Fabrication of High Current and Low Profile Micromachined Inductor With Laminated Ni/Fe Core

Jin-Woo Park, Jae Yeong Park, *Member, IEEE*, Yeun-Ho Joung, and Mark G. Allen, *Member, IEEE*

***Abstract*—A new process for the fabrication of high current and very low profile micromachined inductors has been developed. This process involves the combination of mechanical lamination and electrodeposition of copper windings by means of LIGA-like lithography through thick epoxy photoresists. The dimension of the fabricated inductor is 16 mm × 19 mm × 1 mm. The fabricated inductor has an inductance value of 1.2 μH with dc saturation current of 3 A and an electrical resistance of less than 30 mΩ at 10 kHz.**

***Index Terms*—Eddy current, inductance, lamination, microinductor, micromachining, saturation current.**

I. Introduction

As the complexity of many electronic systems such as microprocessors increases, higher and higher power consumption levels along with a drop in driving voltage in an effort to control the consumed power are becoming evident. Therefore, the current that must be delivered to these systems is steadily increasing. Traditional methods that use printed wiring board traces to conduct currents are becoming inadequate. An alternate approach is to use a dc/dc converters integrated with the electronic package. Such an approach requires a device that can convert a power with relatively high voltage and low current into a power with low voltage and high current, as required by the system. This conversion takes place as physically close as possible to the electronic system so that ohmic losses associated with the transmission of high currents are greatly reduced.

Such dc/dc converters are usually assembled from discrete components. One of the major difficulties in implementing the integration of theses devices arises from the general geometry of the magnetic component: surface-mount magnetic components often have an unacceptably high profile, especially when compared to the rest of the converter module. In order to address this problem, various fabrication approaches of low-profile micromachined inductors have been reported [1]–[4]. However, due to the fabrication approach that often introduces limitations in terms of achievable dimensions, many of these devices did not have sufficiently high saturation currents for high power energy conversion. The goal of this work is to present a new fabrication technology that allows the realization of very low profile and yet very high current ($>$3 A) carrying inductors. These inductors should have high saturation currents and specific inductance, while maintaining low coil resistance.

Nonconducting ferromagnetic materials such as Ferrite cores are often used in the fabrication of such inductors in order to minimize eddy current losses. However, metallic alloys such as Ni/Fe show higher magnetic permeability and saturation flux density than many ferrites, allowing for the storage of larger amounts of magnetic energy per unit volume. This feature is attractive when attempting to minimize the volume of the inductive component in dc/dc converter applications. Yet, the typical disadvantage of these metallic alloys is linked to their low electrical resistance, which can cause substantial eddy current loss at high frequency.

Reduction of eddy current loss is usually achieved through appropriate lamination of the magnetic core. Micromachined magnetic components with electroplated [1]–[4] or sputtered [5], [6] laminated magnetic cores have already been reported. However, the reported fabrication approaches show limitations when the application requires a relatively large core cross-sectional area to achieve high saturation currents. This is especially true when the application calls for cores as thick as 500 μm.

To realize a core with such a thickness, a mechanical lamination technique using a hot press is introduced. In this approach, multiple magnetic and insulating layers are stacked together and mechanically laminated using a hot press. This fabrication approach is far more time efficient when compared to previously reported techniques when building very thick cores. Also, eddy current losses can be reduced by controlling the thickness and number of films laminated, without significantly increasing fabrication cost. This core approach was combined with micromachined coil-winding technology to produce the inductors.

II. Design and Modeling

As mentioned above, Ni/Fe alloy was chosen as a magnetic core material, since it has high saturation flux density and high permeability compared with ferrite materials. One problem with these materials is that as the operating frequency of the inductor increases, the eddy current loss in the magnetic core becomes significant, and the device efficiency falls rapidly. Since the currents in these inductors are large, the total cross-sectional areas of the magnetic core must be large to avoid saturation. In this work, mechanical lamination of thinner films, instead of bulk Ni/Fe, was introduced to obtain a thick magnetic core while reducing eddy current losses at the operation frequencies of in-

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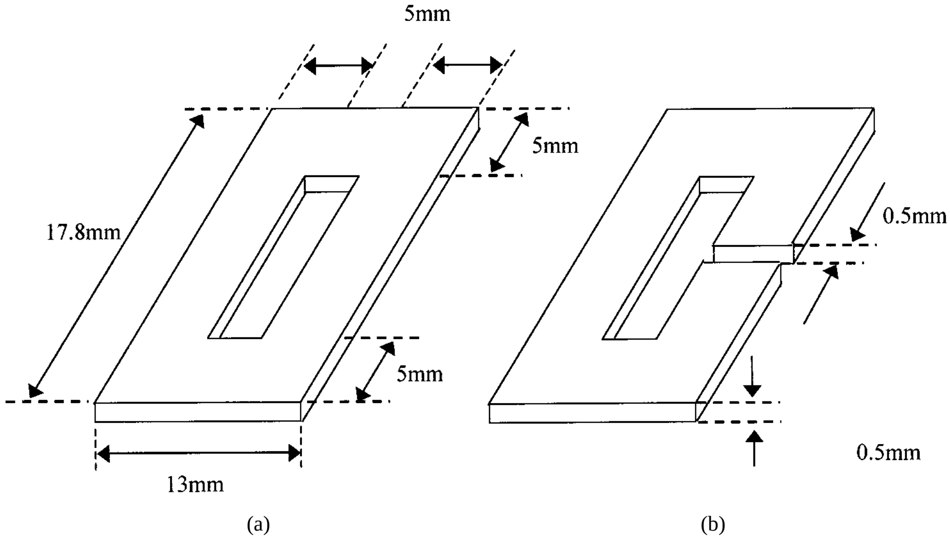

Fig. 1. Schematic diagram of the fabricated test cores (the two cores have the same dimension except for the air gap): (a) the laminated core without air gap and (b) the laminated core with air gap.

terest (up to about 100–200 kHz). Thin polyimide coatings were used to insulate the magnetic laminations from each other.

As an example of the application of this technology, consider a low profile micromachined inductor with inductance of 1 μH and current-carrying capability of 3 A, operating at a frequency of 100 kHz. Since the currents will be relatively large, it is desirable to consider the inclusion of an air gap in the magnetic path [2]. This inductor will have the following design parameters: core thickness, lamination thickness, air gap length, and the number of and geometry of the copper windings.

In order to design appropriate laminations, the effects of eddy current losses on the performance of the device have been modeled. To minimize eddy current losses, the lamination thickness can be chosen to be on the order of or less than the skin depth [7]. For a given magnetic material assuming the device is an ideal toroid inductor, the core permeability (μ_c) and the skin depth (δ_c) of the core can be calculated as [8], [9]

$$\mu_c = \frac{L_o l_c}{N^2 A_c} \tag{1}$$

$$\delta_c = \sqrt{\frac{\rho_c}{\pi f \mu_c}} \tag{2}$$

where L_o is the low frequency static inductance, l_c is the magnetic path length, N is the number of turns, A_c is the effective cross sectional area of the core, ρ_c is the resistivity of the core material, and f is the frequency of the alternating magnetic flux.

Although it would be possible to use supplied data from lamination manufacturers in (1) and (2) to determine the skin depth, since the material may experience degradation of magnetic properties, e.g., due to the lamination process and/or geometric demagnetization, it was decided to fabricate and measure some sample structures to provide empirical magnetic data for subsequent magnetic modeling. A NiFe alloy foil from Magnetic Shield Corporation (Co-Netic AA, 50 μm in thickness) was chosen as the basis material for the test inductors. This material has an electrical resistivity of 55×10^{-6} Ω-cm.

A test inductor, consisting of a core fabricated as described in Section III, combined with standard hand-wound coils, was assembled in order to assess the properties of the magnetic material after fabrication. The core consisted of eight laminated foil sheets and had dimensions as shown in Fig. 1(a). For this test, five turns of insulated copper wire were used as the excitation coil. The inductance was measured at a frequency sufficiently low (120 Hz) that skin depth effects should be negligible in these thin (50 μm) foils. From the inductor geometry and the measured low frequency inductance, the permeability of the core was calculated from (1) and the skin depth from (2). The calculated relative permeability of the core is about 8000. The calculated skin depths at 100 kHz are 13 μm. Lamination can reduce the eddy current losses effectively when the thickness of the film is on the order of or less than the skin depth. Since the thinnest easily obtainable shielding material for lamination in the fabrication process described below was 50 μm in thickness, it was decided to continue to use 50 μm thick films as a magnetic material in the fully integrated device.

To further increase the saturation current of the inductors, an air gap was introduced in the magnetic core [Fig. 1(b)]. Assuming negligible fringing in the air gap, the equivalent permeability (μ_e) of the core with an air gap can be calculated as [9]

$$\mu_e = \mu_c \frac{l_c}{l_c + \mu_{rc} l_a} \tag{3}$$

where μ_c is the permeability of the core, l_c is the magnetic path length of the core, μ_{rc} is the relative permeability of the core, and l_a is the length of the air gap. The equivalent relative permeability of the test core calculated from (3) for the core geometry of Fig. 1(b) is approximately 80. To verify this result, a second test inductor was fabricated with the core geometry shown in Fig. 1(b), and same number of turns as the previous (no-air-gap) test inductor, and the equivalent permeability calculated using measured results at low frequency (120 Hz) and application of (1). The equivalent relative permeability calculated from (1) using this method is approximately 800. One explanation for this discrepancy is that (3) assumes that there is no fringing magnetic flux in the air gap. This is a good assumption in many conventional magnetic core geometries, which pos-

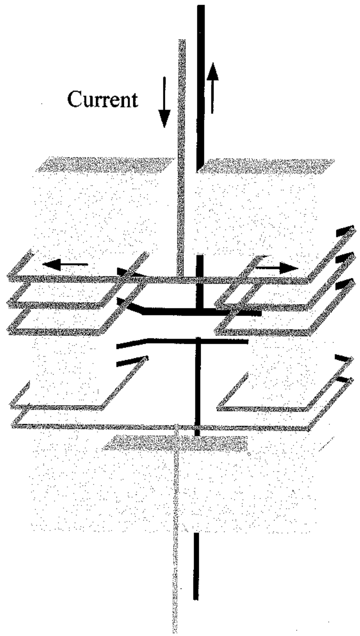

Fig. 2. Schematic diagram of the high current inductor with the auxiliary control winding.

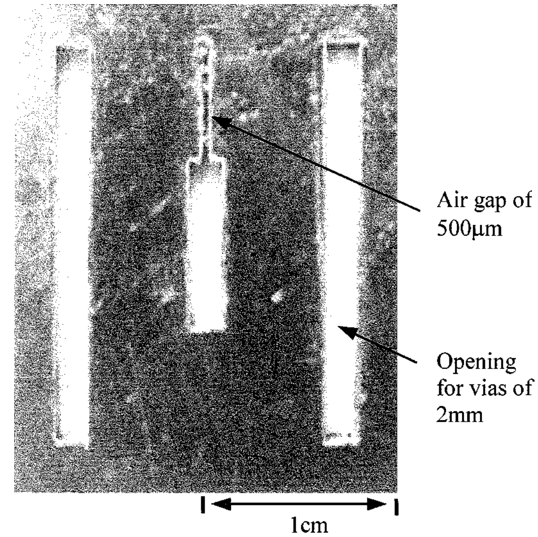

Fig. 3. Photograph of the prepared magnetic plate for fabrication of the high current inductor.

sess small air gaps and large air-gap cross-sectional areas (i.e., high-aspect-ratio). In the cores fabricated using the micromachining techniques described in this paper, geometrical constraints result in a low-aspect-ratio air gap, and the assumption behind (3) is not applicable. The fringing flux of the low aspect ratio air gap decreases the magnetic reluctance of the air gap resulting in a reduced effective length of the air gap. In our test core, an effective air gap length of 46 μm satisfies both (1) and (3) (equivalent permeability of 800). This effective air gap length is smaller by factor of 10 than the geometrical length of 500 μm.

Based on the above analysis and preliminary data, the inductor with integrated windings can be designed. The schematic diagram of the laminated high current inductor is shown in Fig. 2. To reduce the dc resistance of the winding, a parallel connection of coils was chosen. The main thick winding for high load current has a parallel connection of two 5-turn coils. The cross-sectional area of each turn is 350 μm $\times$ 170 μm. In some inductors, an auxiliary thin winding, having a parallel connection of two 18-turn coils, was added for inductor control current. The cross-sectional area of each turn is 120 μm $\times$ 170 μm.

III. Fabrication

The power inductor was fabricated using three major techniques: lamination of thin magnetic films, LIGA-like lithography of thick SU-8 photoresist, and electrodeposition of copper. First, eight Ni/Fe alloy sheets (Co-Netic AA) coated with polyimide on one side were stacked. They were laminated using a hot press with an epoxy powder interlayer adhesive. The thickness of each sheet is 50 μm and total after-lamination thickness of the Ni/Fe core is 500 μm, yielding an average lamination insulation thickness of 12.5 μm. Rectangular openings were formed through the magnetic plate using a milling machine. These openings will contain the via connections between the upper conductors and the lower conductors. An additional opening that defines the air gap of about 500 μm in the core was formed. A Kapton film of 50 μm was then laminated on the bottom side of the plate. This isolates the lower conductor from the magnetic core. The Kapton film was then cut with openings corresponding to the openings in the core. A photograph of the fabricated magnetic core is shown in Fig. 3.

Subsequent fabrication steps were performed on the magnetic core to add the coil windings as summarized in Fig. 4. A copper foil of 12.5 μm thickness (to be used as a seed layer) was laminated on the Kapton film side of the plate. The bottom side of the copper foil was coated and hard-cured with a polyimide as a protection from any chemicals during the following process steps. Next, thick photosensitive epoxy SU-8 was applied on the laminated Ni/Fe plate to form the electroplating molds for the vias. Due to the excellent planarizing properties of the SU-8, the openings in the Ni/Fe plate are filled during this step. After a long soft bake of 8 h at 95 °C, the epoxy was UV-exposed through the via pattern mask. This was followed by a post exposure bake of 30 min at 95 °C. The epoxy was finally developed in propylene glycol methyl ether acetate (PGMEA). The thickness of the fabricated via mold was approximately 600 μm.

The vias were then filled with electroplated copper, using the laminated copper foil as a seed layer. A current density of 50 mA/cm^2 was used for electroplating. A photograph of the electroplated vias surrounded by the SU-8 epoxy mold is shown in Fig. 5. After via formation, a seed layer (Ti/Cu/Ti) was deposited by sputtering. It was patterned using conventional photolithography and wet-etching. SU-8 was spun on the patterned seed layer. UV photolithography was performed to form the electroplating mold of 170 μm for upper conductors. The mold was then filled with electroplated copper using a current density of 50 mA/cm^2. The fabricated vias were used to supply electroplating current to the patterned seed layer for conductors. Note that the patterning of the seed layer eliminates the need for removal of the second SU-8 plating mold, and that

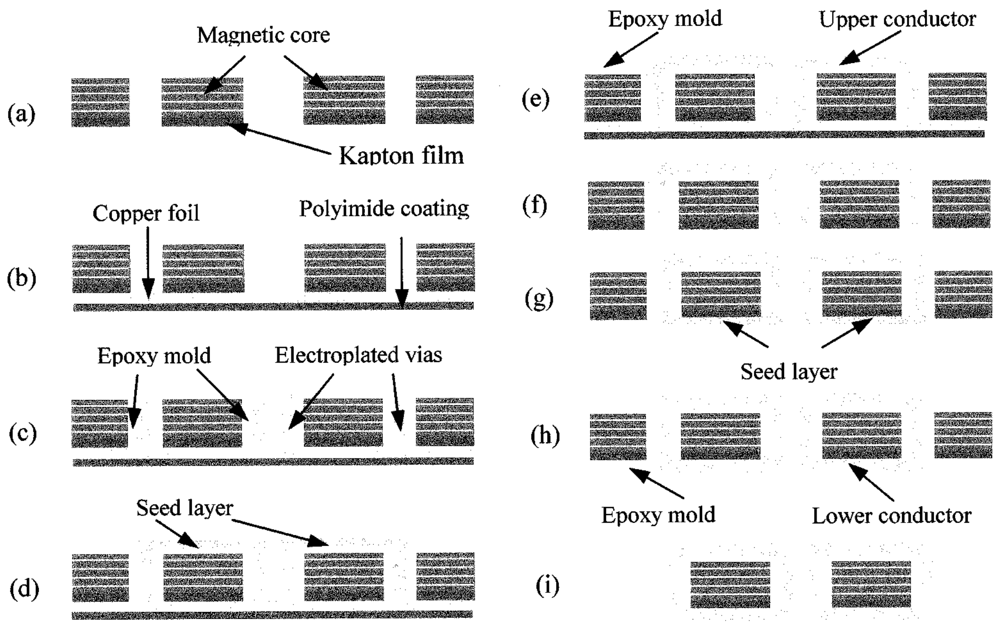

Fig. 4. Fabrication sequence of laminated high current micromachined inductors: (a) prepared Ni/Fe alloy plate, (b) lamination of copper foil and coating of polyimide, (c) formation of SU-8 molds and electroplating of via conductors, (d) deposition and patterning of seed layer for upper conductors, (e) formation of SU-8 molds and electroplating of upper conductors, (f) removal of the bottom copper foil, (g) deposition and patterning of seed layer for lower conductors, (h) formation of SU-8 molds and electroplating of lower conductors, and (i) dicing a device from the plate.

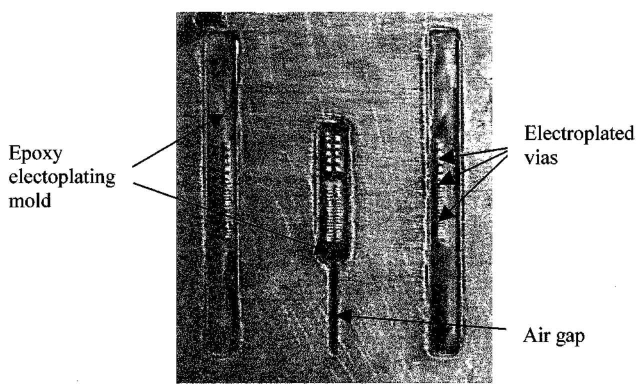

Fig. 5. Photograph of electroplated vias surrounded by the SU-8 epoxy mold.

the thin copper conductor is safely supported in the epoxy mold in the final device. Next, the lower conductors were formed. The copper foil used as a seed layer for the vias was removed. A seed layer (Ti/Cu/Ti) was deposited and patterned, and SU-8 was spun on it. UV photolithography and electroplating of copper were then performed to form the lower conductors. Finally, the inactive boundaries of the device were cut away and the device was coated with parylene for insulation. Fig. 6 shows the photograph of a fabricated high current and low profile inductor with the laminated core. The size of this device is 16 mm $\times$ 19 mm $\times$ 1 mm.

IV. Experimental Results and Discussions

The fabricated high current inductor without the auxiliary thin winding was characterized using a Wayne-Kerr 3245 precision inductance analyzer. The effective value of the AC drive signal was 50 mA. The achieved inductance and resistance of the thick winding is shown in Figs. 7 and 8.

The data show a falloff in inductance and an increase in resistance with increasing frequency. To interpret these results, recall that the inductance $L(f)$ of an inductor with a laminated core can be expressed as [8], [9]

$$L(f) = L_o \frac{1}{\frac{d}{\delta(f)}} \times \frac{\sinh \frac{d}{\delta(f)} + \sin \frac{d}{\delta(f)}}{\cosh \frac{d}{\delta(f)} + \cos \frac{d}{\delta(f)}} \quad (4)$$

and the component of the series resistance $R_e(f)$ representing the eddy current loss as

$$R_e(f) = 2\pi f L_o \frac{1}{\frac{d}{\delta(f)}} \times \frac{\sinh \frac{d}{\delta(f)} - \sin \frac{d}{\delta(f)}}{\cosh \frac{d}{\delta(f)} + \cos \frac{d}{\delta(f)}} \quad (5)$$

where L_o is a low frequency static inductance, d is the thickness of the magnetic film, f is the frequency of the magnetic flux, and $\delta(f)$ is the skin depth for the magnetic core at that frequency. Equations (4) and (5) assume that the length of the magnetic lamination stack is much larger than either of its cross-sectional dimensions; and that the cross-sectional thickness is much small compared to the cross-sectional width. Under these assumptions, edge effects of the film can be neglected.

Equations (4) and (5) are derived for magnetic cores with no air gap [8]. It is shown in [9] that (4) and (5) can be applied to the case of nonsaturated magnetic cores with air gaps if $\delta(f)$ is replaced by $\sqrt{\rho_c/\pi f \mu_e}$. Here, ρ_c is the resistivity of the core material, f is the frequency of the alternating magnetic flux, and μ_e is the equivalent permeability of the core with an air gap.

The measured and calculated [from (4)] inductances are shown in Fig. 7. As the frequency increases, the overall inductance values decrease due to the skin effect of magnetic flux in the laminated magnetic core. Observing (4), it can be seen that a small value of d will result in large inductance at the given frequency indicating small eddy currents generated

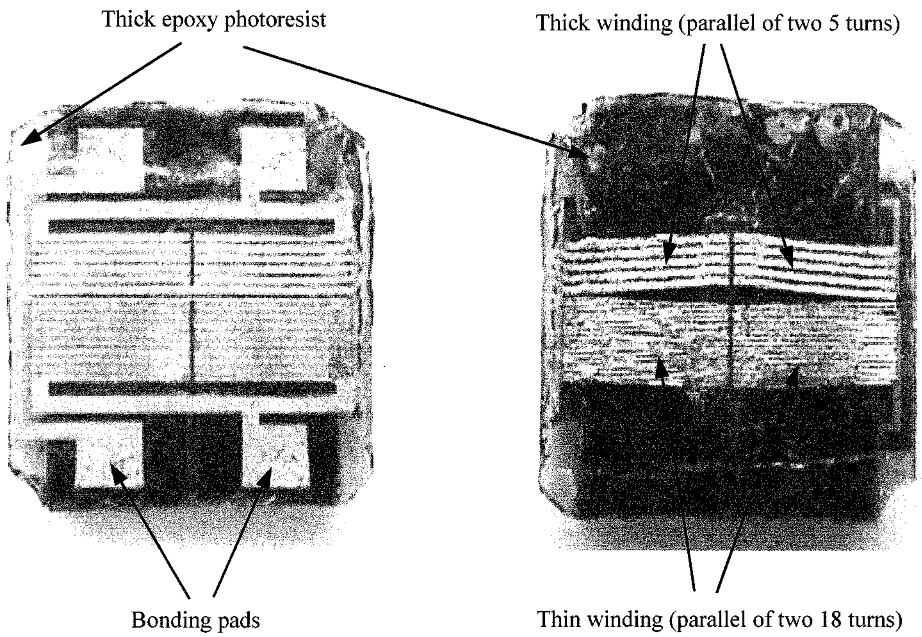

Fig. 6. Photograph of a fabricated high current inductor with the laminated Ni/Fe alloy core (device dimension: 16 mm × 19 mm × 1 mm).

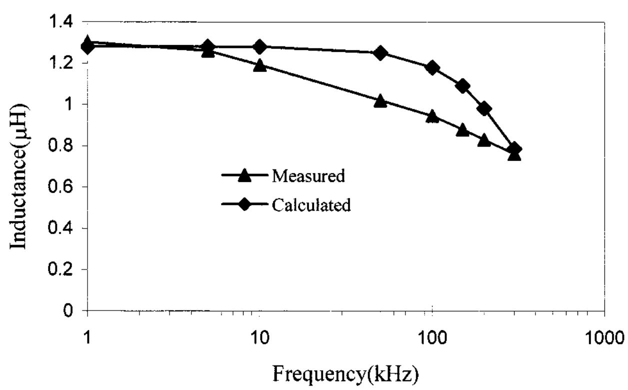

Fig. 7. Measured and calculated inductances of the thick winding.

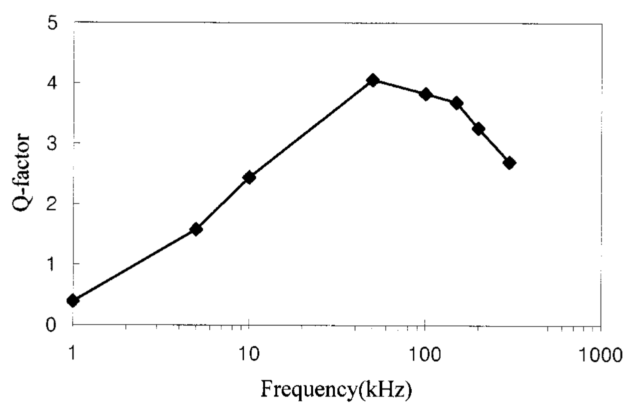

Fig. 9. Q-factor of the fabricated inductor.

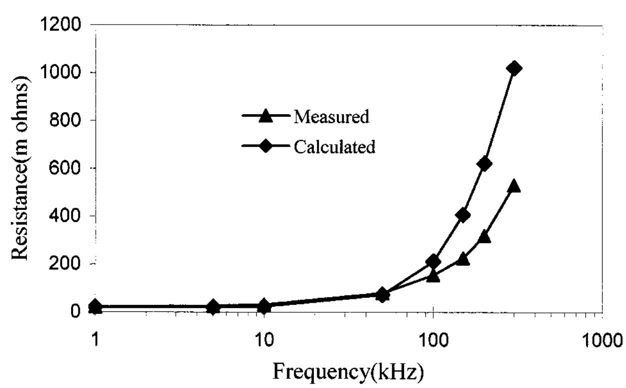

Fig. 8. Measured and calculated resistances of the thick winding.

in the core. The self-resonant frequency of the fabricated inductor caused by parasitic capacitance was not observed at frequencies below 100 MHz. Therefore, the effect of parasitic capacitance of the coils is considered to be negligible at the frequency of interest (approximately 100 kHz). The measured and calculated resistances of the inductor are shown in Fig. 8. The calculated resistance is the sum of the resistance $R_e(f)$ [from (5)] representing the eddy current loss and the measured dc resistance of the winding. The hysteresis loss in the core was neglected in this resistance calculation. The skin effect in the copper winding at these frequencies was also neglected, since the thickness of the fabricated copper was less than the calculated skin depth. Thus, the increase of the measured resistance is attributed solely to the eddy current loss. The Q-factor of the fabricated inductor, defined as the ratio of the imaginary to real parts of the inductor impedance, is shown in Fig. 9. The maximum Q-factor occurred around 50–100 kHz regions, presumably meaning the chosen thickness of lamination is acceptable for operation in the designed frequency ranges.

Fig. 10 shows the measured inductance of the thick winding as a function of dc bias current. The inductance was measured at 10 kHz while dc current (up to 5 A) was applied to the thick winding. The decrease of inductance value at the higher bias current range means that the magnetic core begins to saturate. dc saturation current is generally defined as the current at which the inductance value falls by 20% from the measured inductance without the applied dc current. The dc saturation current of the inductor is approximately 3 A.

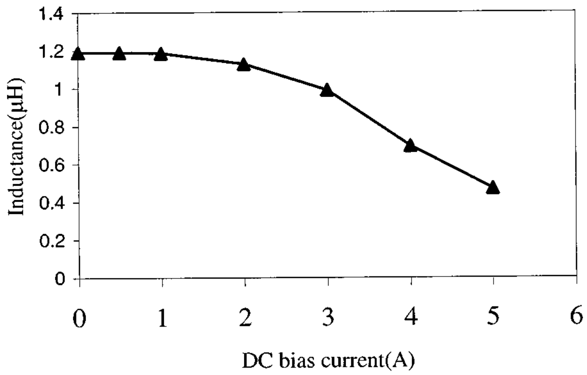

Fig. 10. Measured inductance of the thick winding as a function of dc bias current at 10 kHz.

V. Conclusions

In this work, high current and low profile (1 mm) micromachined inductors with a laminated Ni/Fe core have been designed, fabricated, and characterized. A new fabrication process consisting of conventional lamination techniques using a hot press and LIGA-like lithography of thick photoresist SU-8 was developed. The fabricated inductor has dc saturation current of 3 A with an inductance value of 1.2 μH, a low electrical resistance (less than 30 mΩ) at 10 kHz, and a maximum Q-factor of approximately 4 at 50 kHz. These inductors may have potential as enabling elements for high density, high power, miniaturized dc/dc converters.

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