Coreless Planar Printed-Circuit-Board (PCB) Transformers—A Fundamental Concept for Signal and Energy Transfer

S. C. Tang, *Member, IEEE*, S. Y. (Ron) Hui, *Senior Member, IEEE*, and Henry Shu-Hung Chung, *Member, IEEE*

***Abstract*—Magnetic cores have been used in transformers for over a century. In this paper, the authors present a fundamental concept of using "coreless" printed-circuit-board (PCB) transformers. With the aid of a high-frequency equivalent circuit, the use and basic characteristics of coreless PCB transformers are described. Optimal operating conditions for minimum input power requirement and maximum efficiency operations are identified. Coreless 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. A printed planar PCB transformer with a diameter of about 1.0 cm and power capability of 19W has been successfully tested. The power density of the PCB transformer demonstrated in this paper is 24 W/cm^2. The maximum efficiency can be greater than 90%. The analysis has been confirmed with experiments. Coreless printed transformers have great potential in applications in which stringent height and space requirements have to be met.**

***Index Terms*—Coreless printed circuit board transformer, high frequency magnetics, microcircuits, passive components, power conversion.**

I. INTRODUCTION

BASED ON the Faraday's law of the electromagnetic induction, transformers have been designed and used for over a century. Transformers are commonly used for electrical isolation and energy and/or signal transfer. Normally, traditional transformers consist of copper windings manually 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 60 Hz) operations. Even when the operating frequency of many modern power electronics applications (such as switched mode power supplies) has been significantly increased to several hundreds of kilo-Hertz or recently up to a few Mega-Hertz, the core-based transformer concept remains more or less intact.

The main reasons for the continuous use of magnetic cores are primarily to provide a high degree of magnetic coupling and to reduce the leakage inductance. Transformers made of twisted coils without magnetic cores has been proposed [1] for high-frequency applications. In reference [1], it was demonstrated that the twisted-coil transformer 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 transformer in large quantity with high quality control. On another research front, 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.

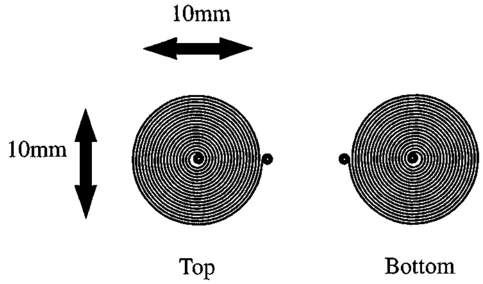

Fig. 1. Dimension of coreless PCB transformer Tr7.

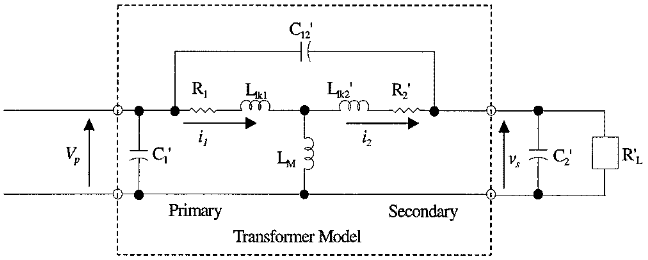

Fig. 2. High-frequency model for coreless PCB transformer.

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The authors are with the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong (e-mail: eeronhui@cityu.edu.hk).

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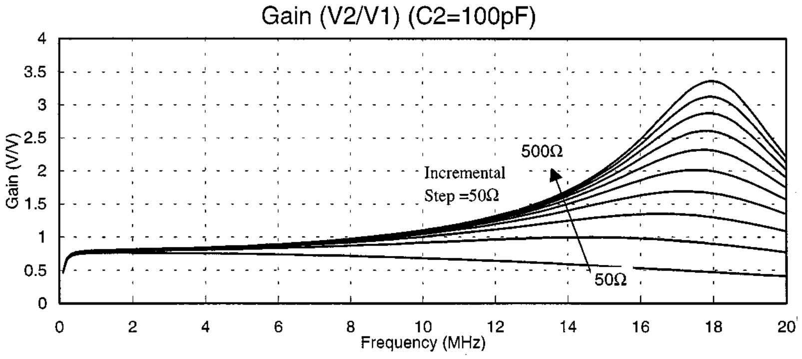

Fig. 3. Gain of transformer versus operating frequency of Tr7 with $C_2 = 100$ pF.

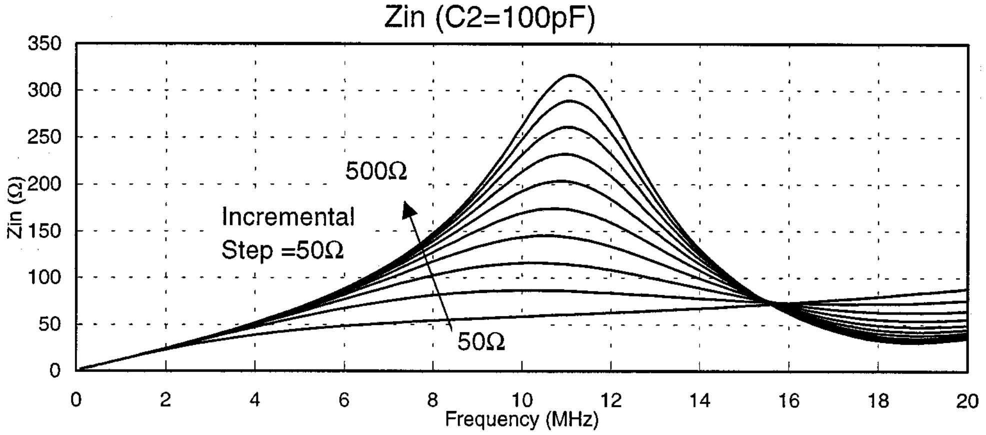

Fig. 4. Input impedance of transformer versus operating frequency of Tr7 with $C_2 = 100$pF.

In most of the literature mentioned above, the planar inductors and transformers are of low output power (typically less than 2 W). Except in [1], [10], the magnetic designs require the use of magnetic cores in one form or another. Additionally the apparent problems of coreless planar PCB transformers, namely low coupling factor and high leakage inductance, have not been solved. In this paper, we present an alternative way to design coreless transformers on doubled-sided printed-circuit-board (PCB) and demonstrate that coreless printed planar transformers can have very high power density. With the aid of a high-frequency equivalent circuit, the use and the basic characteristics 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). The practical implementation considerations of the transformers are included in the analysis. Optimal operating techniques for using coreless PCB transformers under 1) minimum input power conditions and 2) maximum energy efficiency conditions are described. The coreless PCB transformers should be operated at or near the "maximum impedance frequency" (MIF) in order to reduce input power requirement. For maximum energy efficiency, the transformers should be operated at or near the "maximum efficiency frequency" (MEF) which is below the MIF. The operating principle has been confirmed with measurement and simulation. The proposed operating technique [14] can be applied to coreless PCB transformers in many circuits that have to meet stringent height requirements. The proposed transformers [13] have the potential to be developed in microcircuits. A printed planar PCB transformer with a diameter of about 1.0 cm and power capability of 19 W is demonstrated. The power density of the PCB transformer demonstrated in this paper is about 24 W/cm2 (or 600 W/cm^3 if the surrounding air is not included). The maximum efficiency is over 90%. The analysis has been confirmed with experiments.

II. STRUCTURE, MODELING AND ANALYSIS OF CORELESS PCB TRANSFORMERS

Some initial results of using coreless PCB transformers for signal and energy transfer have been reported by the authors in [11]–[14]. In these reports, it has been successfully demonstrated that the coreless PCB transformers can be used for both energy and signal transfer for industrial applications such as gate drive circuits for power mosfets and insulated gate bipolar transistors (IGBT). The applications of these applications reported so far are less than 2 W. In this section, the structure and the modeling of a coreless PCB transformer (named Tr7) that has a

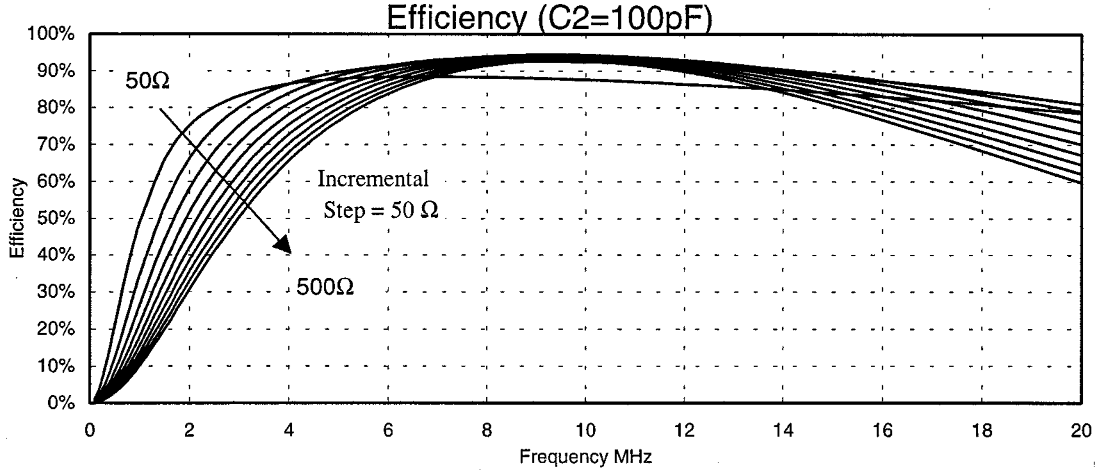

Fig. 5. Energy efficiency of transformer versus operating frequency of Tr7 with $C_2 = 100$ pF.

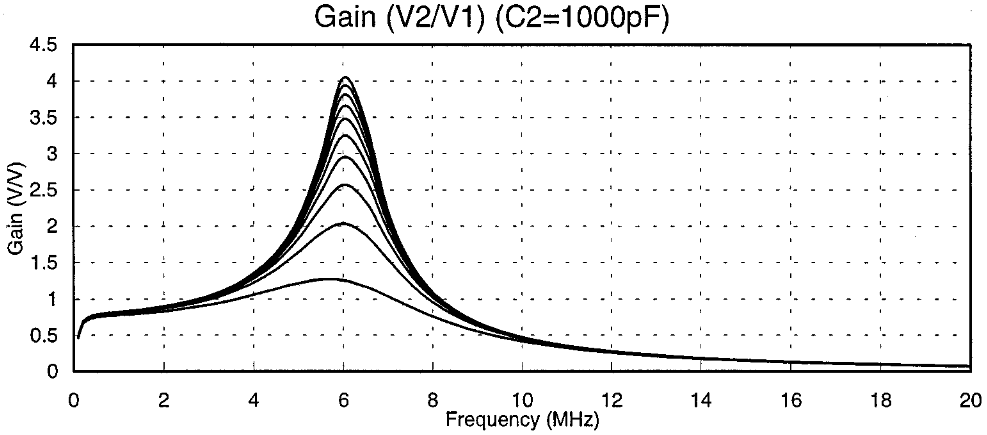

Fig. 6. Gain of transformer versus operating frequency of Tr7 with $C_2 = 1000$ pF.

power density of at least 24 W/cm^2 are described. An analysis of the coreless transformer with emphasis on its applications will be presented.

The dimension of the coreless transformer Tr7 is shown in Fig. 1. The diameter of the printed windings is about 1.0 cm. The thickness of the PCB is 0.4 mm. Both the primary and secondary windings have 19 turns and they are printed directly on the opposite sides of a double-sided PCB. A high-frequency transformer model as shown in Fig. 2 can be used to describe the coreless PCB transformer, where

R_1	primary winding resistance;
R'_2	secondary winding resistance referred to the primary;
R_L	resistive load;
L_{lk1}	primary leakage inductance;
L'_{lk2}	secondary leakage inductance referred to the primary;
L_M	mutual inductance;
C_{12}	capacitance between primary and secondary windings;
C_1	primary winding capacitance;
C'_2	sum of the secondary winding capacitance and an externally connected capacitance referred to the primary;
R'_L	load resistance referred to the primary;
n	turn ratio.

As explained in [11]–[14], the external capacitance C_2 plays an instrumental role in determining the resonant frequency of the transformer. For coreless PCB transformer with primary and secondary windings printed directly on the opposite sides of a doubled-sided PCB, the intrawinding capacitance is negligible (typically in the order of a few pico-Farads). Thus, the intrawinding capacitance of the secondary winding can be ignored in the high frequency model because it is much smaller than the externally added capacitance C_2. The parameters of Tr7 are $L_{lk1} = 0.355\,95$ μH; $L_{lk2} = 0.355\,95$ μH; $L_M = 1.4936$ μH. For small coreless PCB transformer with a small diameter (as in Tr7), C_{12} is typically a few pico-Farads and can thus be ignored in the analysis. However, for the sake of generosity, C_{12} is included in the following vigorous analysis. The approximate

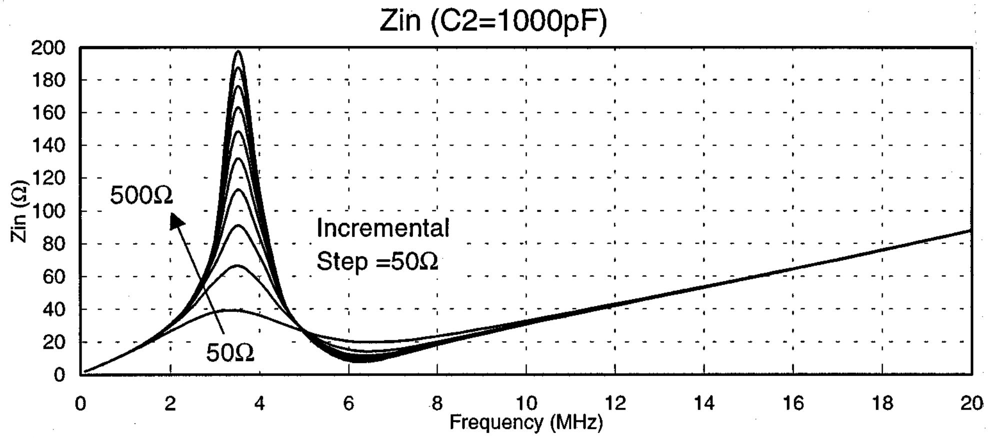

Fig. 7. Input impedance of transformer versus operating frequency of Tr7 with $C_2 = 1000$ pF.

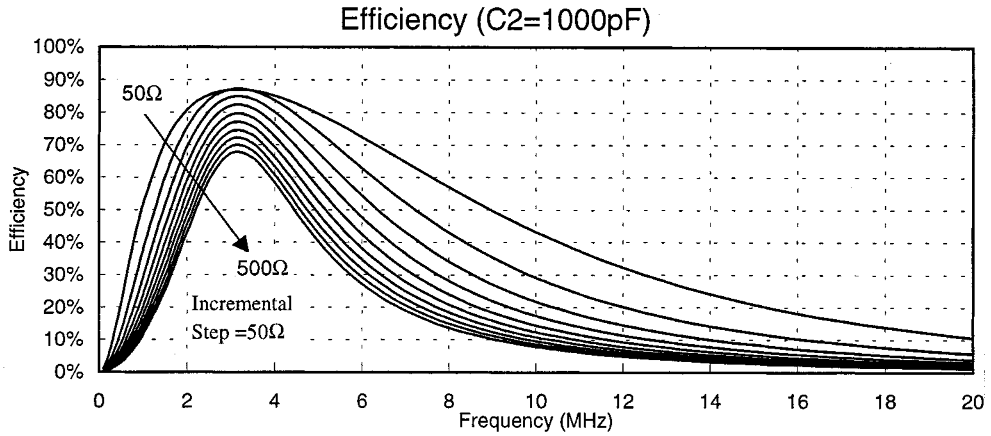

Fig. 8. Energy efficiency of transformer versus operating frequency of Tr7 with $C_2 = 1000$ pF.

no-load resonant frequency of the transformer circuit (Fig. 2) is given [9] by

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

where $L_{eq} = L'_{lk2} + L_{lk1}||L_M$ and $C_{eq} = C'_2 + C'_{12}$. (Here C'_2 includes the load capacitance.) It should be noted that the choice of C_2 is a flexible means to design the optimal operating conditions of the coreless PCB transformers.

A. Energy Efficiency η

Since no magnetic core is involved, there is no magnetic core loss. Power dissipation of the transformer due to the conductor loss is

$$P_{Loss} = |i_1|^2 R_1 + |i_2|^2 R_2 \tag{2}$$

where R_1 and R_2 are the a.c. winding resistances of the primary and secondary windings, respectively. They are functions of the operating frequency due to skin effect. Currents i_1 and i_2 are the primary and secondary winding currents, respectively. The measured relationships of the resistances as functions of frequency are

$$R_1(f) = -1.65 \times 10^{-15} f^2 + 1.04 \times 10^{-7} f + 1.59 \tag{3a}$$

$$R_2(f) = -1.65 \times 10^{-15} f^2 + 1.04 \times 10^{-7} f + 1.59 \tag{3b}$$

where f is the operating frequency.

Input power to the transformer

$$P_{\text{in}} = |V_p|^2 \cdot RE\left\{\frac{1}{Z_{\text{in}}}\right\} \tag{4}$$

where V_p is the primary voltage of the transformer and Z_{in} is the input impedance of the transformer. Output power delivered from the transformer

$$\begin{aligned} P_{\text{out}} &= \frac{|V_s|^2}{R_L} \\ &= \frac{|G(s) \cdot V_p|^2}{R_L} \\ &= \frac{|G(s)|^2 \cdot |V_p|^2}{R_L} \end{aligned} \tag{5}$$

where V_s is the secondary voltage of the transformer, $G(s)$ is the voltage gain, V_s/V_p, of the transformer in s-domain.

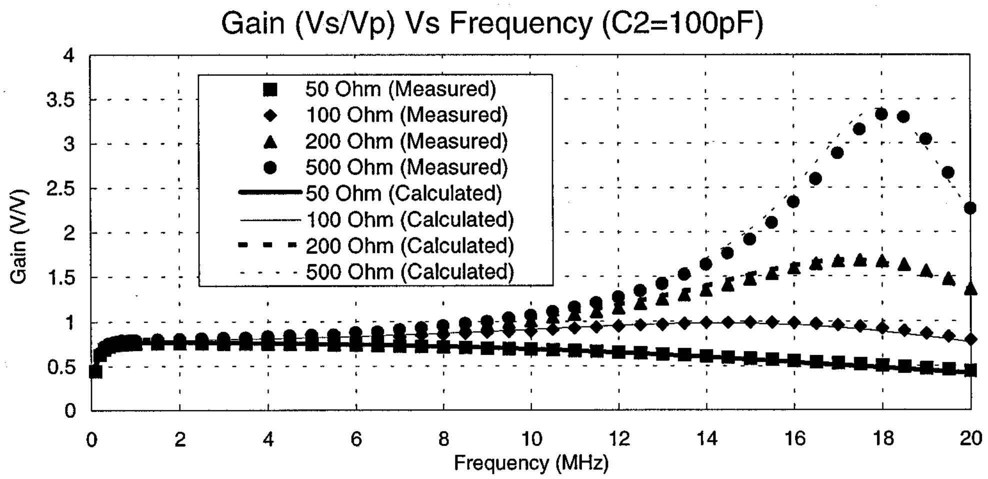

Fig. 9. Measured and predicted voltage gain of Tr7 with $C_2 = 100$ pF.

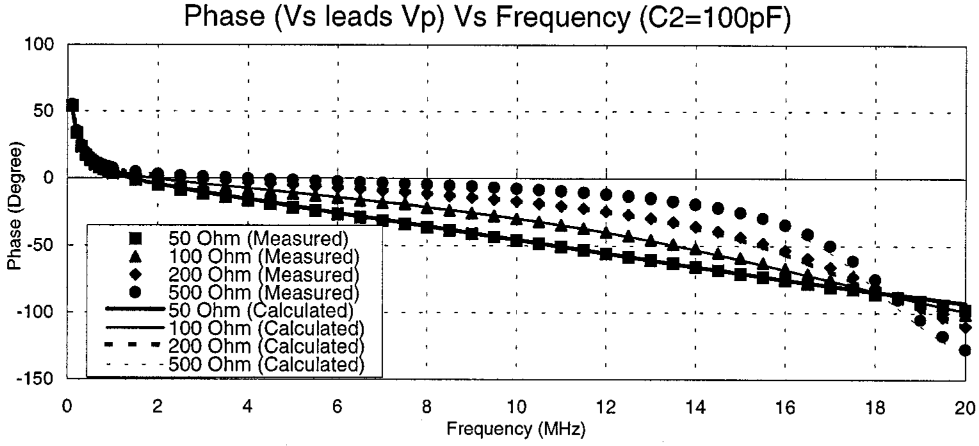

Fig. 10. Measured and predicted phase angle of Tr7 with $C_2 = 100$ pF.

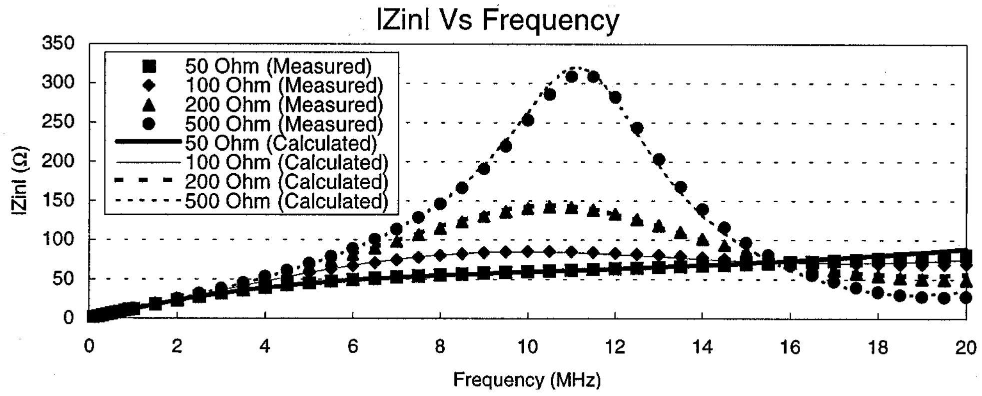

Fig. 11. Measured and predicted input impedance of Tr7 with $C_2 = 100$ pF.

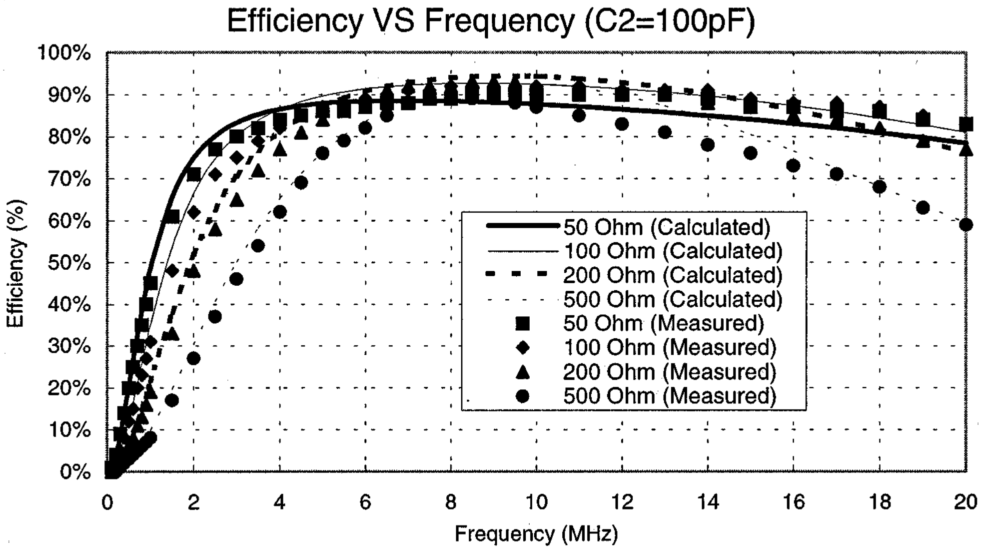

Fig. 12. Measured and predicted energy efficiency of Tr7 with $C_2 = 100$ pF.

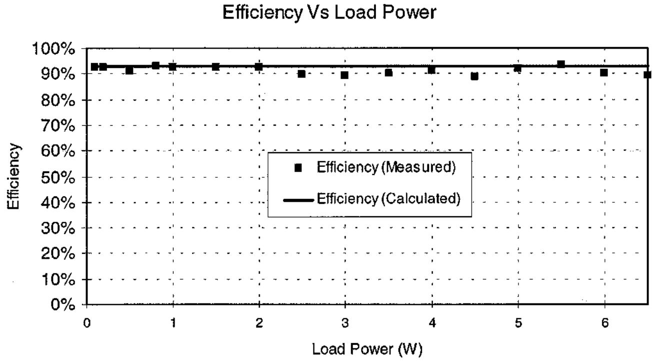

Fig. 13. Measured and predicted energy efficiency of Tr7 with $C_2 = 100$ pF and operating frequency = 8.4 MHz.

Energy efficiency of the transformer is

$$\begin{aligned}\eta &= \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% \\ &= \frac{\dfrac{|G(s)|^2 \cdot |V_p|^2}{R_L}}{|V_p|^2 \cdot RE\left\{\dfrac{1}{Z_{\text{in}}}\right\}} \times 100\% \\ &= \frac{|G(s)|^2}{R_L \cdot RE\left\{\dfrac{1}{Z_{\text{in}}}\right\}} \times 100\% \end{aligned} \tag{6}$$

where the expression of Z_{in} can be found later in (8).

B. Voltage Gain and Input Impedance

Based on the high-frequency model, the voltage gain (V_s/V_p) and the input impedance (Z_{in} referred to the primary side) of the coreless transformer can be expressed as follows:

$$\frac{V_s}{V_p} = B = \frac{\dfrac{1}{X_1} + sC'_{12}Y_1}{nY} \tag{7}$$

and

$$Z_{\text{in}} = \frac{1}{sC'_{12}(1-nB) + \dfrac{(1-A)}{X_1} + sC'_1} \tag{8}$$

where

$$\begin{aligned} R'_2 &= n^2 R_2 \\ L'_{lk2} &= n^2 L_{lk2} \\ C'_1 &= C_1 + \frac{n-1}{n} C_{12} \\ C'_2 &= \frac{1}{n^2} C_2 + \frac{1-n}{n^2} C_{12} \\ C'_{12} &= \frac{1}{n} C_{12} \\ X_1 &= R_1 + sL_{lk1} \\ X_2 &= R'_2 + sL'_{lk2} \\ Y_1 &= X_2 \left[\frac{1}{X_1} + \frac{1}{sL_{M1}}\right] + 1 \\ Y_2 &= \frac{1}{X_2} + sC'_{12} + sC'_2 + \frac{1}{n^2 R_L} \\ Y &= -\frac{1}{X_2} + Y_1 Y_2 \\ A &= \frac{sC'_{12} + \dfrac{X_2}{X_1} Y_2}{Y}. \end{aligned}$$

III. CHARACTERISTICS OF CORELESS PCB TRANSFORMERS

Based on the transformer model and the equations derived in Section II, the characteristics of the coreless PCB transformers are investigated. The use of capacitor C_2 is to increase the gain (V_s/V_p), input impedance (Z_{in}), and the transformer efficiency (η). The choice of C_2 can also determine the resonant frequency of the transformer circuit. In this analysis, the transformer Tr7

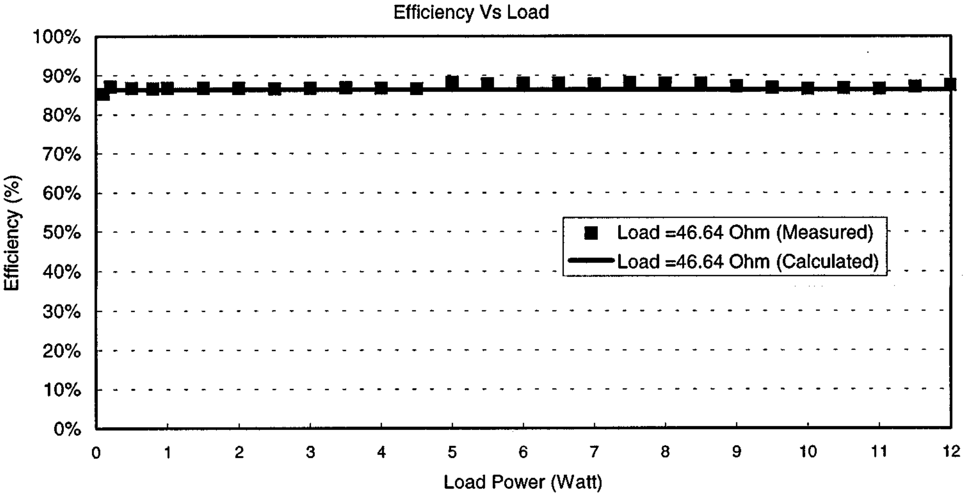

Fig. 14. Measured and predicted energy efficiency of Tr7 with $C_2 = 100$ pF and operating frequency = 11 MHz.

is studied with two different external capacitors of 100 pF and 1000 pF.

A. Maximum Impedance Frequency (MIF)

When an 100 pF capacitor C_2 is connected in parallel with the secondary winding of the transformer, the gain (V_s/V_p), input impedance ($Z_{\rm in}$), and the efficiency (η), of the transformer versus operating frequency are plotted in Figs. 3–5, respectively. The load resistance (R_L) varies from 50–500 Ω with 50 Ω incremental step. With $C_2 = 100$ pF, the approximate no-load resonant frequency f_o is about 19 MHz. Fig. 3 shows that the resonant frequency of Tr7 approaches this value when the load resistance is increased. Fig. 4 indicates that the maximum impedance frequency (MIF) occurs at around 11 MHz.

This MIF is an important characteristic in the operating of the coreless PCB transformer. It is important to note the following.

1) The input impedance $Z_{\rm in}$ is at its' maximum at this MIF.
2) For Tr7, the input impedance can be well about 50 Ω for a wide range of operating frequency (say from 6–16 MHz). This indicates that the coreless transformer, despite its short conducting tracks, can have high input impedance. This feature clears the misunderstanding that the short printed tracks are always like short-circuit paths.
3) The voltage gain can be greater than 1.0 at MIF due to the partial resonant effect of the leakage inductance and the external capacitor C_{12}. This dispels the misconception that coreless PCB transformer has low voltage gain due to low coupling factor. It also indicates that the traditional "undesirable" leakage inductance can be made desirable with the proposed resonant technique.
4) Therefore, the MIF is a suitable operating frequency if minimum input power is required (such as in isolated gate drive circuits for power mosfets and IGBT's or in signal transfer applications where minimum power requirement is preferred).

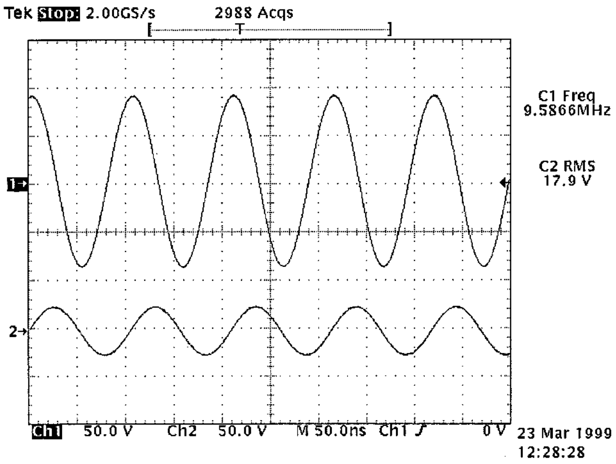

Fig. 15. Measured waveforms of the primary voltage (upper trace: 50 V/div.) and secondary voltage (lower trace: 50 V/div) when the secondary is loaded with an external capacitor of 100 pF and a resistor of 17 Ω. (Output power is about 19 W.)

B. Maximum Efficiency Frequency (MEF)

The efficiency curves for various load resistances are plotted in Fig. 5. It can be seen that the maximum efficiency frequency (MEF) is slightly less than the MIF (around 9–10 MHz). In fact, the transformer can be operated with the frequency range of 8–11 MHz in order to achieve high efficiency (say >90%). The MEF is another important characteristic of coreless PCB transformers. It is important to note the following.

1) When the load resistance is very large, i.e., load power is very low, the load current and i_2 are very small that the power dissipation of the transformer is dominated by i^2R loss component due to the current i_1. On the other hand, increasing the transformer input impedance reduces the primary winding current, i_1. Thus, the MEF tends to approach the MIF as the load current decreases. For example, power consumption of MOSFET/IGBT gate drive

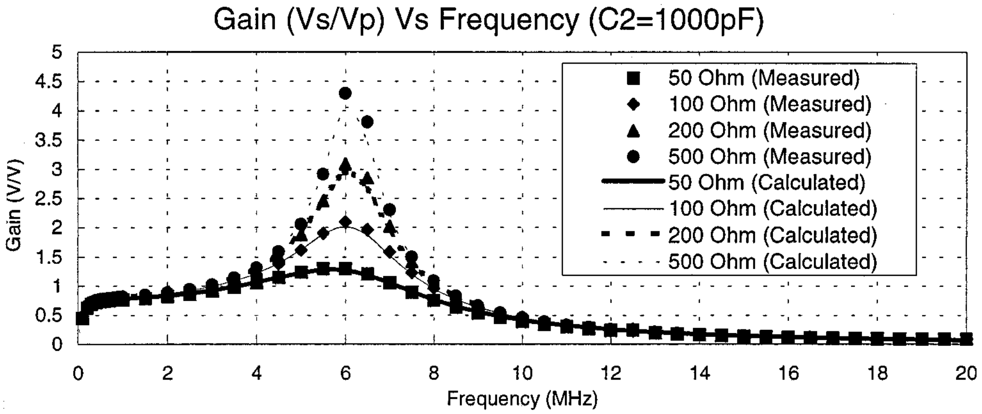

Fig. 16. Measured and predicted voltage gain of Tr7 with $C_2 = 1000$ pF.

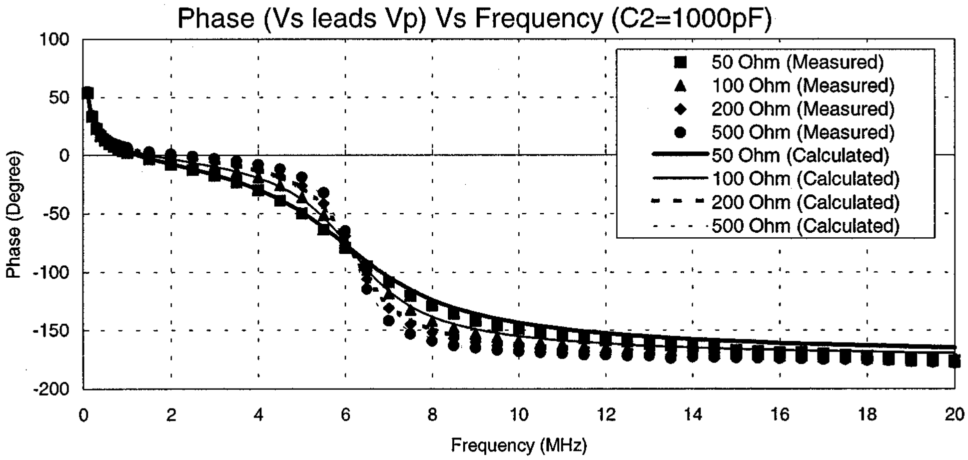

Fig. 17. Measured and predicted phase angle of Tr7 with $C_2 = 1000$ pF.

circuits is small enough that the MEF is regarded as the MIF [11]–[14].

2) When the load resistance decreases, i.e. load power increases, (2) shows that the increasing secondary winding current, i_2, will increase the transformer i^2R loss. From (3), the winding resistance increases as operating frequency increases. As a result, operating the transformer in relatively low frequency can reduce the power loss of the transformer when i_2 is significant. As shown in Fig. 5, the MEF is below the MIF. MEF decreases when the load resistance decreases (i.e. the load power increases).
3) For power conversion applications such as switched mode power supplies, the MEF or the frequency range around MEF can be chosen as the suitable operating frequencies in order to achieve high energy efficiency.
4) Generally, the overall efficiency of a power converter is affected by the power loss in the driving circuit of the transformer (i.e. the electronic circuit on the primary side of the transformer). In order to reduce the overall power loss, one may like to choose a lower operating frequency. The operating frequency can flexibly be determined by choosing the appropriate C_2 according to (1).

In order to highlight the flexible choice of the operating frequency, the transformer Tr7 is also studied with a larger capacitance C_2. As the C_2 increases, the voltage gain, resonance frequency, MIF and the MEF decrease. An example with $C_2 = 1000$ pF is used to illustrate these phenomena. Figs. 6–8 show the frequency response of the gain (V_s/V_p), input impedance (Z_{in}) and the efficiency (η) of the transformer Tr7, respectively. The calculated approximate no-load resonant frequency is at about 6.2 MHz. Fig. 6 shows that the loaded resonant frequency approaches this value when the load resistance increases. The MIF is about 3.8 MHz and the MEF is about 3.2 MHz. Thus, the coreless PCB transformer, when used in a power converter, should be operated at or near the MEF (which is lower than the MIF) in order to achieve high energy efficiency. Comparing the characteristics of the transformer with 100 pF and 1000 pF shows that the spread of the resonant frequencies, the MIF and MEF become smaller when C_2 becomes larger. The reason is that, as C_2 increases, the impedance of C_2 at high frequency become much smaller. The load resistance becomes relatively high when compared with the impedance of C_2, and thus the resonant frequency approaches the no-load resonant frequency.

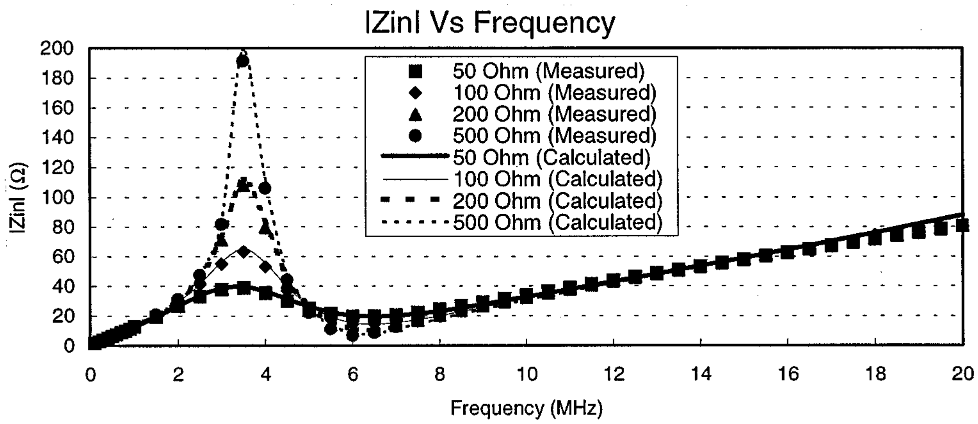

Fig. 18. Measured and predicted input impedance of Tr7 with $C_2 = 1000$ pF.

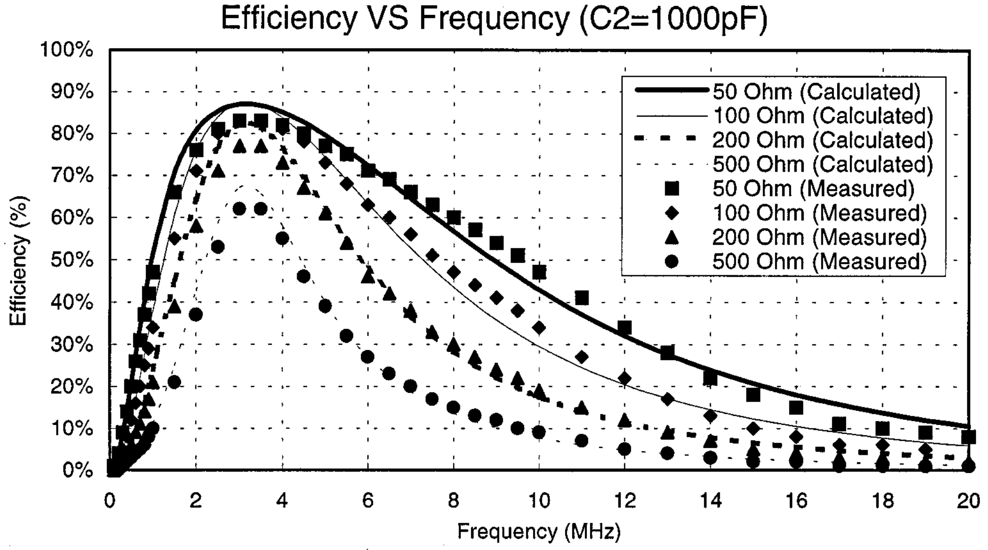

Fig. 19. Measured and predicted energy efficiency of Tr7 with $C_2 = 1000$ pF.

IV. EXPERIMENTAL VERIFICATION

The transformer Tr7 has been tested experimentally. An Amplifier Research 25A100 Radio-Frequency power amplifier was used as the variable frequency voltage supply to feed the primary winding of Tr7. The power amplifier has a frequency range from 10 kHz to 100 MHz and a nominal maximum power capability of 25 W. The secondary winding was loaded with a capacitor C_2 and a resistor R_L. The amplitude of the sinusoidal input voltage was increased just before the sinusoidal voltage was distorted.

A. $C_2 = 100$ pF

With $C_2 = 100$ pF, the maximum output power of Tr7 under test was up to about 12 W before the sinusoidal input voltage from the 25A100 Radio-Frequency power amplifier became distorted. However, this is the limitation of the power amplifier used in the test and 12 W is not necessarily the maximum power capability of Tr7.

Fig. 9 shows the measured and predicted voltage gain versus operating frequency of Tr7 with $C_2 = 100$ pF. The measured and predicted phase versus operating frequency is displayed in Fig. 10. It can be seen that the analysis of the coreless PCB transformer is essentially correct and that the high frequency transformer model is very accurate. As predicted, the MEF is about 11 MHz as shown in Fig. 11. The predicted high-efficiency frequency range is experimentally confirmed and included in Fig. 12. Because the MEF of Tr7 is at about 8.4 MHz when $C_2 = 100$ pF. A test was carried out to set the operating frequency at 8.4 MHz for a range of resistive loads. Fig. 13 shows the predicted and measured energy efficiency for the output power up to about 6.5 W. These results confirm that efficiency over 90% (maximum at about 93%) can be achieved in Tr7. As the analysis indicates that high efficiency can be achieved over a range of frequency. Another test was carried out on Tr7 with the operating frequency set at about 11 MHz. Fig. 14 shows the measured and predicted efficiency under this operating frequency. The output power was increased up about 12 W before the distortion of the input sinusoidal voltage became serious in the power amplifier.

In order to check the maximum power of Tr7, an Amplifier Research 25A1000 Radio-Frequency power amplifier (with bandwidth from 1–1000 MHz) was used to power the transformer. The measured waveforms of the primary and secondary voltage and the primary current when the output power is 19 W and the resistive load is 17 Ω are shown in Fig. 15. For the dimension of Tr7, the power density of the transformer is about 24 W/cm^2 or 600 W/cm^3 if the surrounding air is excluded.

B. $C_2 = 1000\ pF$

With C_2 changed to 1000 pF, similar tests have been carried out on Tr7. Figs. 16 and 17 show the frequency response of Tr7. The loaded resonant frequency is about 6 MHz which is very close to the calculated approximate no-load resonant frequency of 6.2 MHz. This resonant frequency confirmed an important point that the operating frequency of coreless PCB transformers can be determined and controlled easily with the choice of appropriate value of C_2. The MIF is now changed to about 3.8 MHz as predicted and shown in Fig. 18. The MEF is around 3 MHz as included in Fig. 19. These experimental results confirm the accuracy of the analysis and the transformer model, and the desirable features of coreless printed transformers at high frequency operation.

V. CONCLUSION

In this paper, a fundamental concept of using coreless printed transformers suitable for both signal and/or energy transfer is described. Several misconceptions about using transformers without magnetic cores are clarified. A general analysis of coreless printed planar transformers is presented. With the emphasis on its practicality, the coreless transformers basic characteristics are described. Using a resonant technique, it has been demonstrated that the transformer's leakage inductance can form a resonant circuit with a small external capacitor C_2. Consequently, desirable features such as easy choice of operating frequency, high voltage gain (>1), high input impedance at MIF, high energy efficiency at MEF can flexibly be achieved. The transformer has been tested with an output power of at least 19 W and a power density of 24 W/cm^2 (or 600 W/cm^3). A maximum efficiency greater than 90% can be achieved. In principle, coreless printed transformers can be fabricated in microelectronic circuits. Coreless printed transformers have the potential in many low power (say <100 W) applications in which stringent height and space requirements have to be met.

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S. C. Tang (M'98) was born in Hong Kong in 1972. He received the B.Eng. degree in electronic engineering (with first class honors) from the City University of Hong Kong, Kowloon, Hong Kong, in 1997 where he is currently pursuing the Ph.D. degree.

His research interests include coreless PCB transformers, high-frequency magnetics, MOSFET/IGBT gate drive circuits, and switched-capacitor converters.

Mr. Tang received the Li Po Chun Scholarships and Intertek Testing Services (ITS) Scholarships in 1996 and 1997, respectively. In 1997, he received the First Prize Award from the IEEE HK Section Student Paper Contest'97 and was the second winner in the Hong Kong Institution of Engineers (HKIE) 50th Anniversary Electronics Engineering Project Competition. He received the Certificates of Merit in the IEEE Paper Contests (Hong Kong Section) in 1998 and 1999, respectively.

S. Y. (Ron) Hui (SM'94) was born in Hong Kong in 1961. He received the B.Sc. degree (with honors) from the University of Birmingham, Birmingham, U.K., in 1984, and the D.I.C. and Ph.D. degrees from the Imperial College of Science, Technology and Medicine, London, U.K., in 1987.

He was a Lecturer in power electronics at the University of Nottingham, U.K., from 1987 to 1990. In 1990, he went to Australia and took up a lectureship at the University of Technology, Sydney, where he became a Senior Lecturer in 1991. Later, he joined the University of Sydney and was promoted to Reader of Electrical Engineering and Director of Power Electronics and Drives Research Group in 1996. Presently, he is a Chair Professor of Electronic Engineering and Associate Dean of the Faculty of Science and Engineering at the City University of Hong Kong. He has published over 150 technical papers, including about 80 refereed journal publications. His research interests include all aspects of power electronics.

Dr. Hui received the Teaching Excellence Award from the City University of Hong Kong in 1999. He is a Fellow of the IEE, the IEAust, and the HKIE. He has been an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS since 1997.

Henry Shu-Hung Chung (S'92–M'95) received the B.Eng. degree (with first class honors) in electrical engineering and the Ph.D. degree from The Hong Kong Polytechnic University, Kowloon, in 1991 and 1994, respectively.

Since 1995, he has been with the City University of Hong Kong. He is currently an Associate Professor in the Department of Electronic Engineering. His research interests include time- and frequency-domain analysis of power electronics circuits, switched-capacitor-based converters, random-switching techniques, digital audio amplifiers, fuzzy-logic control, and soft-switching converters. He has authored two research book chapters and over 110 technical papers including over 50 refereed journal publications. He is currently an Associate Editor of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—PART I.

Dr. Chung received the China Light and Power Prize and the Scholarship and Fellowship of the Sir Edward Youde Memorial Fund in 1991 and 1993, respectively. He is currently Chairman of the Council of the Sir Edward Youde Scholar's Association and IEEE student branch counselor. He was Track Chair of the Technical Committee on Power Electronics Circuits and Power Systems, IEEE Circuits and Systems Society, from 1997 from 1998.