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Design and Evaluation of Nano-Composite Core Inductors for Efficiency Improvement in High-Frequency Power Converters

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***Abstract*— This paper evaluates the performance of a novel nano-composite core inductor. In this digest, a brief explanation of the superparamagnetic magnetite nanoparticle core is given along with magnetic characterization results and simulated design parameters and dimensions. A nearly flat relative permeability (μ_r) of around 5 is measured for the magnetic material to 1 MHz. A synchronous buck converter with nano-composite inductor was constructed and evaluated; the converter demonstrates a 1% improvement in conversion efficiency at higher currents (10% reduction in electrical losses), compared to an identical circuit with benchmark commercial ferrite inductor.**

Keywords—Inductors, superparamagnetic, synchronous buck converters

I. Introduction

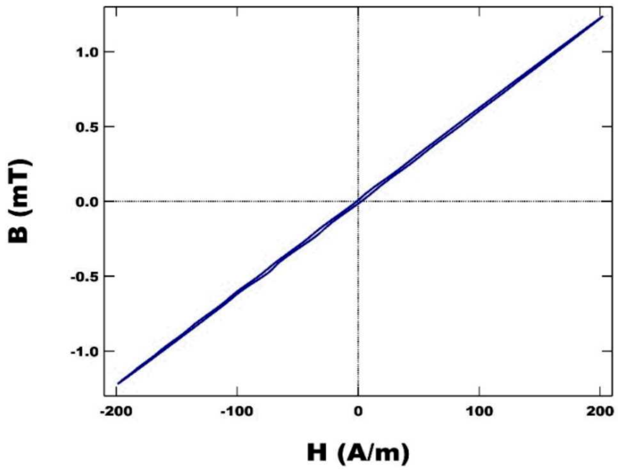
Point-of-load (PoL) converters are an essential component in many electrical systems having distributed components and subsystems. Given the scale of modern data centers, often using power at megawatt (MW) scales and employing expensive thermal management systems, designers are motivated to reduce electrical losses associated with power conversion. Of note is the final conversion stage (converts power from voltages of 12-48 V down to voltages of 1.8-3.3 V for microprocessor loads), which is often the least efficient stage [1, 2].

While the adoption of wide bandgap (WBG) semiconductors, such as gallium nitride (GaN), can reduce electrical losses attributed to the semiconductor, "··· switching frequencies are limited to ≈1 MHz due to the losses in the magnetic components" [3]. To reduce these losses at the MHz-scale switching frequencies, researchers have considered elaborate inductor designs [4], but the performance remains limited by the magnetic material properties. High-Efficiency GaN-based converters have been demonstrated at frequencies above 20 MHz using air core inductors [5].

Recently, a new magnetic material was developed based on nanocomposite technology [2]. This construction virtually eliminates the hysteretic and eddy current losses that accompany high frequency operation. In this paper, the new magnetic material is characterized to 1 MHz and a nano-composite inductor is demonstrated in a simple GaN-based PoL buck converter, with 2 MHz switching frequency, to be higher efficiency than a comparable circuit using a commercial ferrite inductor.

II. Superparamagnetic Magnetite Nanoparticle Composite Core

To achieve the required inductor performance a new generation of materials with high magnetic saturation and permeability are needed and superparamagnetic nanocomposites are an ideal candidate. The ferromagnetic material is formed as 10-20 nm spheres and suspended in an epoxy. Superparamagnets are characterized by an absence of magnetic hysteresis, which makes them especially suitable for high switching frequency applications (Fig. 1). The size of the particle required for superparamagnetism to emerge is also relatively small, which eliminates the contribution from eddy current loss, as the nanoparticles themselves are too small to support eddy currents. Magnetite (Fe_3O_4) is low-cost, non-toxic and possesses the highest room temperature M_{sat} of any metal oxide (92 A·m^2/kg @ 293 K). For any material, control over the size and shape are essential to produce an effective superparamagnetic nanocomposite. For example, a finite size distribution leads to a distribution in relaxation times, which can adversely affect performance in high frequency switching applications [6]. We have developed the synthesis of superparamagnetic magnetite (Fe_3O_4) nanoparticles with an extremely narrow size distribution and incorporated them as the



magnetic component in a strongly magnetic nanocomposite [7].

Fig. 1. Hysteresis loop of a toroidal nano-composite core collected at 1 MHz.

III. NANO-COMPOSITE CORE MAGNETIC CHARACTERIZATION

To evaluate the AC magnetic properties of our nano-composite core material, toroidal cores with an O.D. of 9 mm, I.D. of 6 mm, and a height of 3 mm were fabricated. A SY-8218 B-H analyzer from Iwatsu was used to characterize the nanocomposite toroids up to a frequency of 1 MHz. The nanocomposite material maintains a nearly flat relative permeability (μ_r) out to 1 MHz, as can be seen in Fig. 2.

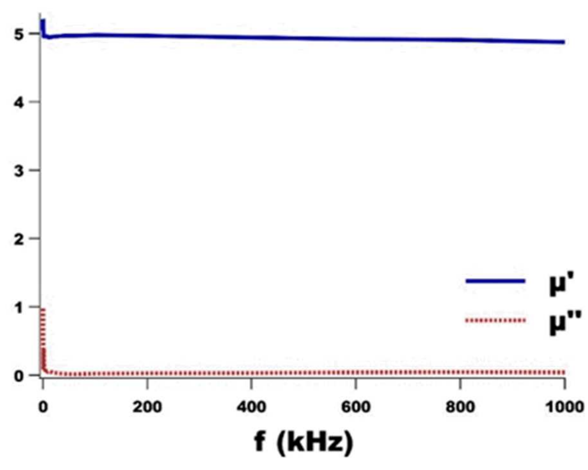


Fig. 2. Real and imaginary permeability of a toroidal nano-composite core versus frequency.

IV. INDUCTOR DESIGN AND SIMULATION

A solenoid-type coil architecture, conducive for manual winding using conventional magnet wire, was chosen for initial prototyping. The inductor employs a bobbin style magnetic core enclosure using our magnetite nanocomposite. To first order, the inductance of a finite solenoid with a magnetic core is governed by the following:

$$L=\mu_r\mu_0 N^2 A/l \quad (1)$$

where μ_r is the relative permeability of the core material, μ_0 is the vacuum permeability, N is the number of wire turns, A is the coil cross section, and l is the coil length. While (1) provides a good, first approximation under DC conditions, this equation does not capture effects due to more complex geometry, nonlinear core materials, and other effects attributed to high frequency AC currents. To improve design accuracy, COMSOL Multiphysics 5.3 commercial finite element software was used.

The inductor is an assembly of three parts: the multi-layer solenoid coil, a nano-composite spindle and base, and a nano-composite cap. The two nano-composite parts are molded and cured as separate pieces. This forms the complete magnetic core enclosure and completes the inductor fabrication process. Figs. 3a & 3b show a 3-D SOLIDWORKS rendering of the two nano-composite parts while Fig. 3c is a cross sectional image of how the two parts are mated with the solenoid coil.

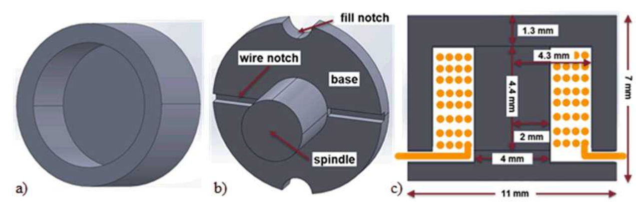


Fig. 3. a) Nano-composite cap. b) Nano-composite spindle & base with notches designed for wire terminals and filling. c) Cross sectional image of the assembled inductor with a 4-layer, 31 total turns solenoidal coil.

The bobbin core offers the advantages of higher power density via the higher magnetic flux nanocomposite, a multi-layer coil for increasing N without significantly increasing l and only a minor increase in the inductor diameter, d, and a completely enclosed flux path for reduced electromagnetic interference (EMI) and power loss through environmental coupling. This flux enclosure is illustrated by the 2-D cross sectional image of the magnetic core polarization, J, shown in Fig. 4. COMSOL was also used to determine that a 4-layer, 31 total turns solenoidal inductor using 24 AWG copper magnet wire would meet the required inductance in the smallest form factor.

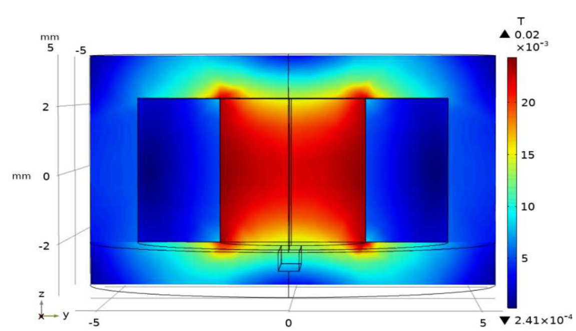


Fig. 4. Cross sectional image of the inductor magnetic core polarization, J, generated by COMSOL.

V. Inductor Electrical Performance Testing

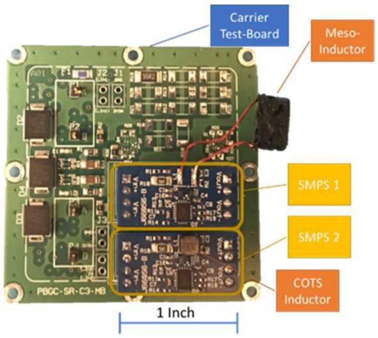


Fig. 5. 3.3 V synchronous buck converter used for testing the inductor performance.

To test the performance of the nano-composite inductor in circuit, a 3.3 V synchronous buck converter was developed with a small form factor using EPC 2012C GaN HEMTs controlled with an LTC7800 step-down controller. The LTC7800 switching frequency was set to 2MHz and put into continuous inductor current mode (i.e. no burst or pulse skipping). Fig. 4 shows both SMPSs on a carrier test board. The efficiency of the buck converter was tested with both the nano-composite inductor and a commercial off-the-shelf (COTs) inductor (ASPI-4030S-3R3). The key parameters of the inductors are compared in the Table 1 below.

TABLE I. Experimental results comparing both inductors.

Measured Parameter	*Nano-Composite Inductor*	*COTS Inductor (measured)*
Inductance @ 1 kHz (μH)	4.38	3.40
Inductance @ 2 MHz (μH)	3.37	3.22
DC Resistance (mΩ)	56	49
AC Resistance @ 2 MHz (Ω)	2.41	1.11
Volume (mm3)	810	48

Fig. 5 below compares the efficiency of the circuits across three input voltages and a range of output currents populated by the nano-composite inductor or the COTS inductor. The output voltage was set to 3.3 V by the LTC7800 controller. With respect to conversion efficiency, the circuits are comparable to about 0.9 A of load current. At this point, the circuit with the nano-composite inductor shows a comparatively better performance than the circuit with COTS inductor, with an approximately 10 % lower electrical loss at load currents above 1.8 A, resulting in approximately 1 % higher conversion efficiency at these higher load currents. This is consistent with the high saturation flux density, low eddy current loss, and low hysteresis loss of the superparamagnetic nanocomposite.

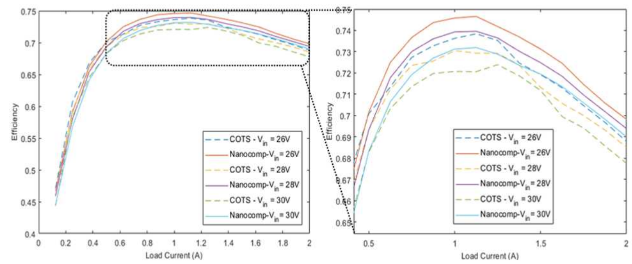


Fig. 6. Circuit efficiency comparison between the nano-composite inductor and the COTS inductor with approx. 1 % lower loss at higher currents.

VI. Future Work

One of the issues encountered with our buck converter measurement was the degree of switching loss in the converter itself. To gain a better understanding of the impact this new nano-composite material may have on the performance of next generation inductors, a direct core loss measurement at frequencies of 10 MHz and beyond will be needed. One promising technique, developed by researchers at Virginia Tech [8], describes a method by which an additional transformer with a lossless (i.e., air) or low-loss magnetic core in the test circuit can be used to cancel the reactive voltage of the inductor. This has the effect of reducing the measurement sensitivity to phase discrepancy which can introduce errors of up to 100% or more if not properly accounted for. It also has the advantages of being wide-band, can be used for arbitrary waveforms, and is relatively easy and inexpensive to implement.

VII. Conclusions

A novel nano-composite core inductor was designed to improve the efficiency of Point-of-load (PoL) converters to reduce electrical losses in modern data centers. This nano-composite consists of 10-20 nm magnetite (Fe_3O_4) spheres and suspended in an epoxy. The superparamagnetic nature of this core material virtually eliminates the hysteretic and eddy current losses that accompany high frequency operation. B-H analyzer measurements of the nanocomposite core were made verifying both it's superparamagnetic behavior and a nearly flat relative permeability (μ_r) of around 5 out to 1 MHz. Finite element modeling using COMSOL Multiphysics 5.3 was used to design an inductor made from this nano-composite material. A comparison between this nano-composite inductor vs. a COTS inductor (ASPI-4030S-3R3) in a 3.3 V synchronous buck converter test circuit shows a 1 % improved efficiency at higher load currents.

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