American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)

ISSN (Print) 2313-4410, ISSN (Online) 2313-4402



http://asrjetsjournal.org/

# Implementation of an Integrated LC Component for the Output Filter of a Step-Down DC-DC Converter

Somo Coulibaly[a]*, Geoges Loum[b], Kadjo Ambroise Diby[c]

[a,b]*Institut National Polytechnique, UMRI EEA (LARIT – SISE), Yamoussoukro, Ivory Coast*

[c]*Université Félix Houphouët-Boigny, SSMT (LPMCT), Abidjan, Ivory Coast*

[a]*Email: somo_c@yahoo.fr*

[b]*Email: loum_g@yahoo.fr*

[c]*Email: dibyka@yahoo.fr*

**Abstract**

The implementation of a fabricated integrated LC component for output filter of a low-power step-down DC-DC converter is presented in this paper. The topology of the LC filter has both inductor and capacitor stacked together in planar structure to form an integrated hybrid LC component. Flexible ferrite sheets are used for inductor magnetic core and capacitor dielectric substrate since ferrite materials combine both magnetic and dielectric properties. The use of these types of ferrite allows new filter topology to be investigated and also simplifies manufacturing process. The active part and the passive integrated LC output filter achieve a maximum power efficiency of 68% for output power of 1.2 W. Experimental results of the functioning of the converter are presented and discussed.

***Keywords:*** Integration; LC filter; Inductor; Capacitor; Flexible Ferrite; Buck Converter.

## 1. Introduction

DC-DC Buck converter are employed in a wide range of applications for the power ranging from watts (mobile phones), through kilowatts (DC motors drives) to megawatts (traction vehicles). Output LC filter contributes to converter performances in terms of efficiency, compactness and power density. The development of integration of passive components is still a challenge to improve the integration level of low power DC-DC converter. The inductor and capacitor used for output filter of DC-DC converter are still the bulkiest elements.

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* Corresponding author.

More than 50% of the area of the converter is occupied by these components. Many progresses have been done concerning integration of inductor for obtaining smallest component. Most researches on integrating passive components for power electronic converters are concentrated on fabricating integrated inductors that will be integrated in a monolithic DC-DC converter [1,2]. Discrete capacitors are sometime associated to the integrated inductor to form the output LC filter for the DC-DC Buck converter [3] since large value of capacitor is needed. Integration of large capacitor is a limiting process for integration of LC filter since capacitance per area goes from 160 to 2500 pF/mm² [4] according to the technology used for integrating capacitor. High switching frequency leads to smaller L and C, but the power efficiency is degraded by the dynamic power of the switching transistors in the high frequency operation. However, several examples of high switching frequency DC-DC converter with low inductance and capacitance for output filter have been reported [5,6,7]. Qinghua Li [5] designs and implements a 5V to 2.5V fully-integrated low-power buck converter operating at 100MHz with on-chip inductor and capacitor for the DC-DC output filter. Values of inductor and capacitor are 40 nH and 5 nF respectively. The converter shows an efficiency of 46% for output voltage of 2.5V at 100mA. The converter was fabricated using CMOS 0.5-µm 2P3M mix-signal silicon technology. Makoto Takamiya and Al [6] built an on-chip Buck converter which has on-chip LC filter. The inductor is a square planar spiral type. The open space at the center of the inductor is filled with a MOS capacitor for the output filter. The calculated inductance is 22 nH and the obtained capacitance is 1 nF. The integrated LC filter has a dimension of 2 mm x 2 mm in 0.35 µm CMOS. Under those conditions, the switching frequency was chosen to 200MHz. Maximum efficiency of 62% is achieved under output voltage and current of 2.3 V and 70 mA respectively.

P. Artillan and al built 3 x 3 mm² integrated LC filter for low-power buck converter. Operating frequency is 5 MHZ. Inductor and capacitor values are 110 nH and 560 nF respectively. Losses in the inductor and capacitor represent 50% of the circuit conversion due to inductor series resistance.

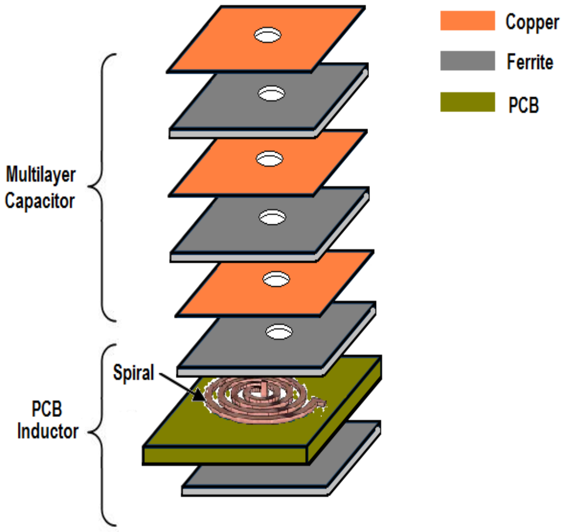
This paper describes the functioning of an integrated LC filter attached to the power stage of a DC-DC Buck converter. In previous work [8], it has been shown that the integrated LC component behaves as an LC low-pass filter.

The specifications of the DC-DC Buck converter are designed to meet the characteristics of the fabricated integrated LC component to be tested. Experimental results are presented to verify the performance of the converter with the LC filter and the limits. Efficiency of 68% is obtained.

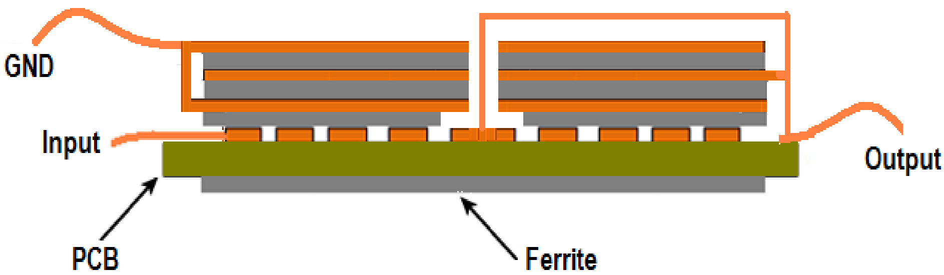
**2. Integrated LC filter overview**

The fabricated integrated LC filter consists of an inductive part, a PCB planar inductor sandwiched between two ferrite layers, and a capacitive part made of ferrite multilayer capacitors. The ferrite layers are flexible ferrite sheets for both inductor magnetic core and capacitor dielectric medium. Inductor and capacitor parts are stacked together in series connection to give an integrated LC component.

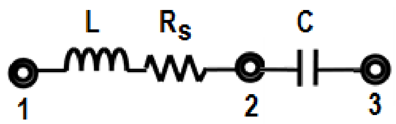
In Figure 1, (a) is the exploded view of the structure; (b) is the cross section view and (c) is the equivalent electrical circuit at low frequency. RS is the series resistance of the inductor. For low pass filter operation, input is applied between terminals 1 and 3 and output is taken between 2 and 3. Design equations for calculation of inductance L, series resistance RS and capacitance C can be found in [8].




(a)




(b)




(c)

**Figure 1:** Exploded (a) and cross section (b) views of the structure,

(c) Equivalent electrical circuit

Table 1 and 2 contain the design parameters for a prototype of the integrated LC module that was fabricated.

**Table 1:** Values of geometrical parameters of the filter structure

| **Design parameters** | **Values** |
|---|---|
| Number of turns, N | 32 |
| Track width, w | 0.5 mm |
| Track spacing, s | 0.25 mm |
| Number of layer, n | 6 |
| Inner diameter, $D_i$ | 10 mm |

The material specifications are shown in Table 2.

**Table 2:** Material Specifications

| **Material** | **Characteristics** |
|---|---|
| PCB (FR4) | Thickness: g = 1.6 mm |
| | Copper film thickness: t = 18 µm |
| | Copper conductivity: $\sigma = 5.8\times10^7$ S/m |
| Flexible Ferrite layer | Size: 60 mm × 60 mm |
| | Thickness: h = 0.3 mm |
| | Relative permeability: $\mu_r = 230$ |
| | Capacitance per area: $C_d = 0.2681$ pF/mm² |
| | Maximum flux density: $B_{max} = 60$ mT |

The photograph of the constructed LC filter module is shown in figure below.

**Figure 2:** Photograph of integrated LC filter prototype

Analytical calculations and measurements are shown in Table 3. Analytical calculations have been obtained from equation established in [8]. The measurement was carried out using RLC meter.

**Table 3:** Comparison of calculated and measured parameters

| Parameters | Calculated | Measured | % Error |
|---|---|---|---|
| Inductance: L (µH) | 107.72 | 140 | 23 |
| Series resistance: $R_S$ (Ω) | 6.50 | 6.18 | 5.17 |
| Capacitance: C (nF) | 5.19 | 5.3 | 2.07 |

The measured inductance is 125 µH when multilayer capacitor is not stacked on inductor structure. The relative error is then 13.8%. The increase of inductance is due to the contribution of the ferrite layers used for the capacitor design. In this kind of application, high value of inductance is not an inconvenient as it allows inductor ripple current to be low. Capacitance and series resistance values exhibit relative error less than 10%; calculated and measured values are very close.

**3. Design of the Buck converter**

Figure 3 shows the topology of the DC-DC Buck converter. It consists of a power stage that includes a power switching transistor and a Schottky barrier diode, the integrated LC filter and a control stage. The control stage is a pulse with modulation (PWM) which is a square wave signal from a function generator to control the switching transistor. Output voltage of the converter is controlled by the PWM.

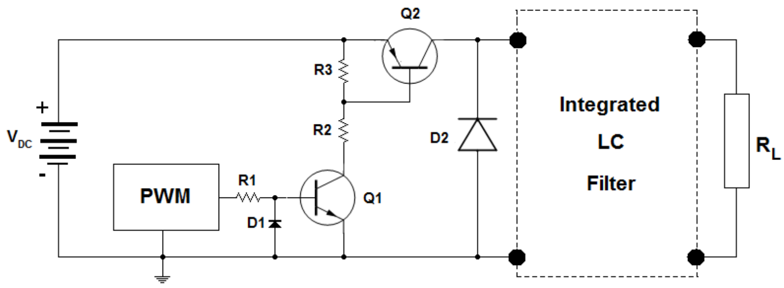



**Figure 3:** Circuit for implementation of the integrated LC filter

The specifications of the converter depend on the parameters and the characteristics of the integrated LC filter.

In the following sections, we describe the determination of the maximum inductance current to ensure that the magnetic core is not saturated, the switching frequency to operate at continuous conduction mode (CCM) at the converter input and output voltage of 12 V and 6 V respectively.

***3.1. Determination of inductor peak current: $I_L$***

Inductor peak current is calculated from maximum volume density of energy which is given by:

$$W_{V\,max} = \frac{1}{2} \cdot \frac{B_{max}^2}{\mu_o \cdot \mu_r} \qquad (1)$$

Where $B_{max}$ is core maximum saturation induction, $\mu_r$ the magnetic material relative permeability and $\mu_o$ the free space permeability ($\mu_o = 4\pi \cdot 10^{-7}$ H/m).

From the specifications of Table 3, the maximum volume density of energy is calculated:

$W_{Vmax} = 6.23$ J/m$^3$

The volume of the magnetic core is: V = 60 mm × 60 mm × 0,3 mm = $10.8 \times 10^{-7}$ m$^3$.

The energy stored in the inductance is: $W = W_{Vmax} \times V = 6.23 \times 10.8 \times 10^{-7} = 67.26 \times 10^{-7}$ J.

The energy stored in the inductance is related to maximum inductor current $I_L$ and inductor self-inductance L as:

$$W = \frac{1}{2} \cdot L \cdot I_L^2 \qquad (2)$$

From this equation, we find that the maximum current in inductor is:

$I_L = 0.342$ A

The maximum inductor current is given by:

$$I_{L\,max} = I_o + \frac{\Delta i_L}{2} \qquad (3)$$

Where: $I_o$ is the output load current and $\Delta i_L$ the inductor ripple current.

Inductor ripple current $\Delta i_L$ is usually 30% of maximum output current [9]. As a result, the maximum output load current is: $I_{omax} = 1.15 \cdot I_{Lmax}$. The output load current is:

$I_{omax} = 0.3$ A

We must verify that the maximum current in the inductor can be flow through safely in the spiral trace. This current is calculated using the following equation [10]:

$$I = k \cdot \Delta T^{0.44} \cdot \left( \frac{w \cdot t}{6.45 \times 10^{-4}} \right)^{0.725} \qquad (4)$$

Where:

w: minimum required track width in mils;

I: maximum current in Amps;

ΔT: maximum allowable temperature rise above ambient in C;

t: thickness of the copper trace;

k: 0.024 for inner layers and k= 0.048 for outer layers.

Using the values in Tables 2 and 3, we get:

I = 0.9 A

Output current $I_{omax}$ can safely flow through the PCB inductor trace.

For output voltage $V_O$ = 6 V and $I_O$ = 0.3 A, the load resistance is $R_L$ = 20 Ω. The maximum output power is 1.8 W.

***3.2. Determination of switching frequency: $f_{sw}$***

If we consider that the inductance of the integrated LC filter is the critical inductance value for the converter to operate in the continuous conduction mode (CCM), the switching frequency must be higher than a minimum switching frequency ($f_{swmin}$) which is given by (5) [11]:

$$f_{sw\,min} = \frac{V_O}{4 \cdot I_O \cdot L} \qquad (5)$$

For load characteristics with $V_O$ = 6 V, $I_O$ = 0.3 A and L =125 µH, the minimum switching frequency is 40 kHz.

Choosing higher values of switching frequency has a good effect on reducing the inductor current ripple. In addition, the inductor current ripple has the greatest effect on output voltage ripple since there is a low value of capacitance. However that will increase loss in the inductor series resistance. Switching frequency will be set to 300 kHz to ensure CCM and to limit resistive loss in inductor series resistance.

**4. Experimental results and discussion**

From the discussion in section 3, the DC-DC Converter specifications are shown in Table 4.

**Table 4:** DC-DC Converter Specifications

| **Parameters** | **Values** |
|---|---|
| Input voltage : $V_{DC}$ | 12 V |
| Output voltage : $V_O$ | 6V |
| Maximum load current : $I_O$ | 0,3 A |
| Switching frequency : $f_{sw}$ | 300 kHz |

The integrated filter and the converter were tested and the performances were evaluated.

### *4.1. Wave forms*

The measurements have been done for $V_O$ = 6 V at $R_L$ = 20 Ω with operating frequency $f_{sw}$ = 300 kHz. The filter waveforms input and output voltages ($V_{sw}$ and $V_O$) and inductor current are captured by Digital Storage Oscilloscope.

Figure 4 shows input switching voltage $V_{SW}$ and output voltage $V_O$ across capacitor.

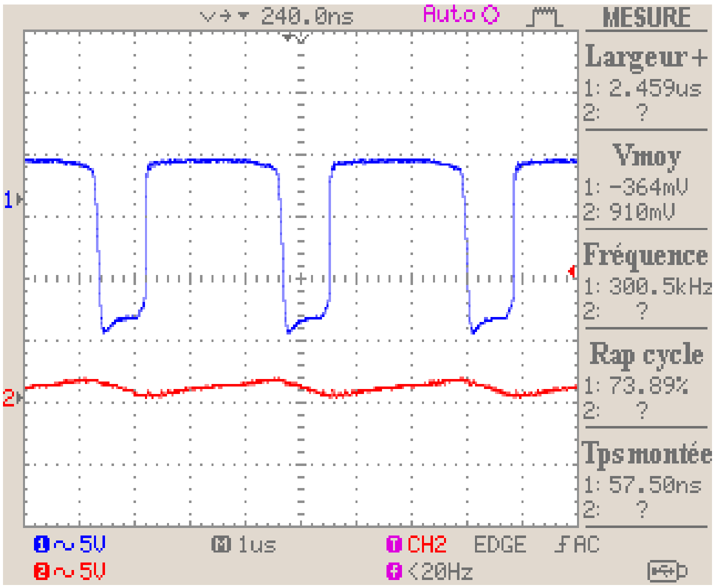



**Figure 4:** Channel 1: Input voltage ($V_{sw}$) ; Channel 2: Output voltage ($V_o$)

The inductor current has been sensed by filtering the voltage $V_L$ across inductor as described in [12], [13]. In Figure 5, the inductor voltage is kept as reference to compare the ON and OFF time durations. The waveforms present some oscillations at the start of conduction of the transistor. It is the transient time of current commutation from freewheeling diode to transistor. It can be seen that the converter is working in continuous conduction mode (CCM).

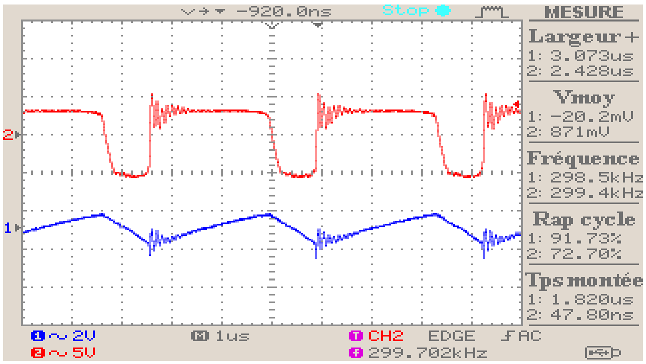



**Figure 5:** Channel 1: Inductor current ($i_L$) ; Channel 2: Inductor voltage ($V_L$)

The measured values obtained at full load are:

- Output current: $I_o$ = 0.295 A
- Output voltage: $V_o$ = 6 V
- Duty cycle: D = 0.73
- Inductor ripple current: $\Delta i_L$ = 0.08 A = 27% of $I_o$;
- Output ripple voltage: $\Delta V_o$ = 2 V = 33.33% of $V_o$;

Inductor ripple current ΔiL and output voltage ripple ΔVo are usually 30% of maximum output current and 1% of output voltage respectively [9]. It can be seen that inductor current ripple is close to the value use to design inductor in Buck Converter. Output voltage ripple is higher by 20 times than the design value. This is due to the low value of output capacitance. The voltage ripple could be reduced by increasing the number of capacitor layers. The duty cycle to get output voltage of 6 V is high than 0.5 due to the inductor series resistance which forms with the load resistance a voltage divider. Assuming that, at operating frequency the voltage dropped in the inductor series resistance is higher than VD and VCE, the voltage dropped across the free-wheeling diode and the power transistor collector to emitter voltage respectively, the duty cycle is expressed as:

$$D = \frac{V_O + R_S \cdot I_O}{V_{DC} + R_S \cdot I_O} \qquad (6)$$

At operating frequency of 300 kHz, the inductor series resistance is around 40 Ω. As a result, the duty cycle is 0.75 which is in good agreement with the experiment value.

### *4.2. Converter efficiency*

An evaluation of the efficiency of the Buck converter was done by measuring input power from the main 12 V supply and output power. The characterization of the efficiency will be done in two ways: firstly the load resistance is constant and efficiency is measured when the duty cycle is varying, secondly efficiency is measured when the output load current is varying while keeping output voltage constant.

For fixe load resistance ($R_L$ = 20 Ω), Figure 6 shows efficiency and output power variations with duty cycle. The low efficiency at low duty cycle is due to the increase in switching loss in power transistor caused by discontinuous conduction mode (DCM). The highest efficiency (η = 65%) is achieved at duty cycle 0.73 where the output power is maximum (outputs voltage and current are 6 V and 0.3 A respectively).

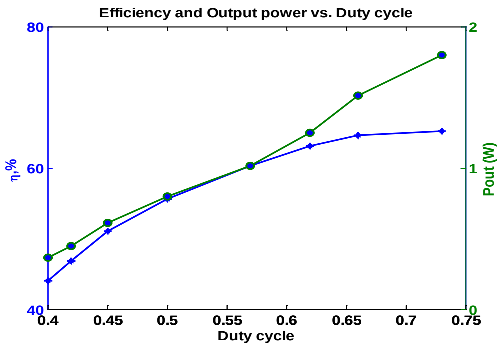



**Figure 6:** Efficiency and Output Power vs. Duty cycle

By varying the load resistance, output current was swept from 100 mA to 300 mA while the output voltage is kept equal to 6 V. This is done by manually controlling PWM duty cycle when load resistance is changed.

Figure 7 shows the curve of efficiency vs. load current. At maximum output power, the efficiency is 65% as it has been shown above. The maximum efficiency is achieved at the output power of 1.2 W and is 68%.

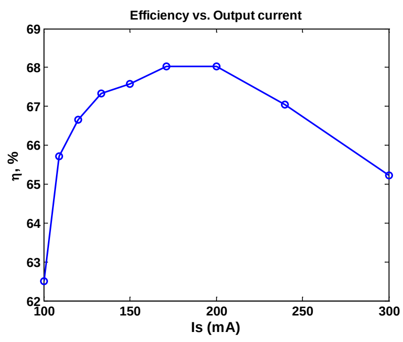



**Figure 7:** Efficiency vs. load current

From the obtained result, the fabricated integrated LC filter can be well applied to Step-Down DC-DC Converter, as expected.

***4.3. Comparison to some integrated LC filter***

Comparison between the results of this paper and those from information collected from different paper [5], [6], [7] with similar output LC filter are presented in Table 5. The elements of comparison are the values of inductor, capacitor, operating frequency, efficiency at rated output power.

**Table 5:** Comparison of the designed Integrated LC filter with works in reported in literature.

| Reference | This work | Qinghua [5] | Makoto T. et al. [6] | P. Artillan et al. [7] |
|---|---|---|---|---|
| L (H) | 125µ | 40n | 22n | 110n |
| C (F) | 5.3n | 5n | 1n | 560n |
| $f_{sw}$ (Hz) | 300k | 100M | 200M | 5M |
| $P_{omax}$ (W) | 1.2 | 0.25 | 0.161 | - |
| η% | 68 | 46 | 62 | < 50 |

It should be mentioned the use of advanced technology such that CMOS process for most of the works in reported papers. These work show high resonant frequency and are designed for very low power DC-DC converters. The switching frequency is above the range of MHz. Efficiencies are not far from the ones of linear regulators. From the foregoing, the integrated LC proposed in this work is promising for building integrated buck converter.

## 5. Conclusion and future work

The integrated LC filter technologies are continuously developing. This study has presented the functioning of a DC-DC Buck converter containing an integrated LC-filter based PCB spiral sandwich type inductor and multilayer capacitor structure. Adhesive flexible ferrite sheets have been used as magnetic core for the inductor and dielectric medium for capacitor. That has simplified the fabrication process. The characteristics of a DC-DC Buck converter are derived from the fabricated LC filter parameters. The converter with the integrated LC filter shows maximum efficiency of 68% for an output power 1.2 W. The efficiency of the converter could be improved by designing a low loss inductor for the integrated LC filter. The effective volume of the integrated LC filter is about 18 $cm^3$. The authors intend to develop a monolithic DC-DC self-oscillating on the same PCB of the integrated LC filter. The PCB will be used as packaged substrate for other components.

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