packaging, core lamination, dc-dc converter, eddy current, spiral power inductor.**

I. INTRODUCTION

THERE HAS been increasing demand for compact dc-dc converters in a variety of electronic systems to keep pace with system trends of miniaturization and increased functionality. The most demanding applications are battery operated portable electronics and distributed dc power conversion. Miniaturized magnetic components in these applications are generally required to have the following properties: High power density (high-frequency operation and high magnetic saturation), efficient power conversion (low eddy and hysteresis loss), compatibility with compact-packaging (low profile), and low cost [1]. The development of magnetic components with the above characteristics is often constrained by the available magnetic materials and fabrication methods. In an attempt to address these limitations, a simple, manufacturable lamination technology using sacrificial Cu etching has been successfully developed for electrodepositable magnetic alloys [2]. These alloys have superior magnetic properties such as high magnetic saturation, low hysteresis loss, and high Curie temperature over many ferrites.

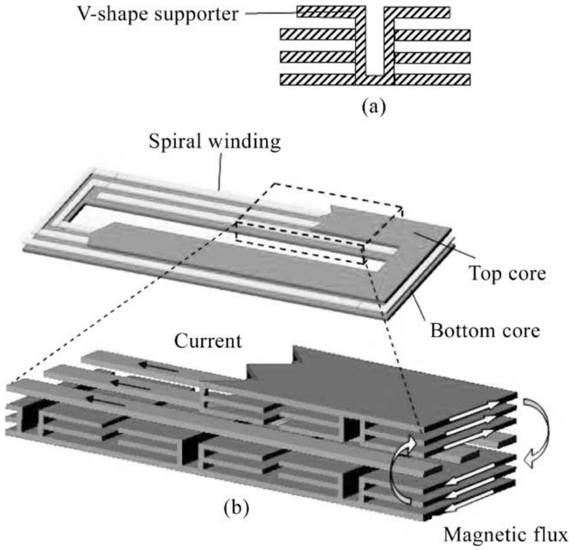

Fig. 1. Illustrations for a spiral inductor with laminated cores.

In this paper, the sacrificial etching approach has been utilized to realize low-profile spiral inductors with laminated NiFe cores for high frequency power applications. Since a spiral winding is inherently two dimensional and can be stretched over a large area, it could result in a lower profile than a toroid inductor (at the expense of a larger footprint). This can be advantageous for compact-packaging driven applications such as power regulators for cellphones and PDAs. Also, with a low profile and large area, thermal concerns for high power density inductors can be reduced [3]. In this paper, the laminated structure design and fabrication for a spiral inductor is presented, along with *in situ* electrical characterization for a compact-packaging environment.

II. LAMINATED STRUCTURE DESIGN

Fig. 1(a) shows the cross section of the laminated toroid core developed using the sacrificial Cu etching technology. This method enables highly laminated cores using a simple fabrication process. The unique V-shape supporter provides mechanical support for the laminated magnetic blades and permits the sacrificial etching solution to etch the Cu interlayers from either side. Fig. 1(b) shows a planar spiral coil sandwiched between a top and bottom laminated core. The V-shaped cores are repeated along the conductor winding with spacings between each V-shaped core to permit the sacrificial Cu etching process. The minimum spacing is limited by photolithography. Using this lamination scheme, the magnetic flux generated by the conductors will be contained in the cores and air-gap as shown Fig. 1(b).

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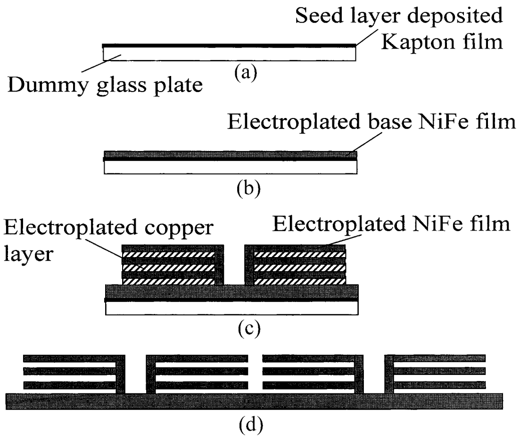

Fig. 2. Fabrication process for laminated cores.

III. FABRICATION

Widely used NiFe alloy was chosen as a plating magnetic material. The fabrication of the inductors includes two major processes: 1) fabrication of laminated magnetic cores and spiral winding; 2) stacking and mechanical lamination of the prefabricated top and bottom cores, and the spiral winding.

A. Fabrication of Laminated Magnetic Cores and Spiral Windings

The top and bottom cores are basically identical and therefore are fabricated simultaneously in one batch. The fabrication process is illustrated in Fig. 2. First, a 50-μm-thick Kapton film with a seed layer was attached to a dummy glass plate using a thin photoresist [Fig. 2(a)]. A 3 μm NiFe film was electroplated to be used as base core substrate [Fig. 2(b)]. Then, seven layers of 1.8 μm-thick NiFe films and seven layers of 1-μm-thick Cu were alternately plated to form a multilayered metal structure [Fig. 2(c), only 4 layers of each materials are shown for simplicity]. The details can be found in [2]. Finally, the Kapton film with the multilayer core structure was separated from the dummy glass plate, and the Cu sacrificial layers were selectively etched away in $\mathrm{NH_4OH}$ saturated with $\mathrm{CuSO_4}$ [Fig. 2(d)]. Separately, a seven-turn planar spiral winding was fabricated by laser cutting 100-μm-thick copper sheet. After cutting, a conformal 0.5-μm-thick $\mathrm{SiO_2}$ layer was deposited on the top and bottom of the spiral winding using a plasma enhanced chemical vapor deposition (PECVD) system in order to insulate the winding. The fabricated top and bottom cores and the coil winding are shown in Fig. 3(a).

B. Mechanical Lamination of the Cores and Spiral Winding

To form a complete inductor, the bottom laminated core, the spiral coil, and the top laminated core were aligned and pressed gently with a mechanical press at room temperature. Two-part-epoxy was used as an adhesive material between the cores and the coil. A photograph of a complete spiral inductor with laminated NiFe core is shown in Fig. 3(b). To assess eddy-current reduction of the laminated inductor, an unlaminated core inductor with the same geometry was also fabricated

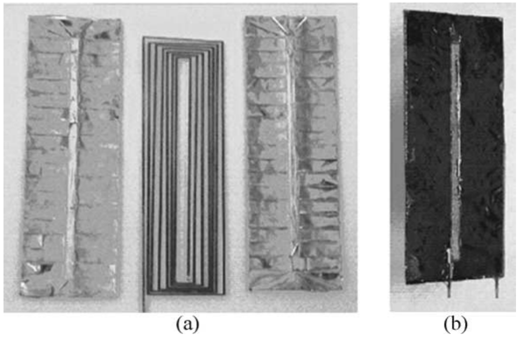

Fig. 3. Photograph of (a) fabricated laminated cores and a spiral winding and (b) a complete inductor.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The dc hysteresis characteristics of a laminated (fabricated with the process of Fig. 2, total magnetic thickness nominally 15.5 μm) and an unlaminated (15.5-μm-thick) core were measured with a vibrating sample magnetometer (VSM). The laminated core shows slightly decreased initial permeability (by 7%) over the unlaminated one. The measured coercivities are 0.9 and 0.7 Oe for the laminated and unlaminated core, and the magnetic saturation density is 0.9 T for both cores.

Three different inductors, a laminated inductor, an unlaminated inductor, and an air-core inductor, were characterized for inductance and Q-factor. The air-core inductor, which is basically the spiral winding itself without any magnetic core, was prepared to assess the electrical improvement of a spiral inductor due to the addition of the laminated NiFe cores on top and bottom of the winding.

Two separate types of measurements were performed: 1) an isolated measurement of inductance and Q-factor, in which the inductor was far from any other electrical surface; and 2) an *in situ* measurement of inductance and Q-factor, in which the inductor was mounted near a copper-coated printed circuit board (PCB) ground plane to mimic the close-packing situation in compact electronic packaging. A 50-μm-thick Kapton sheet is placed between the PCB and the inductors to provide a small air gap.

A. Isolated Measurement of Laminated, Unlaminated, and Air-Core Spiral Inductors

The measured inductances and Q-factors for the laminated, the unlaminated, and the air-core inductors are shown in Fig. 4(a) and (b), respectively. The inductance of the unlaminated inductor rapidly decreases above 50 kHz, while the laminated inductor is stable up to 500 kHz. This implies that eddy current effects are significantly reduced in the case of the laminated core spiral inductor. The Q-factor of the laminated core inductor is higher than four over most of the 0.1–1 MHz range. This value is 3–4 times larger than the unlaminated inductor. As shown in Fig. 4(b), the Q factors of the laminated and the unlaminated inductors increase at low frequency, reach a maximum, and decrease at high frequency. This can be explained by recalling that $\mathrm{Q} = 2\pi\mathrm{fL/R}$, where R is the effective resistance of the inductor. At low frequency, $2\pi\mathrm{fL}$ increases with frequency at a faster increasing rate than that of R, therefore Q increases. At high frequency, R increases with frequency at a faster increasing rate than that of $2\pi\mathrm{fL}$,

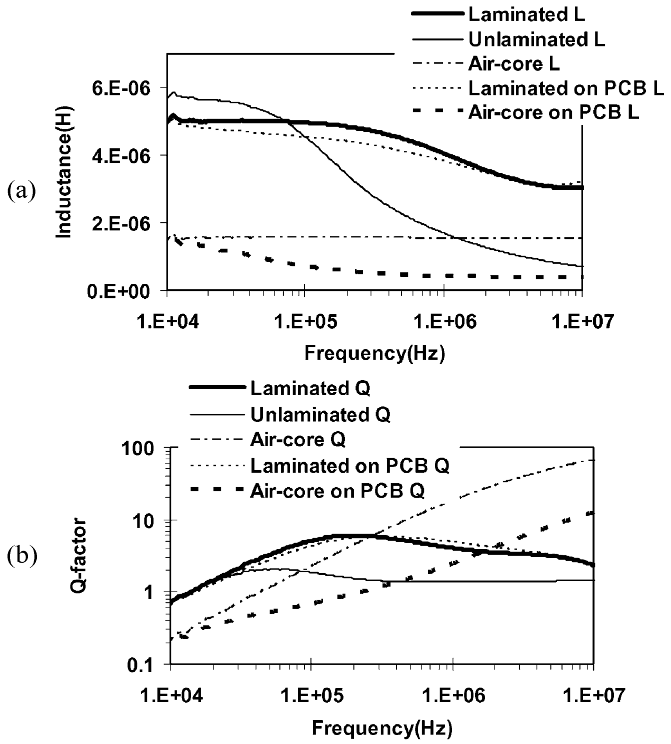

Fig. 4. Measured (a) inductances and (b) Q-factors: isolated measurement and *in situ* measurement on PCB.

due to decreasing L related to eddy current and fast increasing R related to significant core (eddy current and hysteresis) and copper losses, leading to a decrease in Q. The frequency where the maximum Q occurs can usually be shifted to higher frequency by laminating the core as shown in Fig. 4(b) (50 kHz for unlaminated, 200 kHz for laminated). The detailed dependence of Q on core lamination can found in [4]. Self-resonance, due to stray capacitance, of the laminated and unlaminated inductors occurred at 25 and 95 MHz, respectively. The dc saturation current $(\mathrm{I}_{80\%})$ of the laminated inductor was measured to be 0.8 A.

The inductance of the air-core inductor was approximately 1.5 μH for all measured frequencies, which is 3.5 times smaller than the laminated inductor up to 500 kHz. Above the megahertz frequency range, the Q-factor of the air-core inductor increases rapidly, reaching approximately 65 at 10 MHz. However, even though the air-core inductor has high Q at this high frequency, application of it to the compact power application is impractical for several reasons. First, current solid-state power switch technology does not support 10 MHz operation with practical efficiency. Second, a spiral air-core inductor would generally require a certain volume of cleared air regions to support the magnetic flux; otherwise the generated magnetic flux would interact with nearby conductors or lossy materials, resulting in EMI noise in other circuits and decreased inductance and Q-factor in the inductor. This is a significant disadvantage of air-core spiral windings for today's high frequency power applications in ultracompact packaging.

B. *In Situ Measurement of Laminated, and Air-Core Spiral Inductors*

The inductances and Q-factors of the laminated and the air-core inductors measured on top of copper-clad PCB are again shown in Fig. 4(a) and (b). The inductance of the laminated core inductor on the PCB shows a slightly decreased value as compared to the isolated measurements. The inductance decreases by less than 10%, suggesting that majority of magnetic flux is well confined inside the laminated core and the air gap around the perimeter of the inductor. By contrast, the inductance of the air-core inductor on the PCB shows a significant decrease (approximately 75%) at 1 to 10 MHz, as compared to the regular measurements. The Q-factor of the laminated core inductor on the PCB closely matches that of the laminated core inductor in the regular measurement. However, the air-core inductor shows significantly reduced Q-factor over that in the regular measurement due to the EMI loss with the copper coated PCB. It should be noted that even though the Q-factor of the air core inductor on the PCB is higher than that of the laminated inductor at the frequency above 2 MHz, the low inductance and/or large EMI of the air core inductor would limit its use in practice.

C. *Application to DC-DC Boost Converter*

After characterization, the laminated NiFe-core inductor was utilized along with a commercially available switching regulator chip (LT1930A) operating at 2.2 MHz, and discrete passive components to demonstrate a dc-dc boost converter. When load resistors were connected to the output of the converter, the converter showed overall output efficiency $(\mathrm{V}_{\mathrm{load}} \cdot \mathrm{I}_{\mathrm{load}}/\mathrm{V}_{\mathrm{in}} \cdot \mathrm{I}_{\mathrm{in}})$ of 70% at the output range of 0.3 W $\sim$ 1.9 W, converting from 5 to 10 V.

V. CONCLUSION

Planar spiral inductors with laminated NiFe cores were designed, fabricated and characterized for compact-packaging power applications. The *in situ* measurement of the fabricated laminated spiral inductor showed superior electrical performance over an unlaminated and an air-core inductor. The inductor was demonstrated in a dc-dc power converter with power output of 2 W and overall converter efficiency in excess of 70%. The low profile (400 μm) of the developed inductor demonstrates potentials for high frequency compact-power converters of mobile electronics.

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