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# Design of Integrated LC Filter Using Multilayer Flexible Ferrite Sheets

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***Abstract:*** *Dielectric and magnetic materials were developed for use as integrated passive component design. The integrated LC component to be investigated in this paper uses ferrite material which combines both magnetic and dielectric properties. Because of this double property, the ferrite sheet will be used in this design as magnetic core for the inductor and dielectric substrate for the capacitor. The fabrication is simplified by using PCB inductor and adhesive flexible ferrite sheet. To evaluate the inductance, the capacitance including the parasitic resistance, a fabricated prototype of the LC component was simulated and measured. It was confirmed that simulated values were very close to the measured values and the integrated LC component behaves as low-pass filter.*

***Keywords:*** *Integrated passive, Flexible Ferrite, PCB Inductor, Multilayer Capacitor, L-C filter.*

## I. Introduction

In Power Electronic Converters such as DC-DC, output signal filter capacitor and inductor are relatively the largest components. They contribute to increase the size of the whole converter. Size reduction of these components is still a major challenge in low power converters where small and/or low profile systems are expected. Two ways are explored for those works.

The first way is related to the switching frequency of the converter. If it is increased, capacitor and inductor can be reduced while keeping the same equivalent impedance. However, this working frequency has an upper limit imposed by the switching losses in the semiconductors and conductors.

The second way of reducing the size is oriented toward new fabrication technologies which are to build integrated passive component structures (LC, LCL or LCT) to perform an electronic function (low-pass, resonant filter or transformer) [1], [2], [3]. This way gets more attention and has become the subject of research over the last few years.

Both ways can be combined to reach high power-density converter when they are correctly used.

The design of the integrated LC component in this paper is based on Ni-Zn flexible ferrite sheet used as magnetic core for PCB planar spiral inductor and as dielectric substrate for multilayer capacitor design because of the magnetic and dielectric properties of these materials.

With the use of printed circuit board (PCB) windings, the cost of complex fabrication process is eliminated and also it offers the flexibility of winding geometry, shape, size.

The specific permittivity and resistivity value of the Ni-Zn ferrite are 10 – 20 and more than $1M\Omega{\cdot}m$ respectively, with permeability of 125 – 2000 [4]. An integrated LC component using multilayer structure of materials is built. Commercially adhesive flexible ferrite sheets [5] are used to make design simplified and cost reduced.

The resulting integrated LC component performances (cut-off frequency, input impedance and filter attenuation) will then be estimated in order to provide useful information to propose a final filter design having sufficiently good performances to be integrated in the same board of a switching converter.

## II. Structure Of The Integrated Lc Component

The goal of this design is to explore the possibility of using ferrite material that has both magnetic and dielectric properties for integrating inductor and capacitor in multilayer structure which behaves as low-pass filter for switching power electronic converter output signal filtering.

The construction of the integrated LC component is shown in Fig. 1. It is composed of spiral inductor sandwiched between two ferrite layers [6] and multilayer ferrite capacitor.

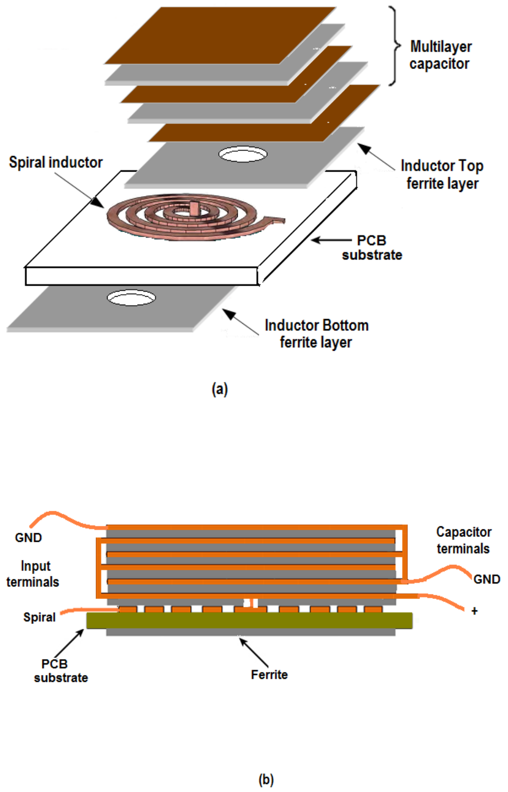



**Fig. 1** - Exploded (a) and cross section (b) views of the structure

The two ferrite layers which sandwich the PCB spiral inductor act as magnetic core. The top ferrite layers act as dielectric for multilayer capacitor design. Alternating layers of electrodes and dielectric material allow higher capacitance in physically smaller packages. The inductor and capacitor are stacked together to implement a structural integration. The total effect of the structure may be considered to behave as a series connection of an inductor and a capacitor. The equivalent circuit model is represented schematically in Fig. 2. There is parasitic inter-winding capacitance due to air between adjacent traces and the PCB substrate.

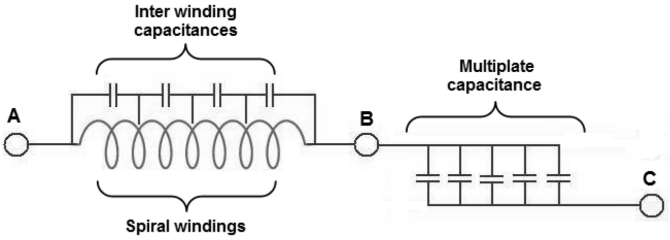



**Fig. 2** - The equivalent circuit model of the structure

Inter winding capacitances appear when working frequency increases and their influences are sensitive beyond 100 MHz [7]. For the application the integrated LC component is designed, inter winding capacitances are left out as open branches.

An LC low-pass filter was obtained by taking terminals A-C as input port and terminals B-C as output port. The equivalent circuit is shown in Fig. 3.

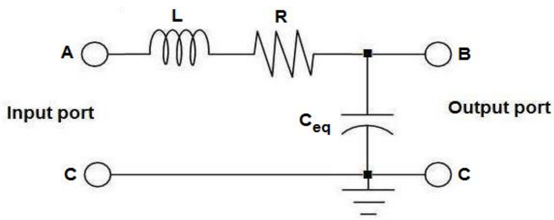



**Fig. 3** - Equivalent circuit of the structure

The structure of the integrated LC component is physically described by the following parameters defined in Table 1.

**Table 1 - Geometry parameters of the integrated structure**

| Geometry parameters | Description |
|---|---|
| N | Number of turns of the spiral windings |
| n | Number of capacitance layers |
| w | Winding width |
| s | Space between windings |
| t | Winding thickness |
| e | PCB thickness |
| α | Distance between ferrite and spiral end |
| $D_o$ | Spiral outer diameter |
| $D_i$ | Spiral inner diameter |
| l×l | Ferrite layer size |

The values of self-inductance, series resistance and equivalent capacitance depend on the geometry parameter magnitudes and electrical and magnetic properties of the material used.

## III. Analytical Calculation Of Model Parameters

The expressions of the parameters related to the integrated LC device model are presented in this section.

### 3.1 Inductance L

When spiral coil is sandwiched by ferrite layers, the inductance value can be derived as [8]:

$$L = K_m \cdot L_o \qquad (1)$$

Where

$L_o$ is the value of inductance without magnetic core,

$K_m$ is a magnetic factor which depends on the relative permeability $\mu_r$, the thickness of the ferrite layer, the size width and the air gap between the two ferrite layers.

The planar inductor under study consists of a circular spiral pattern of copper conductor. Different equations have been proposed in literature to calculate the value of inductance $L_o$. A practical and accurate formula widely used to calculate $L_o$ for circular spiral inductor is presented in [9]. It is given as

$$L_o = \frac{\mu_o \cdot N^2 \cdot D_{av}}{2} \cdot \left[ Ln\left(\frac{2.46}{\rho}\right) + 0.20 \cdot \rho^2 \right] \qquad (2)$$

Where

$\mu_o = 4 \cdot \pi \cdot 10^{-7}\ H/m$ is the magnetic permeability of free space,

N is the number of turns,

$D_{av} = \frac{D_o + D_i}{2}$ is the average diameter,

$\rho = \frac{D_o - D_i}{D_o + D_i}$ is the fill ratio.

Internal and external diameters are related by the following relation:

$$D_o = D_i + 2 \cdot N \cdot w + 2 \cdot (N - 1) \cdot s \qquad (3)$$

Calculation of $K_m$ is more difficult and can be estimated using finite element analysis tool. Circular spiral inductor is considered in this design since 2-D finite element method (FEM) simulation can be used to analyze it easily and predict values of L without time consuming as in 3-D.

Because of the axial symmetry of the structure topology, the circular spiral coil is modeled as concentric rings [10]. The error in using the concentric ring approximation was found to be only about 5%.

To estimate magnetic factor $K_m$ by finite element analysis, arbitrary values have been chosen for conductor width and space between turns (w = s = 1 mm). The flexible ferrite sheet we use has magnetic permeability of

230 and thickness of 300 µm [6]. The separation between the two ferrite layers is constant and is the sum of the thicknesses of spiral conductor (18 µm) and PCB FR4 substrate (1.6 mm). The only variable parameter of $K_m$ is the outer diameter $D_o$. The ferrite layer size is chosen equal to Do + 2 mm to fit the spiral and to allow the flux to flow from top ferrite to bottom ferrite.

The magnetic factor $K_m$ can be obtained as a function of outer diameter $D_o$. Fig. 4 shows the magnetic factor $K_m$ when outer diameter $D_o$ varies from 48 mm to 98 mm and $D_i$ is kept constant and equal to 10 mm.

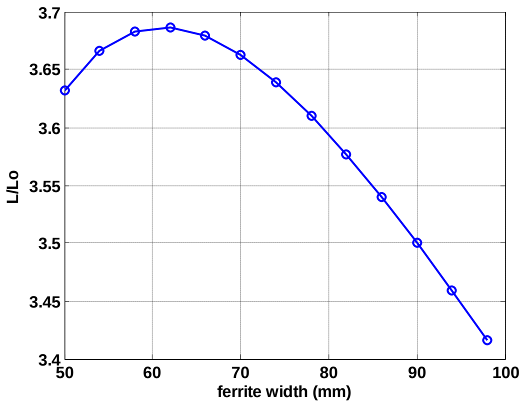



**Fig. 4** - Magnetic factor $K_m$ when $D_o$ varies from 48 mm to 98 mm

Fitting the magnetic factor $K_m$ curve, the inductance of the integrated LC structure can be estimated as:

$$L = \left( -1.9617 \cdot 10^{-2} \times D_o + 6.0823 - \frac{73.3273}{D_o} \right) \times L_o \qquad (4)$$

Where L is given in µH and $D_o$ is in mm.

### 3.2 Series resistance $R_s$

The series resistance is frequency dependence due to the skin effect. It is difficult to estimate analytically, so instead, the ac resistance at the working frequency will be obtained from FEM simulation.
The dc resistance can be estimated by

$$R_{DC} = \frac{l_m}{\sigma \cdot w \cdot t} \qquad (5)$$

where:
**σ** is the conductivity of the copper [S/m],
**$l_m$** the total mean length [m] of the winding,
**w** the width [m] of the spiral and t the thickness [m] of the winding trace.
For circular spiral inductors, the mean length can be expressed as

$$l_m \approx \pi \cdot N \cdot D_{av} \qquad (6)$$

### 3.3 Capacitance C

Calculating capacitance C is based on the formula for a parallel plate capacitor:

$$C = \varepsilon_o \cdot \varepsilon_r \cdot \frac{A}{h} \qquad (7)$$

where $\varepsilon_o = 8.854 \times 10^{-12}$ F/m is for the dielectric constant of air, $\boldsymbol{\varepsilon_r}$ the relative permittivity, **h** the thickness of the dielectric, and **A** the electrode surface area.
The flexible ferrite sheets used in this design are generally composed of Ni-Zn. In general, Ni-Zn ferrite materials have high-volume resistivity and low relative permittivity $\varepsilon_r$ of about 10 to 25 [5].

The flexible ferrite sheets are manufactured with 0.01 mm thick PET layer on one side of the ferrite material and 0.02 mm thick adhesive tape on the opposite side.


**Fig. 5** - Flexible ferrite sheet presentation [6]

Manufacturer did not provide information about permittivity of the three materials. So measurements were done to estimate the capacitor per unit area: $\mathbf{C_d}$.

Fig. 6 shows capacitance C variation for different surface areas. Measurements have been carried out using a digital RLC-meter.

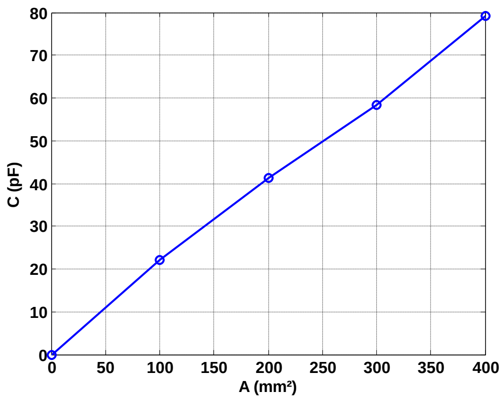



**Fig. 6** - Capacitance variation with surface area

The capacitor factor is deduced from fitting: $\mathbf{C_d = 0.1986 pF/mm^2}$. As expected, Ni-Zn ferrite exhibit low permittivity that leads to low capacitance. Because of the low permittivity of the ferrite material we use, multilayer capacitor technology is employed to increase the capacitance of the integrated LC component. Total capacitance for **n** layers is given as:

$$C = n \cdot C_d \cdot A \qquad (8)$$

Where A [mm] is the parallel plate surface.

The total height of the component is the thickness of PCB FR4 substrate and the sum of number of alternating copper and ferrite sheets. It is given as

$$H = e + (n + 2) \cdot (h + t) \qquad (9)$$

## IV. Design Procedure

There are many ways to design the integrated LC component parameters. Most of the time, the calculation of these parameters depends on the specifications of the converter.

The first thing is to obtain the values of inductance L, capacitance C and output current $I_o$ from the specifications of the converter. The second thing is to choose the dimension of the ferrite layer which is related to the outer diameter of the spiral inductor.

Manufacturers provide flexible ferrite with dimensions of 60 × 60 mm² and 120 × 120 mm²; however any other dimensions could be obtained between these given dimension for area optimization. There will be a compromise between the component thickness and its width.

At the beginning of the procedure, parameter like outer diameter must be specified. The inner diameter of the spiral inductor was set to 10 mm, and the ferrite layer width is set 2 mm more than the outer diameter to allow flux lines to pass through inside and outside the windings.

The algorithm for the design is described by the following steps:

- **Step 1: Number N of turns**

Knowing inductance L and the size of the ferrite layer l from outer diameter $D_o$, combine equations 2 and 4 to calculate the number of turns N.

- **Step 2: Number n of layers for multilayer capacitor**

Knowing capacitance C, the number of layers can be calculated using equation 8:

$$n = \frac{C}{C_d \times l \times l} \qquad (10)$$

- **Step 3: Width w of spiral conductor trace**

Calculate the width **w** of spiral conductor trace based on the maximum current $I_{max}$ to carry using the following equation [11]:

$$w = \frac{6.45 \cdot 10^{-4}}{t} \cdot \left( \frac{I}{k \times \Delta T^{0.44}} \right)^{1.379} \qquad (11)$$

where:
w = Minimum required track width in mm;
t = track thickness in mm;
I = Maximum current in Amps;
$\Delta T$ = Maximum allowable temperature rise above ambient in C;
k = 0.024 for inner layers and k= 0.048 for outer layers.

- **Step 4: Distance s between turns**

It is obtained from equation 3 as:

$$s = \frac{D_o - D_i - 2 \cdot N \cdot w}{2 \cdot (N - 1)} \qquad (12)$$

If s is $\leq 0$, then the outer diameter of the spiral is small; increase it and restart calculation from step 1 until a reasonable positive value is found.

- **Step 5: Calculate series resistance R**

It is calculated using equation 5 and 6 as

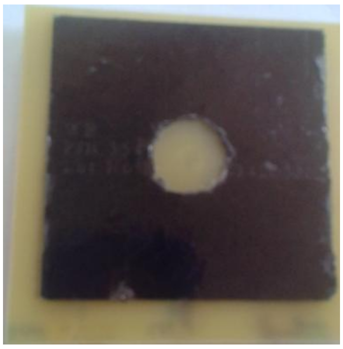
$$R_{DC} = \frac{\pi \cdot N \cdot D_{av}}{\sigma \cdot w \cdot t} \qquad (13)$$

## V. Simulation And Experimental Results

In order to validate the simplified model of the integrated LC component, a prototype has been designed using the available materials in laboratory when writing.

The fabrication of the integrated LC component needs no chemical process except for the realization of the PCB spiral inductor that uses the method of making a single layer PCB. Since capacitor electrodes (copper) and flexible ferrite sheet are adhesive tape, the principle consists on stacking alternate layers of copper and ferrite up. A ferrite sheet is stacked on the bottom side of the PCB FR4 substrate for the spiral to be sandwiched. A photograph of the filter is shown in figures below.


(a)



(b)

**Fig. 7** - Photograph of LC-filter: (a) – top side, (b) – bottom side

The design parameters are as follow in Table 2;

**Table 2 - Integrated LC design parameters**

| **Parameters** | **Values** |
|---|---|
| l × l (mm²) | 60×60 |
| n | 4 |
| N | 38 |
| w (mm) | 0.5 |
| s (mm) | 0.2 |
| $D_i$ (mm) | 6.5 |

Comparisons between analytical calculations and measurements (with digital RLC meter) are listed in Table 5 below:

**Table 3 - Parameters comparison**

| Parameters | Calculated | Measured | % error |
|---|---|---|---|
| L (mH) | 0.137 | 0.127 | 7.29 |
| R (Ω) | 7.26 | 8.14 | 12.12 |
| C (nF) | 2.96 | 3.19 | 7.77 |

As shown by Table 3, measured and modelled values agree to within less than 8% for inductance and capacitance. The difference between calculated and measured values of resistance may be attributed to the non homogeneous of the spiral trace surface.

Frequency response characteristics of inductance and capacitance were recorded using oscilloscope and function generator according to the setup schematic shown in Fig. 8.

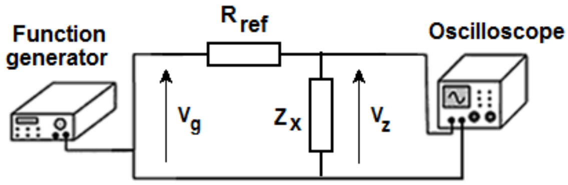



**Fig. 8** - Inductance and capacitance measurement setup

$V_g$ and $V_z$ are the amplitude of AC signal generator and voltage across impedance $Z_x$ respectively. Measurements of inductance and capacitance are carried out separately. The unknown inductor or capacitor ($Z_x$) is connected in series with a current measure resistance $R_{ref}$ and powered by a sinusoidal signal from a function generator. Using a logarithmic frequency sweep between $10^4$ and $10^6$ Hz with a sinusoidal signal level of 1 volt peak, inductance, series resistance and capacitance are recorded as a function of frequency. For best result the reference resistance $R_{ref}$ is selected such that amplitude of voltage $V_z$ is half of the one of voltage $V_g$. The capacitance, self-inductance and series resistance are calculated with the measured amplitudes of $V_g$ and $V_z$, and phase difference θ between $V_g$ and $V_z$ from the expression of the unknown impedance $Z_x$ given as:

$$Z_x = R_{ref} \cdot \frac{V_z \cdot (\cos\theta + j \cdot \sin\theta)}{(V_g - V_z \cdot \cos\theta) - j \cdot V_z \cdot \sin\theta} \qquad (14)$$

By calculating the impedance magnitude and phase of $Z_x$, inductance L, series resistance R and capacitance C can be calculated based on the following equations:

$$L = |Z_x| \cdot \sin(\varphi) \cdot \frac{1}{2\pi \cdot f} \qquad (15)$$

$$R = |Z_x| \cdot \cos(\varphi) \qquad (16)$$

$$C = \frac{-1}{|Z_x|} \cdot \frac{1}{2\pi \cdot f \cdot \sin(\varphi)} \qquad (17)$$

Where:
$|Z_x|$ is the impedance magnitude of $Z_x$;

φ is the phase angle the impedance $Z_x$;
f is the frequency of the AC signal.
Frequency characteristics of inductance, series resistance and capacitance are shown in Fig. 9.

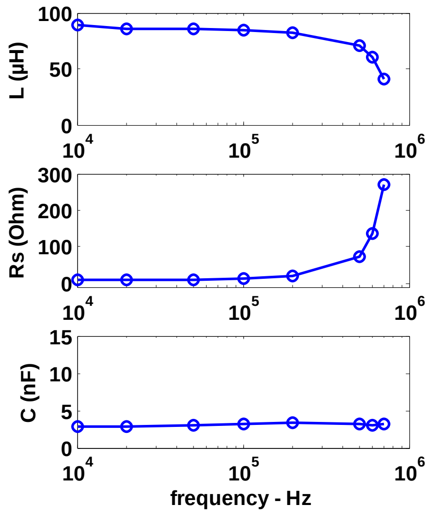


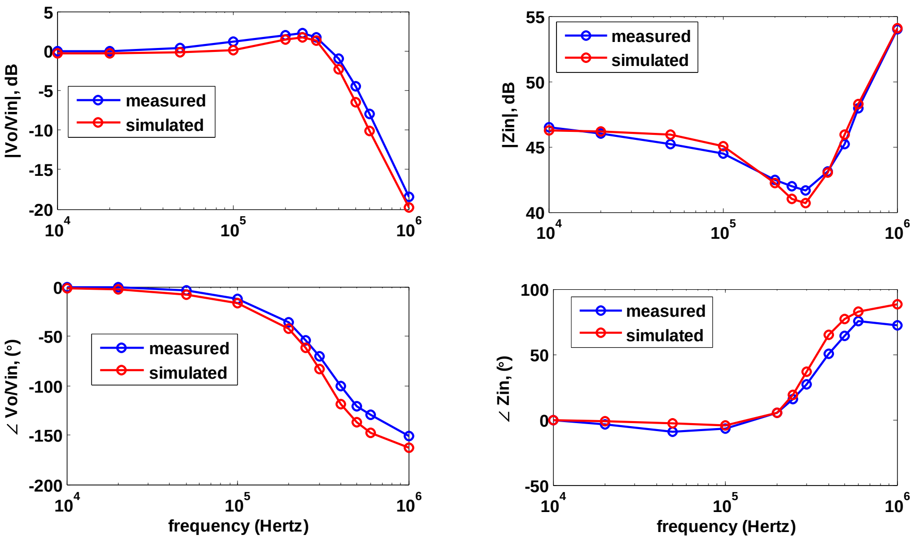

**Fig. 9** - Frequency characteristic of inductance, series resistance and capacitance

It should be mentioned that the phase difference between the voltages $V_g$ and $V_z$ is too small to be picked by the oscilloscope at frequencies below 10 kHz since the inductance and the capacitance were in the range of µH and nF respectively. So no experiments data were provided below 10 kHz in this measurement approach.

Inductance, series resistance and capacitance show good frequency characteristics in the measured frequency range. The initial inductance is around 100.0 µH and the value drops to 88 µH up to 200 kHz. The drop of the inductance is due to the frequency dependence of the permeability of the magnetic core, and probably also by inter winding capacitance effects. Initial value of resistance is 7.68 Ω and rapidly increases above 200 kHz due to the increasing magnetic and winding losses at high frequencies. Capacitance value is almost constant over measuring range with a mean value of 3 nF. It was confirmed that the measurement results of the fabricated inductor coincide with the simulation results.

From Fig. 9, we can deduce an optimal range of working for power converters with switching frequency under 200 kHz to limit loss due to inductor series resistance.

To describe the behavior of the integrated component, output to input ratio $V_{out}/V_{in}$ and input impedance given by the ratio of input voltage to input current have been recorded.
In the experimentation, the load resistance value is set equal to characteristic impedance as it provides a sharp corner frequency. The output to input ratio and the input impedance frequency responses are shown in Fig. 10 and Fig. 11 respectively. The simulated curves have been done using the constant values of the frequency dependence of inductance, series resistance and capacitance: L = 88 µH, R = 8 Ω and C = 3 nF.




(a) (b)

**Fig. 10** - Measured and simulated Frequency response of Output to input ratio $V_{out}/V_{in}$ (a) and Input impedance (b) of the integrated structure

When looking at Fig. 10, agreement between the measured and ideal values is observed since curves have the same shape. This indicates that the constructed prototype behaves like low-pass filter.
Measured resonance frequency is 300 kHz compared to calculated value which is 309.75 kHz.
The output to input ratio shows a slope of -47.07dB/decade and -43.65dB/decade for measured and simulated respectively.

## VI. Conclusion

This study has investigated the design of an integrated LC component on PCB using flexible ferrite sheets as magnetic core for the inductor and dielectric for multilayer capacitor. To determine the electrical characteristics of the LC filter, simulation and measurement were carried out. It is noticed that the proposed integrated LC component behaves like a low-pass filter. It was confirmed that the simulated values were very close to the measured values. For future studies, application to DC-DC buck converter will be investigated.

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