Coreless Printed Circuit Board (PCB) Transformers – Fundamental Characteristics and Application Potential

S.Y.(Ron) Hui, S.C. Tang and H. Chung

Department of Electronic Engineering
City University of Hong Kong

Abstract – In this article, the fundamental concept, characteristics and application potentials of coreless printed-circuit-board (PCB) transformers are described. Coreless PCB transformers do not have the limitations associated with magnetic cores, such as the frequency limitation, magnetic saturation and core losses. In addition, they eliminate the manual winding process and its associated problems, including labor cost, reliability problems and difficulties in ensuring transformer quality in the manufacturing process. The parameters of the printed windings can be precisely controlled in modern PCB technology. Because of the drastic reduction in the vertical dimension, coreless PCB transformers can achieve high power density and are suitable for applications in which stringent height requirements for the circuits have to be met. A transformer's power density of 24W/cm^2 has been reported in a power conversion application. When used in an isolation amplifier application, coreless PCB transformers tested so far enable the amplifier to achieve a remarkable linear frequency range of 1MHz, which is almost eight times higher than the frequency range of 120 kHz in existing Integrated-Circuit products. PCB materials offer extremely high isolation voltage, typically from 15kV to 40kV, which is higher than many other isolation means such as optocouplers. It is envisaged that coreless PCB transformers can replace traditional core-based transformers in some industrial applications. Their application potentials deserve more attention and exploration.

1. Introduction:

The discovery of the Faraday's law of induction is indisputably a corner stone in Electrical and Electronic Engineering. The consequent development of electric generator and transformers has made electricity a common form of energy in modern society. Nowadays, transformers are commonly used for electrical isolation and energy and/or signal transfer. Normally, traditional transformers consist of copper windings 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 core-based transformer concept has not faced much serious challenge in the past, probably because of the fact that most transformer designs were for low-frequency (50 or 60Hz) operations. Even when the operating frequency in many modern power electronics applications (such as switched mode power supplies) has been significantly increased to several hundreds of kilo-Hertz in the 1990's, the core-based transformer concept remains more or less intact. Although it is well known that the size of the magnetic components decreases with increasing operating frequency, the issue: 'When will the size of the magnetic components approach zero and become zero?' was seldom addressed.

The main reasons for the use of magnetic cores are primarily to provide a high degree of magnetic coupling and to reduce the leakage inductance. Transformers formed by using twisted coils without magnetic cores have been proposed [1] for high-frequency applications. In [1], it was demonstrated that the twisted-coil transformers could achieve a coupling factor of 0.8 at about 1 MHz. However, the parameters of twisted coil transformers are difficult to control precisely. In addition, it may not be easy to manufacture identical twisted coil transformers in large quantity with high quality control. Much research effort has been focused on the use of printed planar windings for inductor or transformers [2-10]. The use of printed planar windings not only eliminates the costly manual winding process in traditional transformers but, more importantly, makes it possible to manufacture inductors or transformers with precise parameters in an automated manner. In most of the literature [2-9], magnetic substrates or materials are still used as parts of the magnetic core structures. An interesting attempt of printing two spiral windings on the same surface of a PCB without using magnetic core is reported in [10]. In [10], an integral equation analysis method for predicting the parameters of the printed single-sided PCB transformer is presented.

In the literature mentioned so far, the planar inductors and transformers are of low output power (typically less than 2W). Except in [1,10], the magnetic designs require the use of magnetic cores in one form or another. In this article, we summarize the recent developments of coreless PCB transformer technology [11-17]. The misunderstandings that PCB transformers without magnetic cores might have low coupling factor, low voltage gain and high radiated EMI problems are clarified. With the aid of a high-frequency circuit model, the basic characteristics and application examples of coreless PCB transformers are described. In particular, a resonant technique has been incorporated into the use of the proposed coreless PCB transformers so as to achieve a high voltage gain (to overcome the apparent low magnetic coupling) and take advantage of the leakage inductance (to turn the apparent disadvantage into an advantage). Optimal operating techniques for using coreless printed-circuit-board (PCB) transformers under (1) minimum input power conditions and (2) maximum energy efficiency conditions are described.

2. Basic Structure and Equivalent Circuit of Coreless PCB Transformers

The basic structure of a coreless PCB transformer is very simple. Essentially, transformer windings are printed on a double-sided PCB. An example of coreless PCB transformer (right) is shown in Fig.1, together with a core-based pulse transformer (left). In order to illustrate the characteristic of coreless PCB transformers, a prototype shown in Fig.2 and labeled as transformer Tr6 is used as an example. The width and height of the copper track are 0.22mm and 0.025mm, respectively. The distance between adjacent tracks is about 0.28mm. The number of turns for the primary and secondary printed windings is 10.

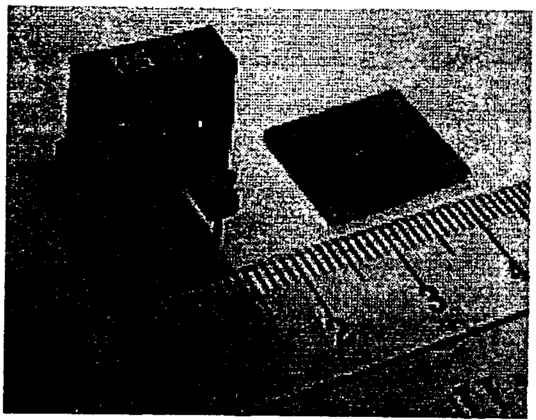


Fig.1 Photograph of a coreless PCB transformer (right) and a core-based transformer (left).

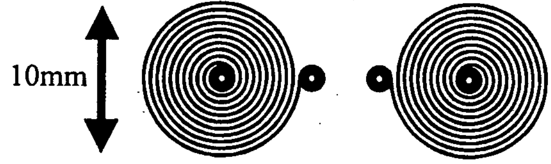


Fig.2 Dimensions of Tr6

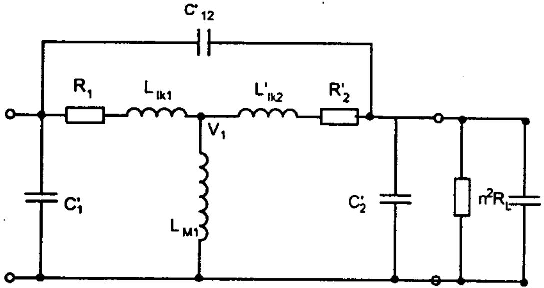


Fig.3 Equivalent circuit of the PCB transformer with a parallel capacitive/resistive load.

The equivalent circuit of a coreless PCB transformer is shown in Fig.3, where

R_1 is the primary winding resistance,

R_2' is the secondary winding resistance referred to the primary,

R_L is the resistive load,

L_{lk1} is the primary leakage inductance,

L_{lk2}' is the secondary leakage inductance referred to the primary,

L_{M1} is the primary mutual inductance,

C_1 is the primary winding capacitance,

C_2' is the capacitance in the secondary winding referred to the primary,

C_{12} is the capacitance between primary and secondary windings, and

n is the turn ratio.

The no-load resonant frequency of the equivalent circuit is given by

$$f_o = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}}$$

where $L_{eq} = L_{lk2}' + L_{lk1} \| L_{M1}$ and $C_{eq} = C_2' + C_{12}'$. (Here C_2' includes the load capacitance.) The parametric values of Tr6 measured at 10MHz are shown in the equivalent circuit in Fig.4.

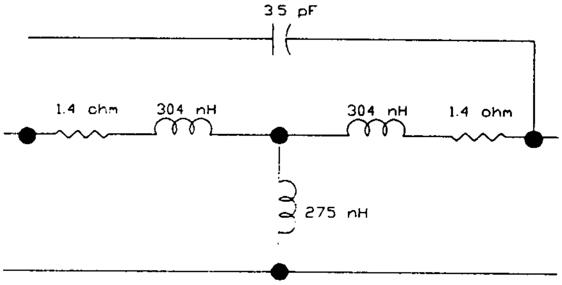


Fig.4 High-frequency Equivalent Circuit Model of Tr6.

It is important to note from (1) that the no-load resonant frequency can be changed by connecting an external capacitor C_2 across the secondary winding terminals. This feature enables the optimal operating frequency to be chosen for a particular application. For example, if the operating frequency of the coreless PCB transformer is limited to 10MHz, connecting a capacitor C_2 of 680pF gives Tr6 a resonant frequency to be approximately 9 MHz.

3.0 Characteristics of Coreless PCB Transformers

Based on the equivalent model, the frequency response of Tr6 loaded with a capacitor C_2 of 680pF and a dummy load of 2kΩ is shown in Fig.5a and Fig.5b. The voltage gain is the ratio of the output voltage and the input voltage (V_2/V_1).

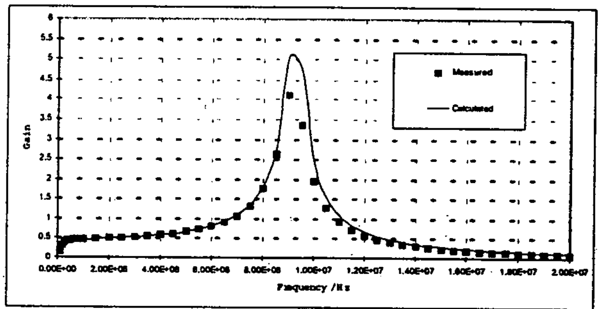


Fig.5a Predicted and measured voltage gain versus operating frequency of Tr6.

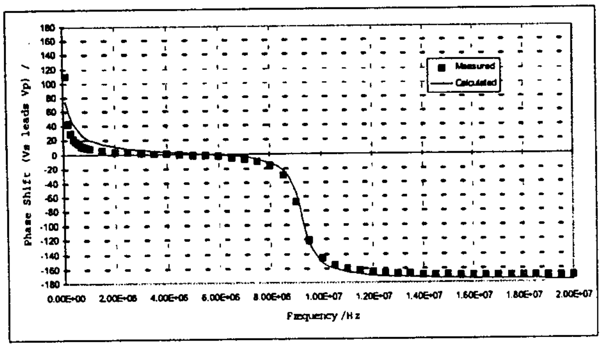


Fig.5b Predicted and measured phase shift versus operating frequency of Tr6.

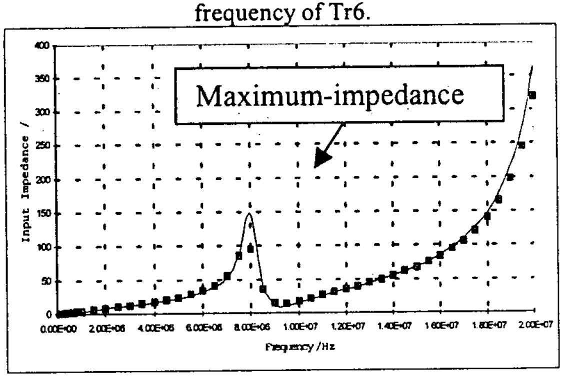


Fig.6 Predicted (solid-line) and measured (dotted) input impedance versus operating frequency of Tr6.

Observation of this typical frequency response leads to the following important points that can be considered to operate the coreless transformer in an optimal manner:

(i) As expected, it can be observed that the voltage gain at low operating frequency (less than 200kHz) is very low. As the frequency increases, the voltage gain increases until it reaches its maximum at the resonant frequency.

(ii) It is interesting to note that the voltage gain of the coreless PCB transformer can exceed 1.0 at the high-frequency region. This dispels the misunderstanding that coreless PCB transformer has low voltage gain.

(iii) The voltage gain of the transformer drops to zero beyond the resonant frequency. Thus the useable frequency range should be ***below*** the resonant frequency.

(iv) The operating frequency of the coreless transformer should be near but below the resonant frequency. This is the high-frequency end of the useable operating range where the magnetizing reactance is large. Otherwise, the equivalent behaves like a short circuit at low-frequency operation.

(v) Near the resonance region (just below the resonant frequency), the voltage gain is higher than the rest of the operating range. This is the "***partial resonant***" region with high gain and small phase shift. One can take advantage of this high-frequency and high-gain region for various applications. For Tr6, the partial resonant region is in the range of 6 MHz -8.5MHz.

4.0 Transformers for Signal Transfer and Power Transfer

4.1 Maximum-Impedance Frequency for Signal Transfer

Transformers are often used to transfer signals within minimum power involved. One example is the gate drive circuit for power electronic devices such as power mosfets and insulated gate bipolar transitors (IGBTs). The gate drive circuit of the power electronic devices requires the gating signal to be transferred to the gate with a small amount of power involved. In order to minimize the input power of the transformer, one can consider the input impedance characteristic. Based on the transformer circuit model, the input impedance of Tr6 can be determined and is shown in Fig.6. Observation of these plots leads to the following important points:

1. The magnitude of the input impedance peaks at a frequency (termed "***maximum-impedance frequency***") which is within the useable frequency range and is slightly below the resonant frequency. For Tr6, this frequency is about 8 MHz and the impedance is about 150Ω.
2. The voltage gain at this "***maximum-impedance frequency***" is high (about 1.8). That is, the signal can be enlarged. The use of the partial-resonance technique overcomes the supposed low-gain problem and can make the voltage gain greater than unity.
3. Operating the coreless PCB transformer at or near this frequency would minimize the power requirement of the transformer for signal transfer applications.

4.2 Maximum-Efficiency Frequency for Power Transfer

Coreless PCB transformers can be used as power transformers for power transfer. Fig.7 shows a prototype (labeled as Tr9) that has been tested for in a 94W DC-DC power converter [15]. Analysis of the energy efficiency of the equivalent circuit for various resistive loads indicates that the coreless PCB transformers can have a wide frequency range within which a high energy efficiency exceeding 90% can be achieved. A plot of the energy efficiency for Tr9 is shown in Fig.8. Because the power consumption of the electronics driving the primary winding increases with operating frequency, the optimal operating frequency should be chosen at the low-frequency end of the high-efficiency region and should be below the resonant frequency of the transformer circuit.

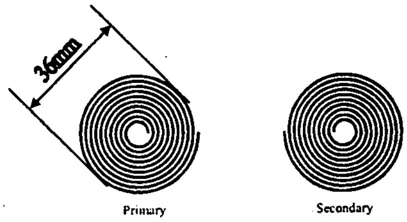


Fig. 7 Dimensions of the Transformer Tr9

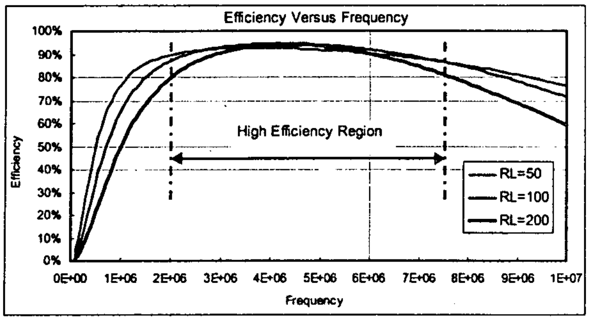


Fig.8 Efficiency of the PCB transformer using FPC sheet with C_r=390pF and various resistive load, R_L.

4.3 Electromagnetic Field

One common misunderstanding about coreless transformers is that there will be a serious radiated EMI problem. For a loop antenna, the radiation is primarily perpendicular to the x-y plane, i.e. $\theta = \pi/2$. The intrinsic impedance η is 120π or 377Ω in free space. If the operating frequency is 8MHz, the wavelength λ of the radiated signal is

$$\lambda = \frac{c}{f_C} = \frac{3x10^8}{8x10^6} = 37.5\text{m} \qquad (2)$$

where f_c is the operating (or carrier) frequency.

The time-averaged radiated power (P) of a loop antenna is

$$P = 160\pi^6 I_o^2 \left(\frac{af_c}{c}\right)^4 \qquad (3)$$

The radiated power depends on (i) the current I_o (or power of the operation), (ii) the dimension (radius a) of the structure and (iii) the operating frequency f_C. The radiated power drastically increases with increasing frequency and the dimension of the radiating structure. According to the antenna theory, a good loop radiator should have a radius that is in the order of magntiude close to that of the wavelength of the radiated signal. For the transformer TR6, the radius of the outermost loop is 0.005m. This radius is only $0.13x10^{-3}$ of the wavelength λ (37.5m). The term $(a/\lambda)^4$ is in the order of 10^{-16}. For a current I_o = 1A, the radiated power of a single loop antenna with a radius of 5mm is $P = 4.86x10^{-11}$ W. Therefore, the averaged radiated power of a single loop with a radius of 5mm is negligible. Although the coreless PCB transformer has 10 turns, the radiated power involved and its radiated EMI effects are still too small to be a concern. Therefore, the calculation indicates that the transformer TR6 is an extremely poor transmitting antenna as far as far-field radiation is concerned. By the reciprocity theorem, a poor transmitter is also a poor receiver for a signal of a certain wavelength. The 3-D field plot of Tr6 excited at 8MHz is shown in Fig.9. The magnetic flux essentially concentrates within and near the structure of the transformer.

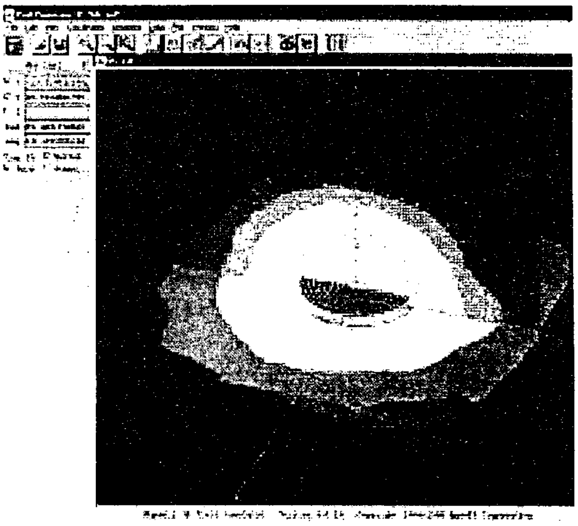


Fig.9 3-D Field plot of coreless PCB transformer Tr6.

5 Some Application Examples

Example 1 – Transformer Isolated Gate Drive Circuit with a Wide Frequency Range (Fig.10)

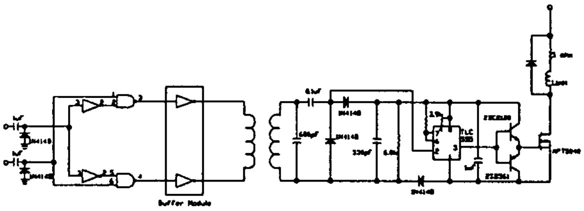


Fig.10 Modulated gate drive circuit using coreless PCB transformer.

Fig.11a and Fig.11b show the waveforms of the input gating signal and the output gate drive signal for the power device at 1 Hz and 300kHz, respectively.

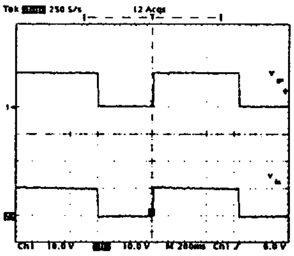


Fig.11a Measured input (V_{in}) and output (V_{gs}) signals of the gate drive circuit at f_{sw} = 1 Hz.

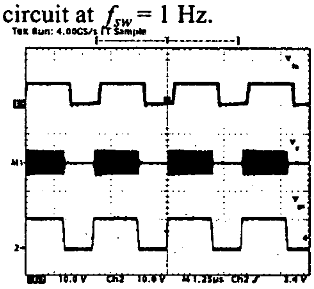


Fig.11b Measured input (upper: V_{in} 10V/div.), carrier (middle: V_c 25V/div.) and output (V_{gs}) signals of the gate drive circuit at f_{sw} = 300 kHz.

Example 2 – Transformer with Multiple Secondary Windings for Totem-Pole Gate drives

Multiple secondary windings can also be constructed for coreless PCB transformers. This can be done either by printing the two secondary windings on the same side or printing them in different layers in a multiple-layer PCB. Fig.12 shows the winding dimensions of a coreless PCB transformer with two secondary windings. This transformer has been used in two totem-pole gate drive circuits which is commonly used in power inverters. Fig.13 shows the practical switching waveforms of power devices at 1 MHz.

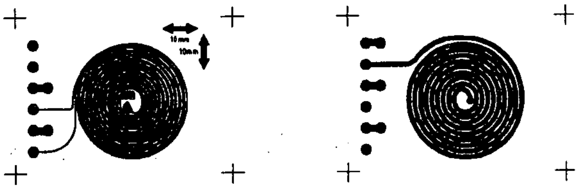


Fig.12 Two secondary windings (left) and one primary winding (right) of the coreless PCB transformer.

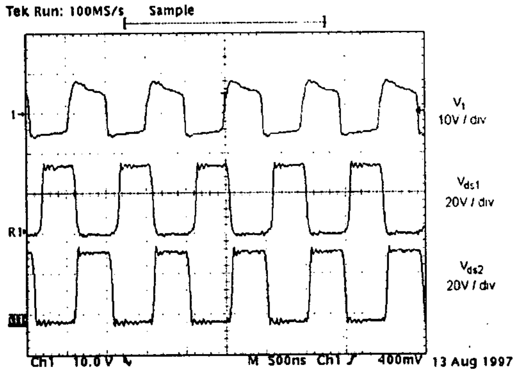


Fig.13 Measured primary gating signal (V_1), Drain-source voltage of the two MOSFETs (V_{ds1} and V_{ds2}) at 1MHz switching operation. (V_1: 10V/div.; V_{ds1} and V_{ds2}: 20V/div.)

Example 3 – Isolation Amplifier with 1MHz Bandwidth

Commercial isolation amplifiers have frequency bandwidth up to about 120kHz [18]. Because of the absence of the core limitations, coreless PCB transformers offer a much higher bandwidth up to at least 1MHz. Fig.14 shows a typical isolation amplifier circuit. The power transformer and the signal transformer are replaced by their coreless counterparts T1 and T2, respectively (Fig.15). Fig.16 shows the voltage gain versus operating frequency in this application example.

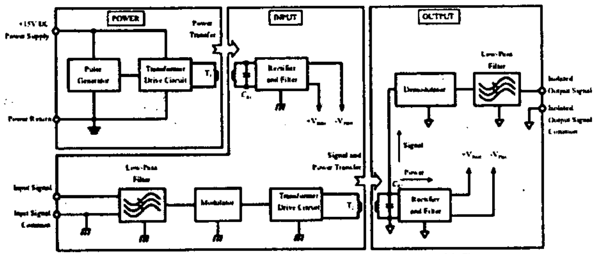
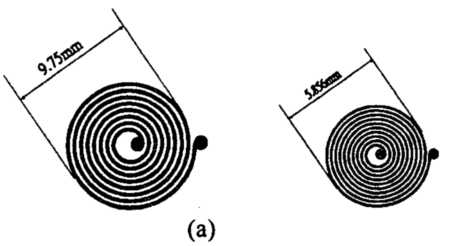


Fig. 14 Block diagram of an isolation amplifier



(a) (b)

Fig. 15 (a) Shape of T_1, (b) Shape of T_2.

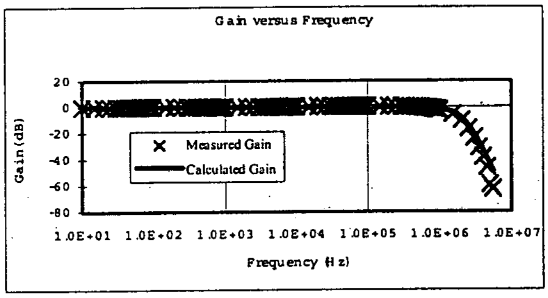


Fig.16 Gain versus Frequency of the Isolation Amplifier Prototype

Example 4 Transformers for Maximum Power Transfer

Coreless PCB transformers have been tested for power conversion applications with different rated power output from 0.5W to 94W. The transformer Tr9 (Fig.7) has been tested in a low-profile switched mode power supply with power output of 94W (Fig.17). A maximum transformer efficiency exceeding 95% (fig.18) and a maximum converter energy efficiency of about 84% have been achieved.

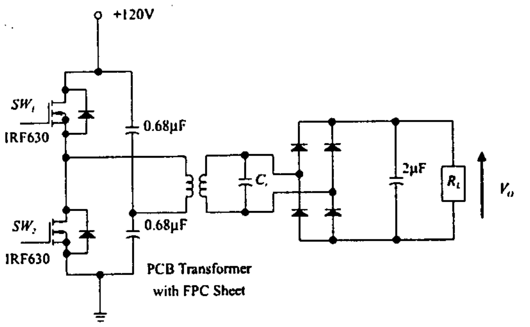


Fig.17 Circuit Schematic of the half-bridge converter

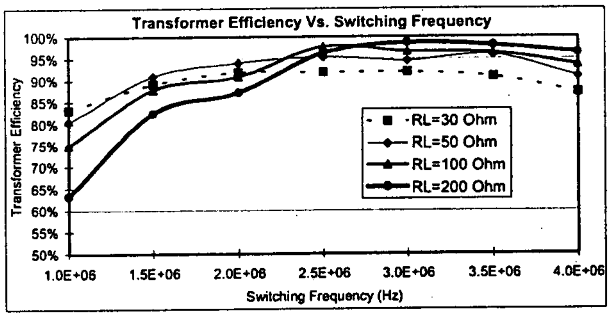


Fig.18 Measured efficiency of the PCB transformer operated in the half-bridge power converter.

6 Conclusions

In this article, the characteristics and some application examples of coreless PCB transformer have been described. Several misunderstandings of coreless PCB transformers have been clarified. Without the limitations of the magnetic cores, coreless PCB transformers offer better performance than their core-based counterparts in the high-frequency operating range. Research into coreless PCB transformers is still in its early stage. It is envisaged that coreless PCB transformers may find applications in many other areas. In particular, the advantages of coreless PCB transformers make them attractive in micro-circuits and in low-profile applications [19,20] in which stringent height requirements have to be met.

References

1. S. Hayano, Y. Nakajima, H. Saotome and Y. Saito, "A new type high frequency transformer", IEEE Transactions on Mangetics, Vol. 27, No.6, Nov. 1991, pp.5205-5207.
2. W. Roshen, "Effect of finite thickness of magnetic substrate on planar inductors", IEEE Transactions on Magnetics, Vol.26, No.1, January 1990, pp.270-275.
3. K. Yamaguchi, S. Ohnuma, T. Imagawa, J. Toriu, H. Matsuki and K. Murakami, "IEEE Transactions on Magnetics, Vol.29, No.5, September 1993, pp.2232-2237.
4. M. Mino, T. Yachi, A. Tago, K. Yanagisawa and K. Sakakibara, "A new planar microtransformer for use in micro-switching converters", IEEE Transactions on Magnetics, Vol.28, No.4, July 1992, pp.1969-1973.
5. C.H. Ahn and M.G. Allen, "Micromachined planar inductors on silicon wafers for MEMS applications", IEEE Transactions on Industrial Electronics, Vol.45, No.6, Dec. 1998, pp.866-875.
6. C.R. Sullivan and S.R. Sanders, "Design of microfabricated transformers and inductors for high-frequency power conversion", IEEE Trans. on Power Electronics, Vol.11, No.2, 1996, pp.228-238.
7. C.R. Sullivan and S.R. Sanders, "Measured performance of a high-power-density microfabricated transformer in a DC-DC converter", IEEE Technology Update Series: Power Electronics and Applications II, IEEE Press, 1997, pp.104-111
8. Balakrishnan, W. Devereux Palmer, W. Joines and T. G. Wilson, "The inductance of planar structures", IEEE Power Electronics Specialists Conference Proceedings, 1993, pp. 912-921.
9. W.G. Hurley, M.C. Duffy, S. O'Reilly and S.C. O'Mathuna, "Impedance formulas for planar magnetic structures with spiral windings", IEEE PESC proceedings, 1997, pp.627-633.
10. I. Marinova, Y. Midorrikawa, S. Hayano and Y. Saito, "Thin film transformer and its analysis by integral equation method", IEEE Trans. on Magnetics, Vol.31, No.4, July 1995, pp.2432-2437.
11. S.Y.R. Hui, S.C. Tang and H. Chung, "Coreless Printed-Circuit-Board (PCB) transformers for Signal and Energy Transfer", IEE Electronics Letters, vol.34, No.11, May 1998, pp.1052-1054.
12. S.Y.R. Hui, S.C. Tang and H. Chung "Coreless PCB-based transformers for power MOSFET/IGBT gate drive circuits", IEEE Trans. on Power Electr., Vol. 14. No.3, May 1999, pp.422-430.
13. S.C. Tang, S.Y.R. Hui and H. Chung, "Coreless printed circuit board (PCB) transformers with multiple secondary windings for complementary gate drive circuits" IEEE Trans. on Power Electronics, Vol. 14. No.3, May 1999, pp.431-437.
14. S.Y.R. Hui, S.C. Tang and H. Chung, "Optimal operation of coreless PCB transformer-isolated gate drive circuits with wide switching frequency range," IEEE Trans. on Power Electronics, Vol. 14. No.3, May 1999, pp.506-514.
15. S.C. Tang, S.Y.R. Hui and H. Chung, 'Coreless printed circuit board (PCB) transformers with high power density and high efficiency', IEE Electronics Letters, Vol.36, No.11, May 2000, pp.943-944.
16. S.Y.R. Hui, S.C. Tang and H.S.H. Chung, 'Some electromagnetic aspects of Coreless PCB transformers', IEEE Transactions on Power Electronics, Vol.15, No.4, July 2000.
17. S.Y.R. Hui and S.C. Tang, 'Coreless Printed Circuit Board Transformers', US patent pending
18. Analog Devices Manual: Isolation amplifier AD215.
19. S.Y.R. Hui and S.C. Tang, 'Planar Printed-Circuit-Board Transformers with Effective Electromagentic Interference (EMI) Shielding, US patent pending
20. S.Y.R. Hui and S.C. Tang, 'Coreless PCB Transformers and operating techniques', US and Euorepan patent pending