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Fabrication, characterization and comparison of composite magnetic materials for high efficiency integrated voltage regulators with embedded magnetic core micro-inductors

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Abstract

High-efficiency integrated voltage regulators (IVRs) require the integration of power inductors, which have low loss and reduced size at very high frequency. The use of a magnetic material core can reduce significantly the inductor area and simultaneously increase the inductance. This paper focuses on the fabrication, characterization and modeling of nickel zinc (NiZn) ferrite and carbonyl iron powder (CIP)-epoxy magnetic composite materials, which are used as the magnetic core materials of embedded inductors in a printed wiring board (PWB) for a system in package (SIP) based buck type IVR. The fabricated composite materials and process are fully compatible with FR4 epoxy resin prepreg and laminate. For 85% weight loading of the magnetic powder (around 100 MHz at room temperature), the composite materials show a relative permeability of 7.5–8.1 for the NiZn ferrite composite and 5.2–5.6 for the CIP composite and a loss tangent value of 0.24–0.28 for the NiZn ferrite composite and 0.09–0.1 for the CIP-composite. The room temperature saturation flux density values are 0.1351 T and 0.5280 T for the NiZn ferrite and the CIP composites, respectively. The frequency dispersion parameters of the magnetic composites are modeled using a simplified Lorentz and Landau–Lifshitz–Gilbert equation for a Debye type relaxation. Embedded magnetic core solenoid inductors were designed based on the composite materials for the output filter of a high-efficiency SIP based buck type IVR. Evaluation of a SIP based buck type IVR with the designed inductors shows that it can reach peak efficiencies of 91.7% at 11 MHz for the NiZn ferrite-composite, 91.6% at 14 MHz for CIP-composite and 87.5% (NiZn ferrite-composite) and 87.3% (CIP-composite) efficiency at 100 MHz for a 1.7 V:1.05 V conversion. For a direct 5 V:1 V conversion using a stacked topology, a peak efficiency of 82% at 10 MHz and 72% efficiency at 100 MHz can be achieved for both materials.

Keywords: integrated voltage regulators, NiZn ferrite, CIP, magnetic composite material, debye type relaxation, embedded inductor, SIP buck converter

(Some figures may appear in colour only in the online journal)

1. Introduction

The continuous advances in microelectronics and packaging technology along with increased power demand and performance have created a need for integrated voltage regulators (IVRs) [1] as a part of the power delivery network (PDNs) in electronic systems. IVRs improve efficiency by reducing the resistive losses due to the reduced interconnect length in the PDN and through dynamic voltage and frequency scaling (DVFS). The first reported IVRs were designed to operate with air-core inductors, which were either surface mount technology (SMT) devices [1], on die [2] or package embedded inductors [3, 4]. They had led to relatively low-efficiency IVRs with either low-inductance density [3] or large inductors due to the number of windings required with large cross sectional area [3, 4]. This is a major issue for high-efficiency IVRs which require the integration of power inductors with large inductance per unit area and low-loss. Recently, air-core inductors for IVRs were reported with on-chip planar spiral inductors in a fourth-order LC low-pass filter [5] and a 3D Integrated fan-out (InFO) rectangular inductor using thick copper vias through the InFO (TIV) [6]. A small area air-core inductor has been shown [5] compared to [1, 4, 7, 8], but the FIVR peak efficiency was relatively low due to the inductor AC losses dominated by the proximity effect and substrate coupling. A high peak power efficiency, 93%, was predicted at a high switching frequency [6], however, the achieved inductance density was still relatively small compared to other studies [1, 4, 5, 8]. By using a low-loss magnetic material and switching at high frequency, the specific inductance can be increased. IVRs with magnetic core inductors embedded in the package [9, 10], SMT [11] or on-die [12] have been demonstrated. A ferromagnetic metal alloy has been used as the core material [9]. The IVR efficiency was relatively low because of the AC losses in the magnetic material due mainly to eddy currents and magnetic hysteresis at frequencies beyond a few MHz. Another approach used senfoliage flake magnetic material (NEC/Token) for the package integrated inductors in a 3D integrated voltage regulator [10]. While the magnetic core material was easily processed using standard printed circuit board (PCB) lamination processes [10, 12], the core had high-loss density which could impact significantly the overall IVR efficiency. The peak efficiency was 91.5% at 100 MHz when converting 3.3–2.4 V [13]. However, the use of an SMT inductor reduces the design flexibility of the IVR module in terms of size reduction, short interconnect length and suppression of parasitics. Moreover, IVR module optimization can only be done on the chip side since the inductor is an off the shelf component. A fully integrated buck VR, switching at 100 MHz was implemented in 14 nm tri-gate CMOS with on-die solenoid magnetic core inductors for ultra-thin form factor applications [11]. The integration showed lower losses and higher current density than the on-die air core inductor in [2]. However, the relatively thin copper windings used resulted in a relatively high DC resistance which decreased the IVR efficiency to 84% due to the inductor DC power loss. As an alternative approach, we have shown [14, 15] the advantages of a SIP solution using embedded magnetic core

inductors in an organic package for implementing high-efficiency, buck type IVRs by optimizing both the silicon components and the magnetic core inductors in a four-phase design with 25 nH inductance per phase using solenoidal inductors with magnetic composite materials having a relative permeability μ_r from 5 to 10 at 100 MHz. This was optimized for a buck type IVR with three different voltage conversion rates: 5 V:1 V, 3 V:1 V, and 1.7 V:1 V. Based on the selected material properties, two composite materials using NiZn ferrite and carbonyl iron powder (CIP) have been fabricated. Their magnetic properties were characterized and modeled for the design of embedded magnetic core solenoid inductors for high-efficiency buck type IVRs. The rest of the paper is organized as follows. In section 2, the fabrication process of the two composite magnetic materials is described. The experimental work and the characterization results of the fabricated materials are discussed in section 3. The measured magnetic properties of the magnetic materials are modeled in section 4. Finally, section 5 evaluates the efficiency of a SIP IVR with embedded magnetic core inductors designed based on the two fabricated materials.

2. Fabrication of the composite materials

The composite magnetic materials were prepared by mixing an epoxy resin paste (binder) with magnetic powders (fillers). The epoxy paste was obtained as shown in figure 1, by dissolving the bisphenol-A-diglycidyl ether (BPADGE), Epikote resin 523, in acetone. 2 wt% fumed silica was added to the solution to improve the adhesion between the silane activated magnetic powder and the epoxy resin and to adjust the viscosity and increase the pot life of the epoxy. Brominated BPADGE (Epon resin 1134-A-80) was added as the flame retardant and styrene maleic anhydride (SMA 400, Yuang Hong Co, Ltd) as a crosslinking agent. 2-methyl imidazole (2-MIM, Sigma Aldrich) was used as a catalyst. The mixture was degassed in a vacuum chamber for 1 hr and put inside an oven for excess solvent removal and viscosity tuning.

Two magnetic powders were used: FP350 NiZn ferrite (pptechnology) and soft grade (SQ) CIP from BASF. The powders were treated with two different coupling agents to improve the dispersion and adhesion of the powder particles to the epoxy: a silicone based coupling agent, 3-aminopropyl-triethoxysilane (APES) from Sigma Aldrich, or a titanate based coupling agent, LICA 38 Titanium IV 2,2(bis(2-propenolatomethyl)butanolato, tris(dioctyl)pyrophosphato-O, from Kenrich Petrochemicals) [16]. The APES sensitization process is shown in figure 2(a). First, 4 ml of APES was added to 100 ml ethanol containing 50 g of magnetic powder. The mixture was heated to 75 °C and stirred for 2 h. The powder was washed three times with ethanol and dried for 90 min at 75 °C.

For the LICA 38 sensitization (figure 2(b)), 50 g magnetic powder was added to 100 ml acetone and 4 wt% LICA 38 (0.02 g). The mixture was jar-rolled for 24 h. Finally, the surface modified powder was washed three times with acetone and dried for 90 min at 75 °C. The magnetic composites were fabricated by adding the surface modified powder to the

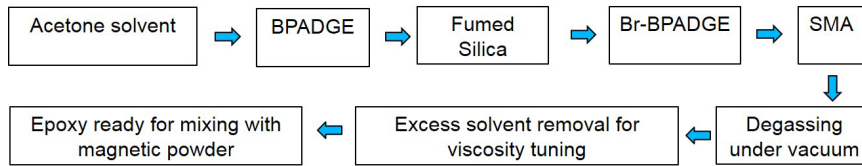


Figure 1. Fabrication steps of the epoxy paste.

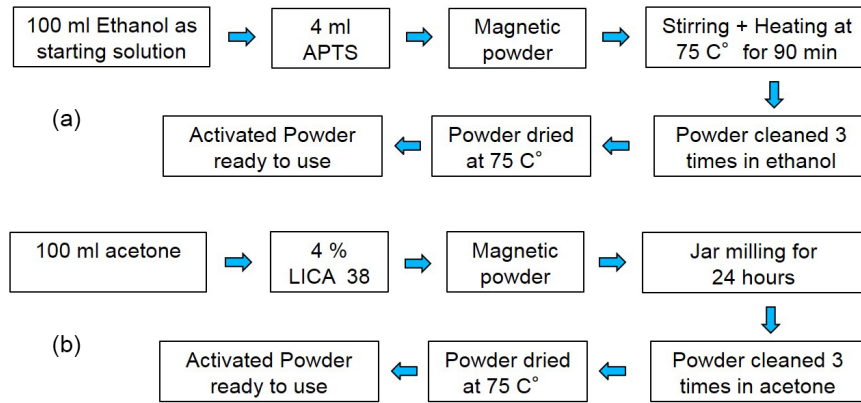


Figure 2. Sensitization of the magnetic powders using (a) APES (b) LICA 38.

epoxy material and jar-rolling for 24 h. The magnetic powder to magnetic composite volume ratio, identified by the variable ' p ' in this paper, is based on the powder, epoxy paste and composite densities. Both the silane and titanates activated powder showed very good dispersion and adhesion to the epoxy material. The dispersion/adhesion of the Lica 38 activated powder in the epoxy matrix was more stable with time compared to the APES activated powder. This can be attributed to the stronger bridging forces between the powder and the epoxy when a titanate based coupling agent was used compared to a silane based coupling agent. The powder to magnetic composite weight and volume fractions in this work are given in table 1 for the NiZn ferrite and CIP composites. The powder-epoxy mixtures were then degassed undervacuum and cured at 180 °C for 1 h to cure the final magnetic composite materials. Figure 3 summarizes the fabrication steps of the magnetic composite materials.

3. Experimental section

The structure and the powder particle distribution within the magnetic composites were examined using a LEO 1530 SEM. The electromagnetic properties of the epoxy and composite materials were measured from 1 MHz to 400 MHz using a Keysight 4291B RF Impedance/Material Analyzer with Keysight 16453A Dielectric Material Test Fixture and Keysight 16454A Magnetic Material Test Fixture. The measurements were done up to 400 MHz to investigate the materials behavior at high frequencies, as the objective is to use them as magnetic cores in power inductors for IVRs switching at 100 MHz. Test samples of the epoxy and composite materials were fabricated using flat surface and toroid aluminum molds. The characterization setup, fabricated molds, and composite samples are shown in figure 4. The magnetization curves of

Table 1. Considered powder to magnetic composite weight and volume fractions for both NiZn ferrite and CIP composites.

Magnetic material	Weight fraction w	Volume fraction p
NiZn ferrite composite	0.5	0.4
	0.6	0.5
	0.68	0.6
	0.85	0.78
CIP composite	0.6	0.19
	0.65	0.23
	0.85	0.47

the composite materials were measured at room temperature (300 K) between -150 kOe and 150 kOe at a sweep rate of 10 Oe s^{-1} using the vibrating sample magnetometer (VSM) of the 14 T Dynacool Popular physical property measurement system (PPMS) from Quantum Design.

4. Results

4.1. SEM observation

Figure 5 shows SEM micrographs of the NiZn ferrite and the CIP composites with 85 wt% loading. The powder particles are randomly distributed in the epoxy matrix and show an irregular shape with an average particle size of $5 \mu\text{m}$ for both composites.

4.2. Electromagnetic properties of the materials

The epoxy material was found to have a permittivity of 3.34 and a loss tangent value of 0.015 at 100 MHz, as shown in figure 6. The permittivity of the composite materials increased with an increase in the magnetic powder volume fraction (figure 7). At

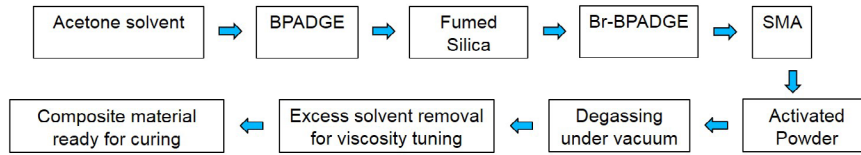


Figure 3. Fabrication steps of the magnetic composite material.

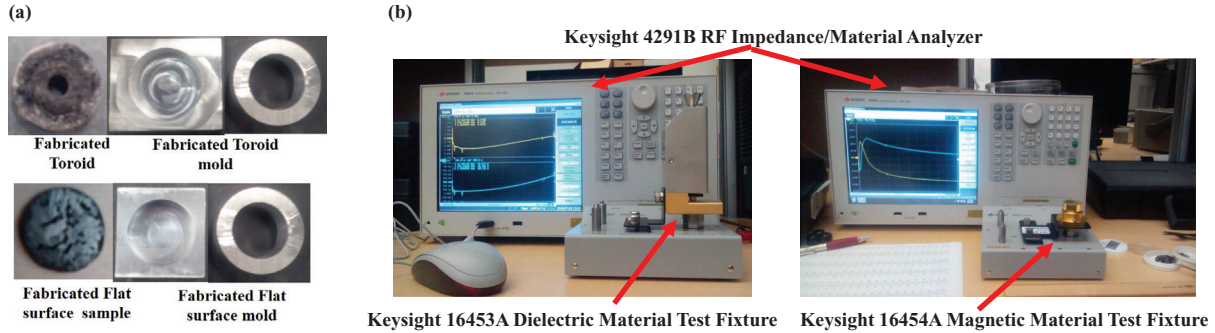


Figure 4. (a) Fabricated aluminum molds and magnetic composite samples (b) experimental setup for the electromagnetic characterization of the magnetic composite materials.

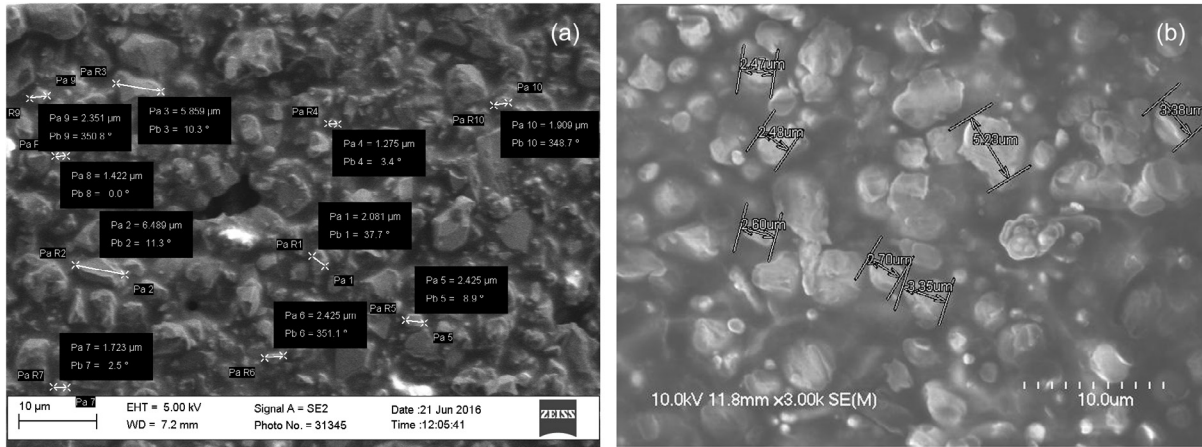


Figure 5. SEM observation of the fabricated magnetic composite materials (a) NiZn ferrite-composite ($p = 0.78$) (b) CIP-composite ($p = 0.47$).

100 MHz and 85 wt% loading, the average permittivity value was 5.2 for the NiZn ferrite composite and 13.3 for the CIP composite while the average loss tangent value was 0.009 for the NiZn ferrite composite and 0.019 for the CIP composite.

The permeability of the composite materials increased with the volume fraction of the magnetic powder for both composites, as shown in figure 8. At a volume fraction greater than $p = 0.78$ for NiZn ferrite and $p = 0.47$ for CIP, there was no significant increase in the composites permeability. Moreover, increasing the volume fraction beyond these values resulted in brittle composite samples because of the corresponding low volume fraction of the epoxy binder. At 100 MHz and 85 wt% loading, the permeability was 7.5–8.1 for the NiZn ferrite composite and 5.2–5.6 for the CIP composite while the loss tangent was 0.24–0.28 for the NiZn ferrite composite and 0.09–0.1 for the CIP composite. The NiZn ferrite composite

had an average permeability which is 70% higher than the CIP composite. However, the CIP composite had an average loss tangent value 40% lower than the NiZn ferrite composite. The dielectric loss tangent values were smaller than the magnetic loss tangent values. Hence, the losses are dominated by the magnetic losses in both composites. The measured magnetic properties of the composite materials at 100 MHz are summarized in table 2.

4.3. Magnetization behavior

The measured magnetization curves of the two magnetic materials are shown in figure 9. The saturation flux density B_{sat} was calculated from the magnetization curves and is 0.1351 T for the NiZn ferrite composite and to 0.5280 T for the CIP composite at room temperature.

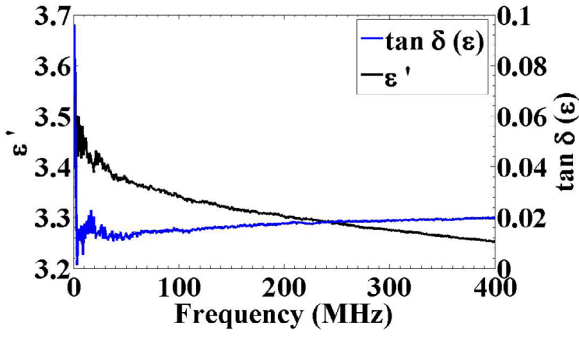


Figure 6. Room temperature permittivity and dielectric loss tangent of the epoxy material.

5. Modeling of the magnetic composite materials

The Maxwell Garnett approximation (MGA) mixing rule [17, 18], Equation (1), can be used as a starting point to estimate the effective permeability μ_e of the composite materials for a given volume fraction of the inclusions using equation (2).

$$\frac{\mu_e - 1}{1 + n_0(\mu_e - 1)} = p \frac{\mu_i - 1}{1 + n_0(\mu_i - 1)} \quad (1)$$

$$\mu_e = 1 + \frac{p}{n_0(1 - p) + 1/(\mu_i - 1)}. \quad (2)$$

In equations (1) and (2), p is the volume fraction, n_0 is the shape factor (demagnetization factor) of the inclusions and μ_i is the permeability of the inclusions. Figure 10 shows the variation in the effective permeability of the NiZn ferrite and the CIP composites as a function of the magnetic powder's volume fraction at 100 MHz where n_0 and μ_i are used as fitting parameters with the fitted values given in table 3.

The MGA model is a good prediction of μ_e at a given frequency for both composites, especially at higher loading ratios as shown in figure 10. However, the model cannot provide the full frequency dispersion spectrum $\mu_e(\omega)$ of the composites unless the frequency dispersion of μ_i is known. The composites' permeability $\mu_e(\omega)$ can be modeled by considering the superposition at resonance of the domain walls oscillation and the gyromagnetic spin rotation as described by the Lorentz and Landau–Lifshitz–Gilbert equation, equation (3).

$$\mu_e(\omega) = 1 + \chi_d + \chi_s = 1 + \frac{\omega_d^2 \chi_{d0}}{\omega_d^2 - \omega^2 + j\beta\omega} + \frac{(\omega_s + j\alpha\omega)\omega_s \chi_{s0}}{(\omega_s + j\alpha\omega)^2 - \omega^2}. \quad (3)$$

In equation (3), χ_d and χ_s are the magnetic susceptibilities, χ_{d0} and χ_{s0} are the static magnetic susceptibilities, $\omega_d = 2\pi f_d$ and $\omega_s = 2\pi f_s$ are the resonance angular frequencies for each contribution (domain walls and spin rotation respectively), α and β are the damping factors and ω is the angular frequency of the applied field. For large values of the damping factors α and β , equation (3) can be simplified to the Debye relaxation equation for both domain walls and spin rotation components [19], equation (4)

$$\mu_e(\omega) = 1 + \frac{\chi_{d0}}{1 + j\frac{\omega}{\omega_{d_r}}} + \frac{\chi_{s0}}{1 + j\frac{\omega}{\omega_{s_r}}}. \quad (4)$$

In equation (4), ω_{d_r} and ω_{s_r} are the relaxation frequencies for the domain walls and the spin rotation contributions, respectively. By fitting the measured permeability spectra of the NiZn ferrite and the CIP magnetic composite materials (figure 8) using equation (4), the permeability spectra of the NiZn ferrite and CIP magnetic composite materials can be modeled with good accuracy for different volume fractions as shown in figure 11. The fitted values of χ_{d0} , χ_{s0} , ω_{d_r} and ω_{s_r} for a given volume fraction are given in table 4.

The variation of χ_{d0} and χ_{s0} , given in table 4 with p can be fitted with good accuracy for both the NiZn ferrite and the CIP composites as shown in figure 12 using simple second order polynomial equations, equations (5) and (6).

$$\chi_{d0} = A_{d0}p^2 + B_{d0}p + C_{d0} \quad (5)$$

$$\chi_{s0} = A_{s0}p^2 + B_{s0}p + C_{s0} \quad (6)$$

In equations (5) and (6), A_{d0} , B_{d0} , C_{d0} , A_{s0} , B_{s0} , C_{s0} are fitting coefficients given in table 5.

Starting from equation (4) and combining the fitting results of tables 4 and 5, the permeability spectrum can be estimated for any volume fraction. First, the static magnetic susceptibilities χ_{d0} and χ_{s0} are computed for a given volume fraction p using equations (5) and (6). Then, the relaxation angular frequencies ω_{d_r} and ω_{s_r} , given in table 4 are used with the calculated χ_{d0} and χ_{s0} values to estimate the relative permeability of the composite material using equation (4).

6. Application to embedded power inductors

6.1. Inductor design and simulation

Magnetic core solenoidal inductors embedded in the package substrate, figure 13, were designed using the measured properties of the two magnetic materials. The designs are for output filter applications for a high-efficiency SIP based buck IVR providing 5 V:1 V, 3 V:1 V and 1.7 V:1.05 V conversions. A solenoid inductor geometry, figure 13(a), was chosen because of its advantages compared to the planar and the racetrack type structures [14].

To study the impact of the fabricated magnetic materials on the IVR efficiency, three inductors of identical size and similar inductance were designed and simulated using Ansys Electronics Desktop ver. 2015.2 [20] with three different magnetic core materials: NiZn ferrite composite, CIP composite and dielectric only (i.e. epoxy). Full-wave simulations account for the complex electromagnetic behavior of the inductors in terms of magnetic field distribution, demagnetizing effects, and skin/proximity effects in the windings. To accurately represent the fabricated materials, their measured frequency-dependent, complex permeability, and complex permittivity were used into the solver. The inductor's simulation results were frequency dependent, two-port network parameters (S -, Y -, or Z -parameters), from which a simple pi-equivalent circuit representation of the inductor was extracted, as shown in figure 13(b), which provided an intuitive representation of the designed inductors in terms of

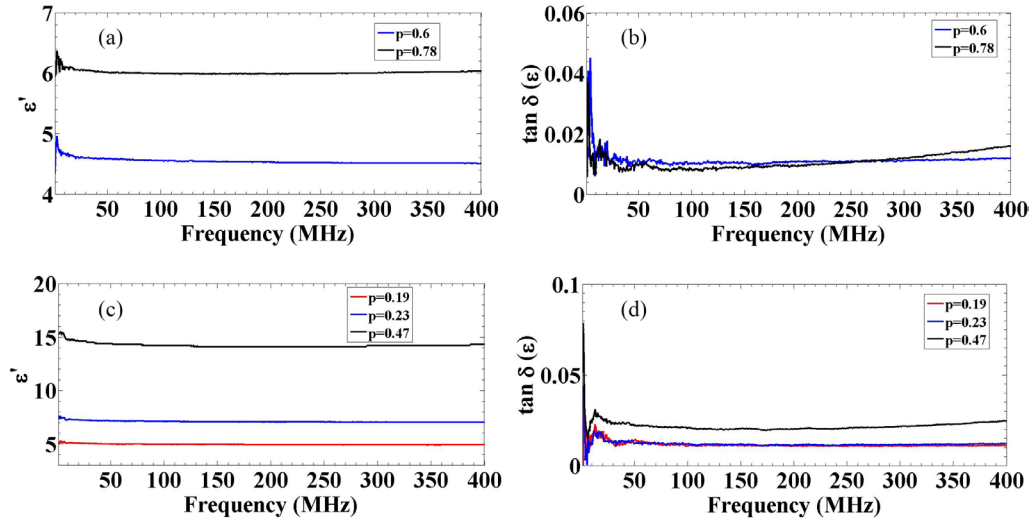


Figure 7. Room temperature permittivity and dielectric loss tangent measurements for different volume fractions of (a) and (b) NiZn ferrite composite (c) and (d) CIP composite.

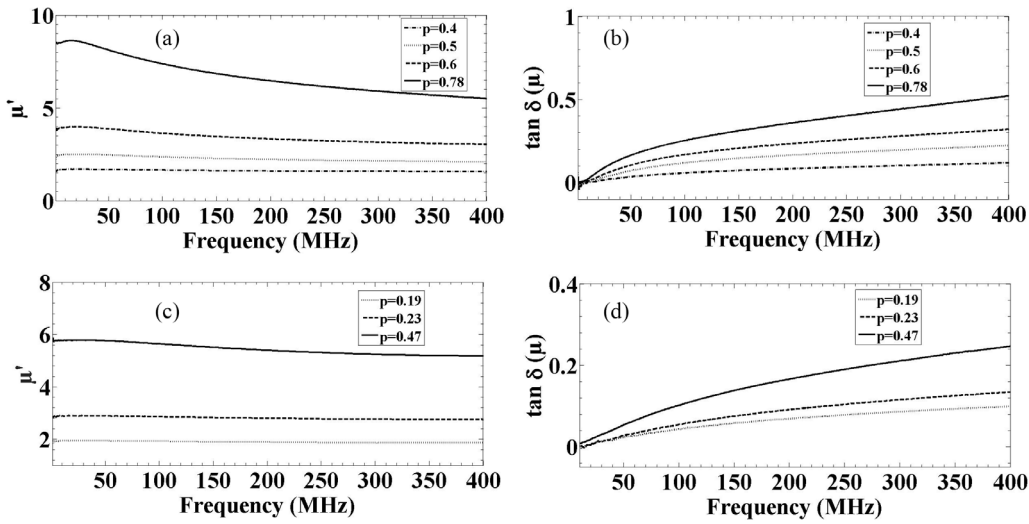


Figure 8. Room temperature permeability measurement for different volume fractions for (a) and (b) NiZn ferrite composite (c) and (d) CIP composite.

Table 2. Measured electromagnetic properties of the magnetic composite materials at 100 MHz.

Magnetic material	μ'	μ''	$ \mu $	$\tan \delta(\mu)$	ϵ'	ϵ''	$ \epsilon $	$\tan \delta(\epsilon)$
NiZn ferrite composite	7.5–8.1	1.86–2.27	7.33–8.42	0.24–0.28	5.9–6.5	0.05–0.06	6.09–6.53	0.0087–0.0094
CIP composite	5.2–5.6	0.4–0.5	5.24–5.67	0.094–0.102	12.6–14.1	0.2–0.4	9.61–19.64	0.016–0.023

inductance, resistance, and capacitance to evaluate the impact of the inductors on the overall buck converter efficiency. A pi topology is acceptable as the frequency range of interest (100 MHz) is below the first resonant frequency of the inductor (>1 GHz) and the impedance is mainly inductive. It provides uniquely defined frequency dependent electrical parameters, without requiring any fitting or optimization procedure. The equivalent circuit parameters for the designed inductors at 100 MHz are listed in table 6.

The magnetic materials and the designs provide a trade-off between the equivalent AC resistance and the DC resistance of

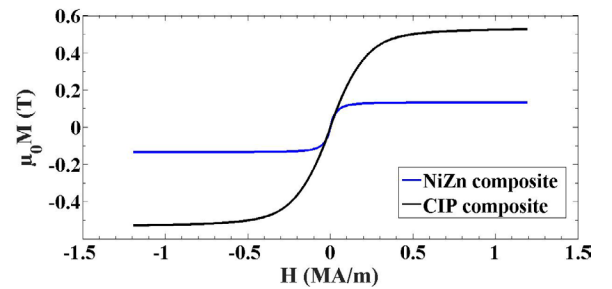


Figure 9. Magnetization curves measurement for the NiZn ferrite and the CIP composites at room temperature.

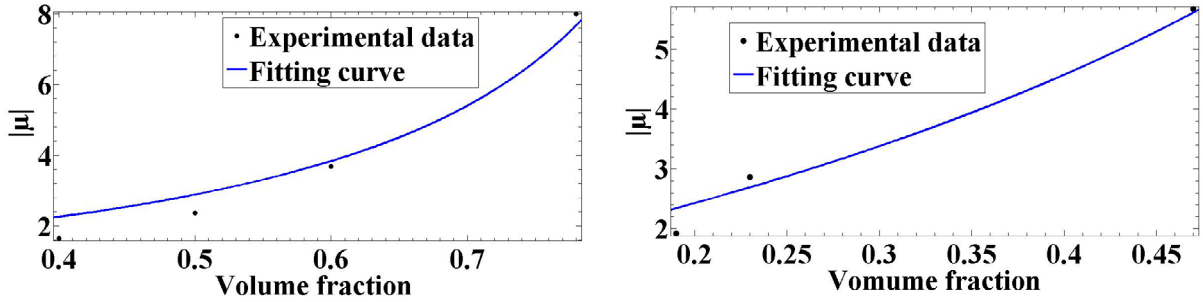


Figure 10. Variation of the absolute value of the effective permeability as a function of the inclusions' volume fraction at 100 MHz for (a) NiZn ferrite composite (b) CIP composite.

Table 3. Fitting parameters of the MGT model for both NiZn ferrite and CIP composite materials.

Magnetic Material	Shape factor n_0	Permeability of inclusions $\mu_i = \mu_{i_r} - j\mu_{i_i}$	
		μ_{i_r} (real part)	μ_{i_i} (imaginary part)
NiZn ferrite composite	0.528	1241	0.001172
CIP composite	0.1431	39.17	0.0006141

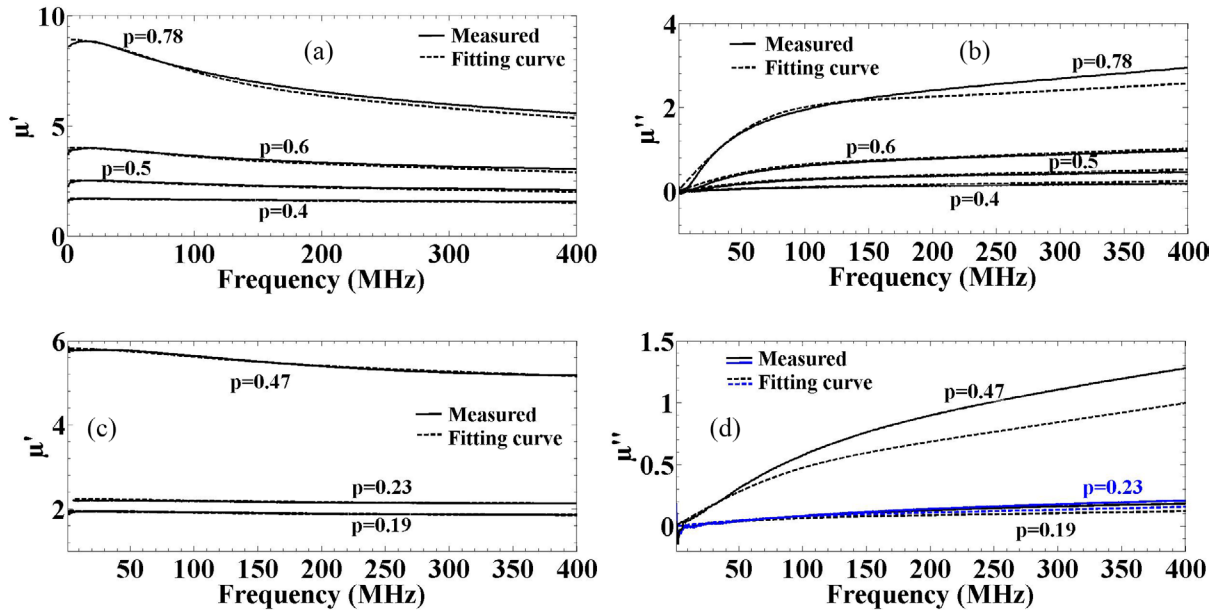


Figure 11. Debye type relaxation spectrum of the relative permeability based on the simplified Lorentz and the Landau–Lifshitz–Gilbert equation for (a) and (b) NiZn ferrite composite (c) and (d) CIP composite.

Table 4. Fitting parameters of the Debye type relaxation spectrum model for both NiZn ferrite and CIP composite materials.

Magnetic material	p (%)	χ_{d0}	χ_{s0}	ω_{d_r} (rad s^{-1})	ω_{s_r} (rad s^{-1})
NiZn ferrite composite	0.78	2.918	4.993	6.51×10^8	7.615×10^9
	0.6	0.8044	2.207		
	0.5	0.3349	1.181		
	0.4	0.07742	0.6081		
CIP composite	0.47	0.5683	3.821	9.04×10^8	2.25×10^{10}
	0.23	0.10437	1.131		
	0.19	0.08708	0.857		

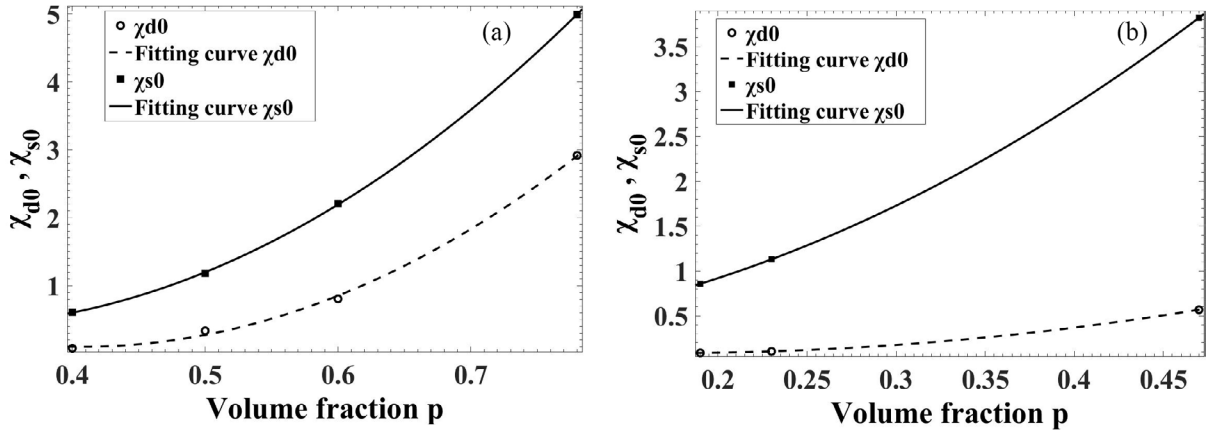


Figure 12. Variation of the static magnetic susceptibilities χ_{d0} and χ_{s0} as a function of the inclusions volume fraction for (a) NiZn ferrite composite (b) CIP composite.

Table 5. Fitting coefficients of the static magnetic susceptibilities variation model for both NiZn ferrite and CIP composite materials.

Magnetic material	$\chi_{d0} = A_{d0} \cdot p^2 + B_{d0} \cdot p + C_{d0}$			$\chi_{s0} = A_{s0} \cdot p^2 + B_{s0} \cdot p + C_{s0}$		
	A_{d0}	B_{d0}	C_{d0}	A_{s0}	B_{s0}	C_{s0}
NiZn ferrite composite	20.18	-16.42	3.44	20.01	-12.05	2.22
CIP composite	5.36	-1.819	0.2392	15.67	0.2438	0.245

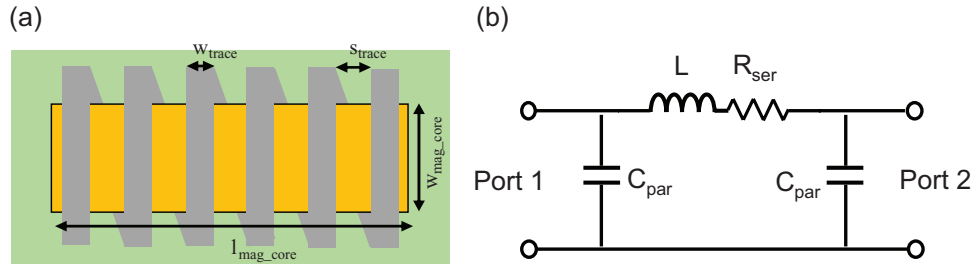


Figure 13. Package-embedded magnetic core inductor (a) considered solenoidal topology [6] (b) simple pi equivalent circuit representation of the inductor as suggested in [6].

Table 6. Equivalent circuit parameters of the designed inductors for a frequency of 100 MHz.

	NiZn ferrite composite	CIP composite	Dielectric (epoxy) core
L (nH)	22.8	24.8	24.0
RAC (mΩ)	2.362	1.112	0.452
C (pF)	1.765	1.676	1.475
RDC (Ω)	14.7	22.4	67.2

the inductor. The NiZn ferrite composite, which has the higher permeability of the two magnetic materials, also has the highest magnetic loss tangent, which is reflected in the high AC resistance of the NiZn ferrite based inductor. It should be noted that this is true at 100 MHz and also at lower frequencies. At the same time, the NiZn ferrite inductor has the lowest DC resistance, because it required the smallest number of windings to reach the targeted inductance. Based on the extracted equivalent circuit parameters, the inductor design (figure 13(a)) was modified and re-simulated to obtain an inductance close to the targeted value of 25 nH. It should be noted that the DC resistances of the inductors were obtained from separate

Table 7. Geometrical properties of the designed inductors.

	NiZn ferrite composite	CIP composite	Epoxy (dielectric) core
$L \times W = \text{Area}$ (mm ²)	11.56	11.56	11.56
Volume (mm ³)	7.64	7.64	7.64
Number of windings	6	7	10
Trace length W (μm)	3097	3097	3097
Trace width W_{trace} (μm)	508	388	190
Trace thickness (μm)	70	70	70
Separation width strace (μm)	203.2	203.2	203.2

simulations in Ansys Maxwell ver.2015.2 [21]. This was done because an accurate value for the DC resistance is critical to the overall IVR efficiency. The key geometrical properties of the inductors are listed in table 7. As previously stated, all the inductors have the same size, with an area of 11.56 mm² and

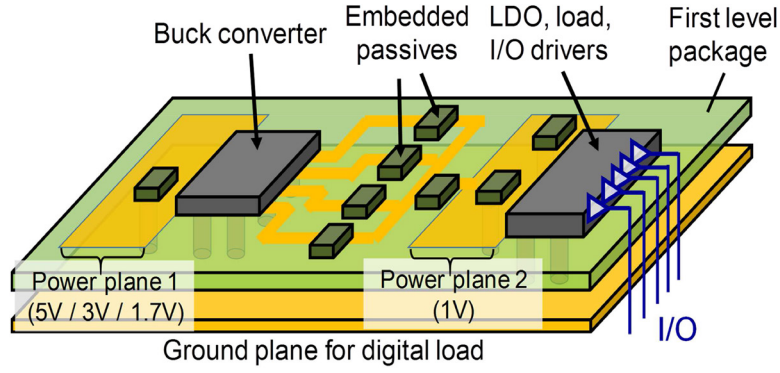


Figure 14. Proposed architecture for the SIP based IVR.

Table 8. Saturation current estimation of the solenoid inductors with NiZn Ferrite and CIP composite magnetic cores.

Magnetic material	N	μ_r	MPL (mm)	$B_{sat_300\text{ K}} (T)$	$I_{sat_300\text{ K}} (A)$
NiZn ferrite composite	6	8.1	4.064	0.1351	9
CIP composite	6	5.64	4.064	0.528	50.46

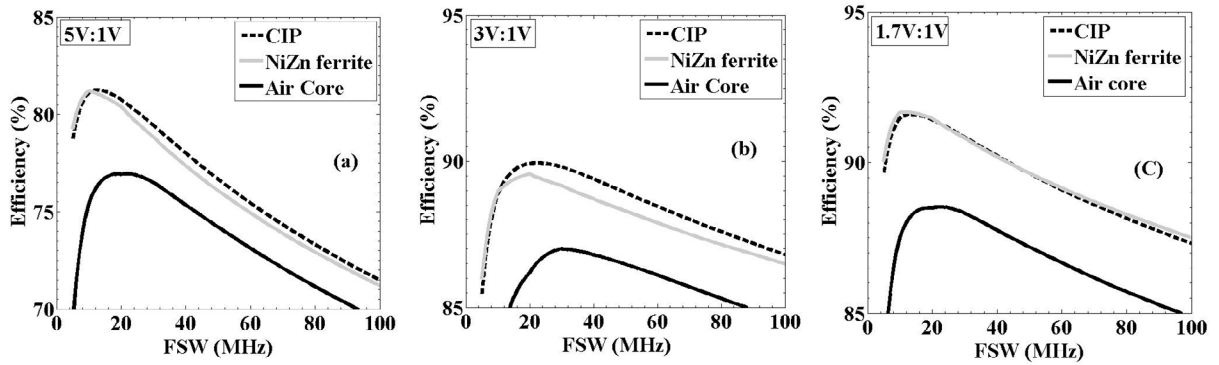


Figure 15. Overall buck converter efficiencies for the three designed inductors (a) 5 V:1 V (b) 3 V:1 V (c) 1.7 V:1 V.

a total volume of 7.64 mm^3 . Furthermore, the two magnetic core inductors use the same core size. Consequently, the different permeabilities of the core materials are compensated for by changing the width and the number of windings while the windings' length is kept identical for the three designs as shown in table 7.

6.2. IVR architecture

The SIP designed IVR architecture is shown in figure 14 and uses a buck converter, embedded inductors, an output capacitor, and a multi-domain LDO regulator with embedded I/O line drivers and logic circuits. The optimum number of phases for the IVR for the three voltage conversion ratios was determined to be a 4-phase design with a master phase and three slave phases [14]. The buck converter operates in load-dependent pulse width modulation (PWM) mode with a 100 nF output capacitor, overall inductance of 100 nH (25 nH per phase) and 100 MHz switching frequency. These conditions lead to a small ripple current. The buck converter generates 1 V from three different input voltages (voltage conversion ratios of 5:1, 3:1 and 1.7:1). Also, the total load current is 10 A (2.5 A/phase) and 10 W load power. The LDO provides

power management through DVFS and power supply rejection (PSR) for the I/O drivers [14].

6.3. Saturation current

The saturation currents of the solenoid inductors using the NiZn Ferrite and the CIP composite materials were estimated using the measured saturation flux densities of each material and equation (7) [22].

$$I_{sat} = \frac{B_{sat} \cdot MPL}{\mu_0 \cdot \mu_r \cdot N}. \quad (7)$$

In equation (7), B_{sat} is the saturation flux density, MPL is the magnetic path length, μ_0 is the vacuum permeability, μ_r is the relative permeability and N is number of turns. The parameters for the saturation current estimation are given in table 8. At room temperature, the computed saturation currents were found to be about 9 A and 50.46 A for the NiZn ferrite and the CIP composites, respectively. These values are higher than the targeted maximum load current for the IVR (2.5 A/phase) which ensures that both the NiZn ferrite and the CIP core inductors can be operated far from their saturation values.

6.4. IVR efficiency

To study the impact of the inductor designs on the overall IVR efficiency, an analytical evaluation approach was used as described [14] which takes into account all major loss components. Conduction and switching losses from the buck switches were estimated based on the transistor DC resistance and Miller capacitance. The CMOS on-resistance and capacitance values were simulated using the 130 nm CMOS process from Global Foundries. Power losses in the passives (inductor and output capacitor) and PDN losses were computed using their equivalent series resistances [14]. Figure 15 shows the peak efficiencies (at optimum load) obtained for the three inductor designs as a function of the switching frequency of the buck converter.

The NiZn ferrite and CIP inductors lead to very similar overall IVR efficiency for a given conversion ratio even though they have different electrical characteristics. This shows that the differences between the two magnetic core materials (i.e. decrease in the inductor AC loss, the increase in the inductor DC loss, and the small increase in the inductance) compensate for each other in the end. Both magnetic core inductors led to a considerably higher overall efficiency compared to the dielectric core inductor with an identical size at all conversion ratios. The efficiency was 91.7% (peak at 11 MHz for NiZn ferrite-composite), 91.6% (peak at 14 MHz for CIP-composite), 88.5% (peak at 22 MHz for the dielectric core) and 87.5% (NiZn ferrite-composite), 87.3% (CIP-composite), 84.2% (dielectric) at 100 MHz for 1.7 V:1 V conversion. For a 3 V:1 V conversion, the buck converter efficiency was 89.5% at 20 MHz (peak), 86.5% at 100 MHz for NiZn ferrite-composite and 90% at 22 MHz (peak), and 86.8% at 100 MHz for CIP-composite. For a 5 V:1 V conversion, the peak efficiency was 82% at 10 MHz and 72% efficiency at 100 MHz for both materials because of the stacked topology used for the buck power stage [14]. The results show that the high DC loss of the dielectric core inductor outweighs the additional AC loss in the magnetic materials up to switching frequencies of at least 100 MHz. A substantial improvement in the buck converter efficiency for all three-conversion ratios was observed when a magnetic core inductor was used instead of a dielectric core inductor.

7. Conclusion

The use of a SIP solution for IVRs is shown to be a good approach to achieving high integration density and efficiency for point-of-load voltage regulation in different electronic architectures. In this work, two FR4 compatible magnetic composite materials based on NiZn ferrite and CIP materials were fabricated. The magnetic properties were measured and compared at room temperature. The measured magnetic properties of the composite materials were accurately modeled using the MGA mixing rule and a Debye-type relaxation equation based on the Lorentz and Landau–Lifshitz–Gilbert equation. Two embedded magnetic materials were used in the design of a high-efficiency SIP based buck type IVR at three voltage conversion ratios (5:1, 3:1 and 1.7:1). Despite the differences between the two magnetic materials, both magnetic core inductors led to high overall

efficiency which was higher than a dielectric core inductor of the same size. The efficiencies were 82% to 91.7% (peak) and 72% to 87.5% (at 100 MHz) for down conversion ratios of 5 V:1 V to 1.7 V:1 V, respectively.

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