High Frequency Power Converters

(A Low-profile Low-Power Flyback Converter using Coreless Planar Printed Circuit Board Transformer)

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Abstract **:**

Magnetic cores have been used in transformers in most of power converters for over a century.Core-less PCB transformers have the advantages of low costs, very high power density, no limitation due to magnetic cores, no magnetic loss and ease of manufacturing. They have the potential to be developed in microcircuits.

Coreless printed transformers have great potential in applications in which stringent height and space requirements have to be met. This paper is concerned by introduction, modeling, analysis, a historical view and an experiment on coreless printed circuit board (PCB) transformers. The high frequency capability, high reliability and the low profile structure make these transformers a viable and attractive option for reliable mega hertz switching con-verters and micro circuits.

Keywords:

coreless-planar-converter-profile-flyback

Introduction:

Transformers are usually used for electrical solation and energy transfer. Normally, traditional transformers consist of copper windings which are wound on magnetic cores.The use of magnetic cores in transformers is usually thought to be essential because the magnetic cores which are made of ferromagnetic materials provide good conducting paths for the magnetic flux. The main reason for the continues use of magnetic cores is primarily to provide a high degree of magnetic coupling and to reduce the leakage inductance.

Coreless PCB Transformers

One of the new transformers which are made of twisted coils without magnetic cores has been presented and tested for high frequency applications [1]. In reference [1], it was demonstrated that coil transformer could achieve a coupling factor of 0.8 at about 1MHz. However, the parameters of these transformers are so difficult to control precisely. On another research front, much research effort has been focused on the use of printed planar windings for inductors and transformers. The most advantages of these transformers are that these transformers make these possible to manufacture inductors of transformers with precise parameters in an automated manner.

In most of presented works, magnetic substrates or materials are still used as parts of the magnetic core structures and these are of low output power (typically less than 2 W). Additionally the apparent problems of coreless planar printed circuit board transformers, namely low coupling factor and high leakage inductance have not been solved.In reference [2], an alternative way to design coreless transformers on doubled-sides printed circuit board is presented and it demonstrated that coreless printed planar transformers can have very high power density. In this paper, optimal operating techniques for using coreless printed circuit board transformers under minimum input power conditions and maximum energy efficiency conditions are described. In paper [2], with the aid of a high frequency equivalent circuit, the use and the basic characteristics of coreless printed circuit board transformers are described. For the coreless printed circuit board transformer with primary and secondary windings printed directly on the opposite sides of a doubled-sided PCB, the intrawinding capacitance is ineligible. The a.c. winding resistances of the primary and secondary windings, are *Rp* and *Rs* respectively. They are functions of the operating frequency due to skin effect. The measured relationships of the resistance as functions of frequency are:

$$R_p = \psi_1 f^2 + \psi_2 N + \psi_3 \qquad (1)$$

$$R_s = \psi_4 f^2 + \psi_5 N + \psi_6 \qquad (2)$$

In reference [3], the inductive characteristics of coreless printed circuit board transformers with different geometric parameters are described. These factors are:

1) outermost radius,
2) number of turns,
3) conductor width,
4) laminated thickness,

and 5) conductor thickness on the transformer's characteristics are investigated.

Suppose that *N p* and *Ns* are primary turns and secondary turns of transformer,printed on the opposite sides of a doubled-sided PCB.As it explained in [3], all of the inductive parameters depend on geometry of the coreless transformer. In this paper, some simulation and experimental results are presented.In these tests, the coreless transformers are categorized to as following:

a- Different outermost radius with the same number of turns. So, these transformers have different track separation. It is found that the self inductance, mutual inductance and leakage inductance are given by

$$L_P = ar \qquad (3)$$

$$M_{PS} = (a - c_1)r - c_0 + (c_1 r + c_0)e^{\left(-r/c\right)} \qquad (4)$$

$$L_{lk} = (c_1 r + c_0)\left(1 - e^{\left(-r/c\right)}\right) \qquad (5)$$

where a , c , $c0$ and $c1$ are constants that depends on the number of turns, geometry of transformer windings and the laminate thickness.

b- Different number of turns with the same radius. So, in this case, the track separation decreases as the number of turns increases and,

$$L_p = \alpha_1 N^2 + \alpha_2 N \qquad (6)$$

$$M_{ps} = \alpha_3 N^2 + \alpha_4 N \qquad (7)$$

$$L_{lk} = \alpha_5 N^2 + \alpha_6 N \quad (8)$$

where the multipliers are constants that depends on the number of turns, geometry of transformer windings and the laminate thickness.

c- Different number of turns with the same track separation. Since the winding separation is fixed, the transformer radius increases as number of turns increases and,

$$L_p = \beta_1 N^3 + \beta_2 N^2 + \beta_3 N \quad (9)$$

$$M_{ps} = \beta_4 N^3 + \beta_5 N^2 + \beta_6 N \quad (10)$$

$$L_{lk} = \beta_7 N^3 + \beta_8 N^2 + \beta_9 N \quad (11)$$

These results show that the coupling factor can be increased by increasing the transformer area with or without increase number of turns.

d- Different Laminate thickness.

The smaller the separation of the printed windings is, the greater the magnetic flux coupling becomes. As separation increases, the magnetic coupling between primary and secondary windings decreases.

e- Different conductor width.In this case,

$$L_p = \gamma_1 w^2 + \gamma_2 w + \gamma_3 \quad (12)$$

$$M_{ps} = \gamma_4 w^2 + \gamma_5 w + \gamma_6 \quad (13)$$

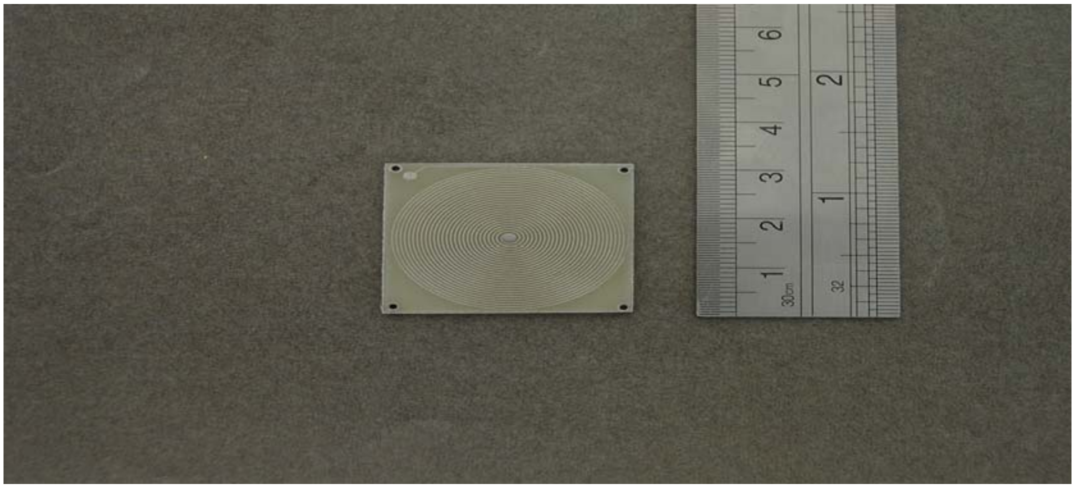
$$L_{lk} = \gamma_7 w^2 + \gamma_8 w + \gamma_9 \quad (14)$$

The test show that the self, mutual and leakage inductances don not vary significantly with track width.

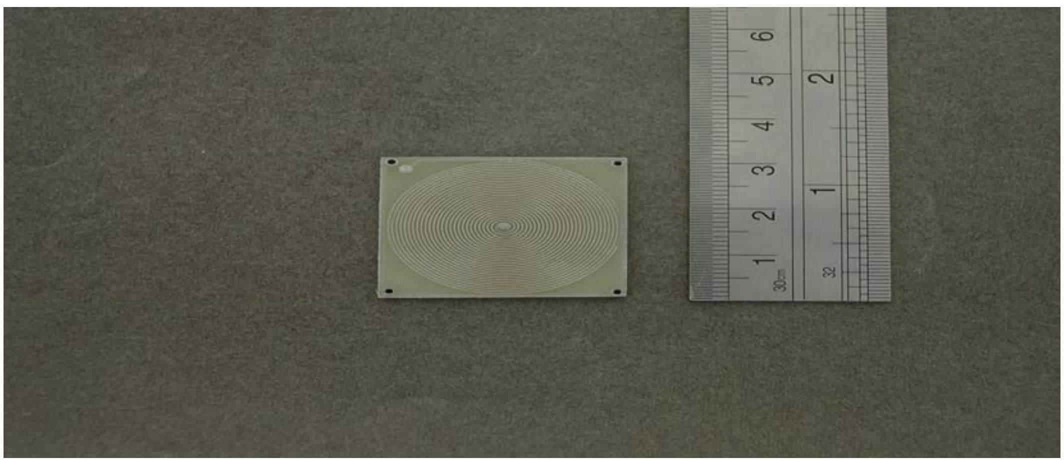
f- Different conductor thickness. The tests show that the variation of inductances is negligible for the coreless PCB transformers with different conductor thickness.Another important parameter that is tested in [3] is frequency variations. The inductive parameters do not change much with frequency because there is no core saturation.

Table 1- Corless PCB Transformer Types

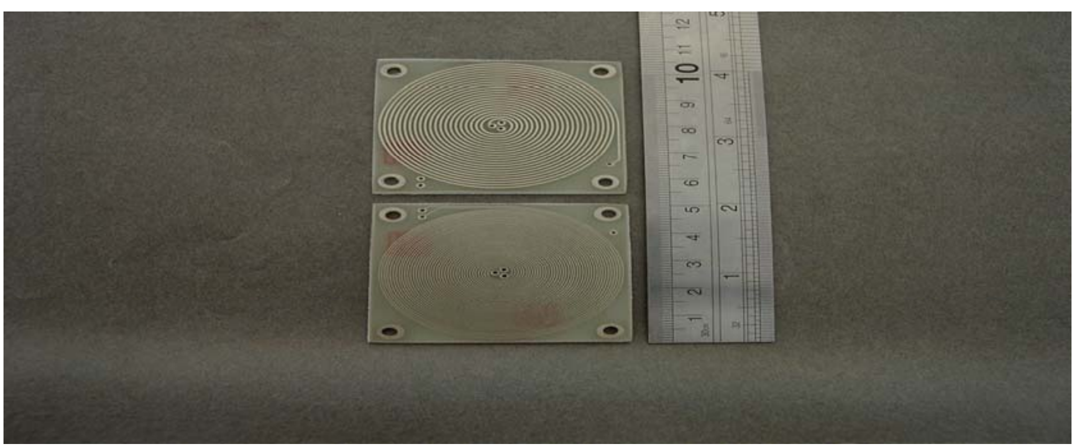
Corless PCB Transformer	**Tickness**	**Turns Ratio**	**Pic**
No. 1	0.5 mm	25:25	01
No. 2	1.6 mm	25:25	02
No. 3	1.6 mm	22:2*20	03



Pic01:Corless PCB Transformer No. 1



Pic02:Corless PCB Transformer No. 2



Pic03:Corless PCB Transformer No.3

Some EMI aspects of the using coreless PCB transformer in power electronic circuits have been addressed in [4]. Based on the antenna theory, it is found that the coreless PCB transformers under consideration has a radius that is much smaller than the wave length of the operating frequency.Thus, the transformer winding is an extremely poor transmitting and receiving antenna and its radiation power is negligible in gate drive applications. Unlike in conducting paths of the power circuit. The isolation of the transformer has very small switching transients and therefore emits relatively insignificant EMI. Field measurements of the entire power circuit have confirmed that the coreless PCB transformer is not a major EMI source in the frequency range from 30MHz to 300 MHz [4].

Experimental :

The principle of using coreless PCB based transformer in isolated gate drive circuit for power MOSFET and IGBT is the topic that is demonstrated in papers [5-10]. Gate drive circuits for modern power electronic switches, such power MOSFET and IGBT, often require electrical isolation. These papers describe simulation and experimental results of some coreless PCB transformers that can be used for MOSFET and IGBT devices at high frequency (500 kHz to 2 MHz) operation [7].

Table 2- Corless PCB Transformer No. 1 Test Result

R_o (Ω)	V_i (v)	V_o (v)	Frequency(MHz)	I_i (ma)	figure
1 M	12.1	12.5	1.21	230	V(out)-pic04
1 M	12.1	12.5	1.21	230	V(drain)-pic05
1 M	12.1	12.5	1.21	230	V(gate)-pic06
33	12	3.2	1.83	270	V(out)-pic07
33	12	3.2	1.83	270	V(drain)pic08
33	12	3.2	1.83	270	V(gate)-pic09

Table 3- Corless PCB Transformer No. 2 Test Result

R_o (Ω)	V_i (v)	V_o (v)	Frequency(MHz)	I_i (ma)	figure
33	12	3.2	1.21	320	V(out)-pic10
33	12	3.2	1.21	320	V(ac-out)-pic11
33	12	3.2	12.1	320	V(gate)-pic12
33	12.1	3.4	1.83	290	V(out)-pic13
33	12.1	3.4	1.83	290	V(ac-out)-pic14
33	12.1	3.4	1.83	290	V(gate)-pic15

Table 4- Corless PCB Transformer No. 3 Test Result

R_o (Ω)	V_i (v)	V_o (v)	Frequency(MHz)	I_i (ma)	figure
33	12.1	3	1.21	260	V(out)-pic16
33	12.1	3	1.21	260	V(ac-out)-pic17
33	12.1	3	1.21	260	V(gate)-pic18
33	12.1	3.3	1.83	350	V(out)-pic19
33	12.1	3.3	1.83	350	V(ac-out)-pic20
33	12.1	3.3	1.83	350	V(gate)-pic21

In addition, PCB offers electrical isolation of typically 15-40 kV, which is much higher than the typical electrical isolation of 2.5 kV offered by many optocouplers.

In [6], riteria for selecting the optimal operating conditions for the coreless transformer in gate drive applications are developed, presented, and experimentally verified. It is found that coreless transformers should be operated at the maximum impedance frequency of the gate drive circuit so that the power requirement of the gate drive is minimized and the voltage gain is high. This optimal operating condition of the coreless transformer has been demonstrated in the modulated gate drive circuit and can, in principle, be applied to the direct gate drive. When used with coreless transformers, direct gate drives are found to be suitable for high switching frequency. The modulated gate drive should be used for low and medium switching operation. The principle of using a coreless PCB transformer with multiple secondary outputs in complementary isolated gate drive circuit applications has been demonstrated in [5].

The modeling issues of the transformer equivalent circuit with two bifilarly printed secondary windings have been addressed.In reference [8], a low profile n-stage switched capacitor dc/dc converter that employs CCS in charging the capacitors is presented. Static and dynamic haracteristics of the converter and the selection of capacitor values have been investigated. Isolation between the power stage and gate signals is achieved by integrating coreless PCB transformer technology.

An isolation amplifier using coreless PCB transformers to transfer an analog signal has been demonstrated in [11].In this paper, operating conditions of the transformers and a design guideline of the isolation amplifier are detailed. Experimental results which are presented in [11] show that the isolation amplifier under investigation can transmit an analog signal from 20 mHz to 1.1 MHz with good linearity.

A model for coreless magnetic components (which are wider than our topic) based on finite element analysis is presented in [12]. This model accounts for geometry and frequency effects (skin and proximity) [13].Reference [14] uses two equivalent circuits for a coreless high frequency transformer. The first model already has been used to study the transformer, and the second model introduced there is more accurate than the first one,particularly in the range of higher frequencies.Some isolated low power converters using a coreless PCB transformer are described in [15-17]. The converter’s power output is about 0.5W with a typical transformer efficiency of above the 50%.In this paper, a flyback converter using a coreless PCB transformer is described. For this converter, the output voltage can be regulated and programmable.

Flyback converter has several advantages, but the major advantage is that the output filter inductors required for all forward topologies is not required for flybacks. Especially for multioutput power converters, this is a significant saving in cost and space [18].In other view, flyback is a current source (so, it is independent of turn ratio), single switch and low component topology. Therefore it is selected for a low power, low profile and small size dc/dc converter.This flyback converter is designed, simulated and tested in 1.21 and 1.83 MHz switching frequencies three type of coreless PCB transformers with different turns ratio and thicknesses. For all of the conditions, the input and output power and energy efficiency are calculated and compared with the converters which presented in [15-17]. Input power to the transformer

$$P_{in} = \left|V_p\right|^2 \operatorname{Re}\left(Y_{in}\right) \qquad (15)$$

where V_p is the primary voltage of the transformer and Y_{in} is the input admittance of the transformer.

Output power delivered from the transformer

$$P_{out} = \frac{|V_s|^2}{R_L} = \frac{|G(s) - V_p|^2}{R_L} = \frac{|G(s)|^2 \cdot |V_p|^2}{R_L} \quad (16)$$

where $V\,s$ is the secondary voltage of the transformer and G(S) is the voltage gain of transformer in s-domain. Energy efficiency of the transformer is

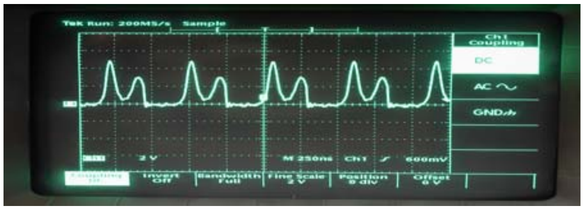
$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{|G(s)|^2}{R_L \cdot \mathrm{Re}(Y_{in})} \times 100\% \quad (17)$$

The experimental results reveal that the proposed converter is efficient and effective in applications in which stringent height and space requirements have to be met.

<u>Conclusion</u> :

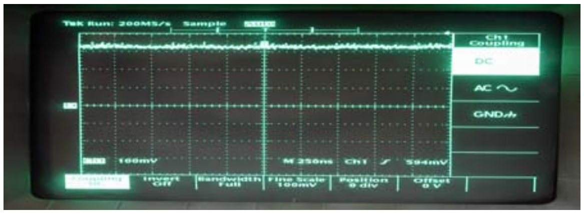
A low-profile, low-power flyback converter with coreless PCB isolation transformer has been demonstrated successfully.
Several coreless transformers with different thicknesses, diameters, and turns ratios at two frequencies is tested. The choice of optimal frequency range of coreless PCB transformers has been addressed. The experimental results confirm that it is feasible to use coreless PCB transformers for developing low-profile power converters with mega hertz switching frequency operation. Coreless PCB transformers eliminate the disadvantages of core-based manually wound transformers and provide a relatively low cost and highly reliable solution to the manufacturing of sub-watt converters with isolated and regulated output.

Out put voltage-pic04



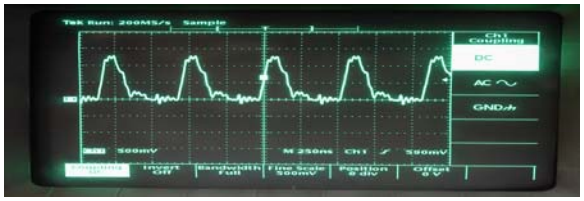
Drain voltage-pic05

Gate voltage-pic06

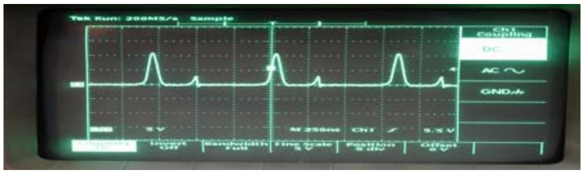


Out put voltage-pic07

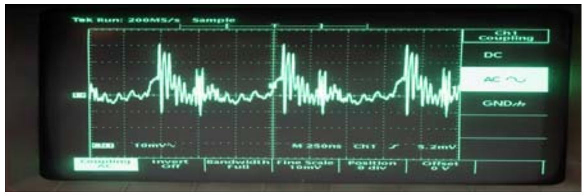
Drain voltage-pic08



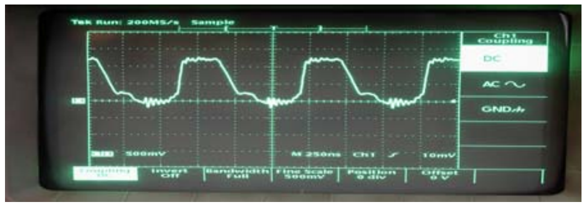
Gate voltage-pic09



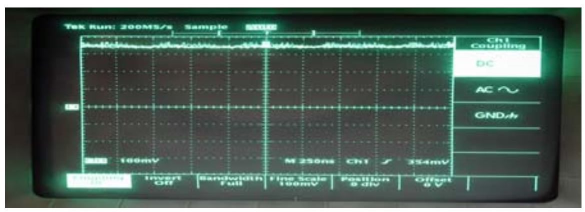
Out put voltage-pic10



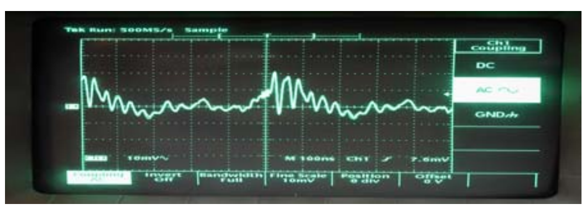
Ac Out put voltage-pic11



Gate voltage-pic12



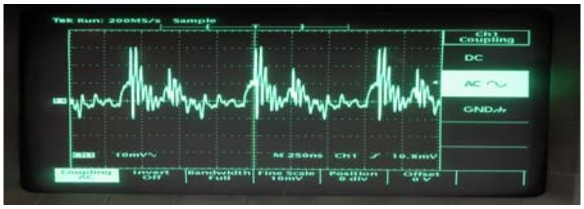
Out put voltage-pic13



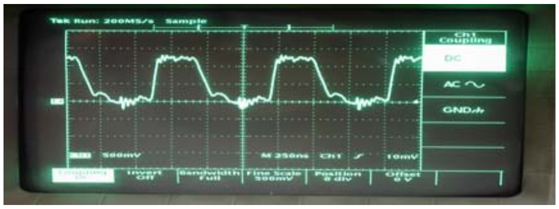
Ac Out put voltage-pic14

Gate voltage-pic15

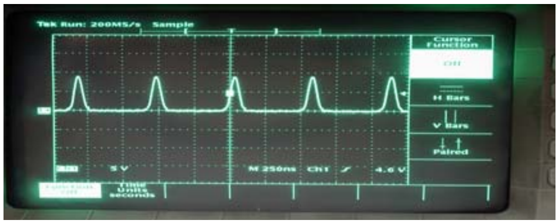
Out put voltage-pic16



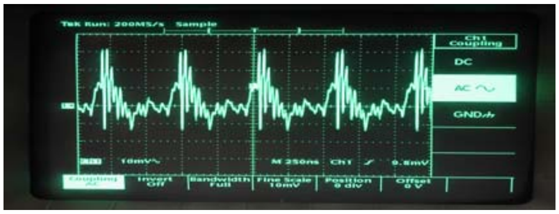
Ac Out put voltage-pic17



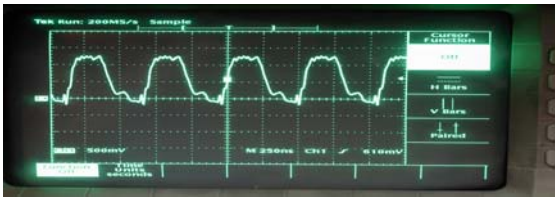
Gate voltage-pic18



Out put voltage-pic19



Ac Out put voltage-pic20



Gate voltage-pic21

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