Evaluation of the Shielding Effects on Printed-Circuit-Board Transformers Using Ferrite Plates and Copper Sheets

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

***Abstract*—This paper presents an effective shielding technique and a simple structure for printed-circuit-board (PCB) transformers. Performance of PCB transformers using the proposed shielding technique is evaluated using thin ferrite plates and copper sheets. Without affecting the transformer energy efficiency, the shielding method under investigation can achieve 28 dB shielding effectiveness (SE), which is much higher than the SE (about 4 dB) obtained by shielding the transformer windings with only two ferrite plates. The proposed PCB transformer structure is very simple and has high energy efficiency (>90%) for Megahertz operation.**

***Index Terms*—EMC, printed-circuit-board transformers, shielding techniques.**

I. Introduction

PLANAR magnetic components are attractive in portable electronic equipment applications such as the power supplies and distributed power modules for notebook and handheld computers. As the switching frequency of power converter increases, the size of magnetic core can be reduced. When the switching frequency is high enough (e.g., a few Megahertz), the magnetic core can be eliminated. Low-cost coreless PCB transformers for signal and low-power (a few Watts) applications have been proposed [1]. It has been proved that the use of coreless PCB transformer in signal and low-power applications does not cause serious EMC problem [2]. In power transfer applications, the PCB transformers have to be shielded to comply with EMC regulations. Investigations of planar transformer shielded with ferrite sheets have been reported [3], [4]. From [4], the energy efficiency of PCB transformer shielded with ferrite sheets can be higher than 90% in Megahertz operating frequency range.

This paper describes a simple and effective technique of magnetic field shielding for PCB transformers. PCB transformers shielded with ferrite plates and copper sheets have been investigated. Performance, such as shielding effectiveness and energy efficiency, of PCB transformers with different kinds of shielding techniques is illustrated. The patent-pending shielding method proposed here is found to have very high shielding effectiveness.

Manuscript received September 23, 2001; revised May 28, 2002. This work was supported by the City University of Hong Kong, the Hong Kong Research Grant Council (CERG CityU1138/99E), and Philips Research Laboratory, Aachen. Recommended by Associate Editor K. Ngo.

The authors are with the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong.

Digital Object Identifier 10.1109/TPEL.2002.805585

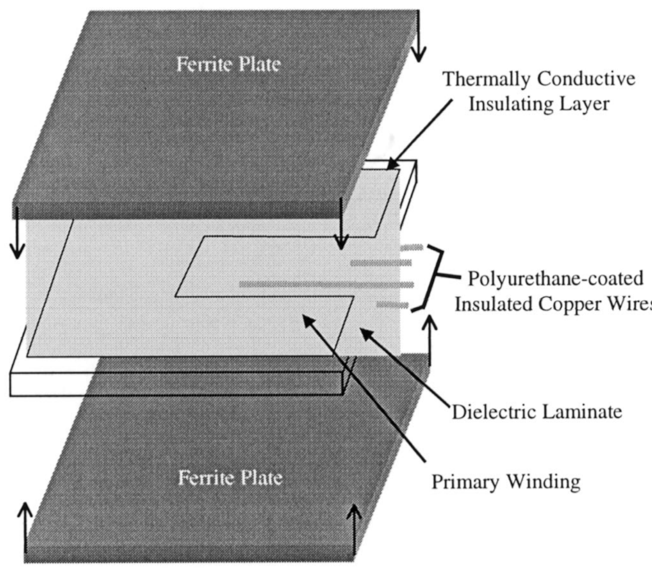

Fig. 1. Three-dimensional structure of a PCB transformer shielded with ferrite plates.

II. Structures of the PCB Transformers

The three-dimensional (3-D) and cross-sectional structures of a PCB transformer shielded with ferrite plates are illustrated in Figs. 1 and 2, respectively. The dimensions of the PCB transformer under test are detailed in Table I. The primary and secondary windings are printed on the opposite sides of a PCB. The PCB laminate is made of FR4 material. The dielectric breakdown voltage of typical FR4 laminates range from 15 kV to 40 kV [5]. Insulating layers between the copper windings and the ferrite plates should have high thermal conductivity in order to facilitate heat transfer from the transformer windings to the ferrite plates and the ambient. The insulating layer should also be a good electrical insulator to isolate the ferrite plates from the printed transformer windings. A thermally conductive silicone rubber compound coated onto a layer of woven glass fiber, which has breakdown voltage of 4.5 kV and thermal conductivity of 0.79 $\mathrm{Wm^{-1}K^{-1}}$ [6], is adopted to provide high dielectric strength and facilitate heat transfer. The ferrite plates placed on the insulating layers are made of 4F1 material from Philips [7]. The relative permeability, μ_r, and resistivity, ρ, of the 4F1 ferrite material are about 80 and 10^5 Ωm, respectively.

The shielded transformer shown in Figs. 1 and 2 can be modified to improve the magnetic field shielding effectiveness by

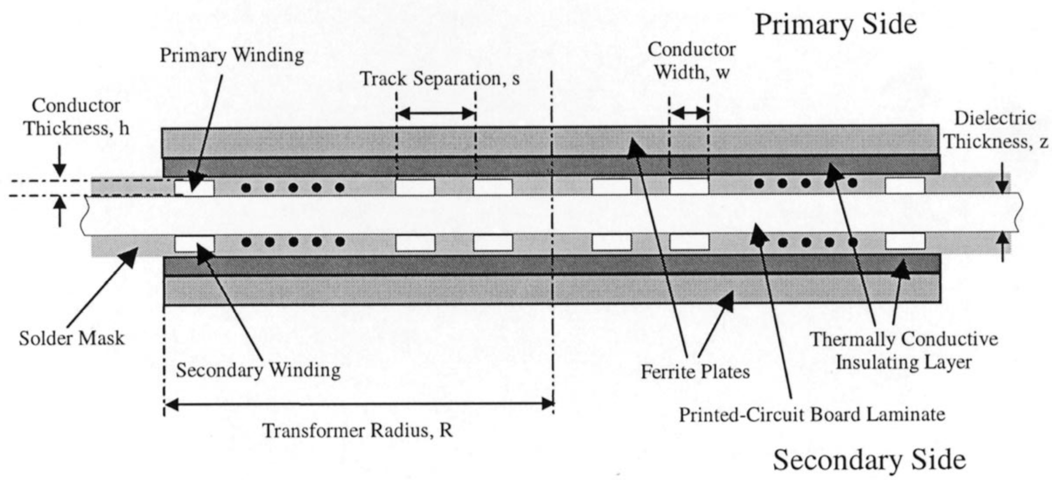

Fig. 2. Cross-sectional structure of a PCB transformer shielded with ferrite plates.

TABLE I
GEOMETRIC PARAMETERS OF THE PCB TRANSFORMER

Geometric Parameter	Dimension
Copper Track Width	0.25mm
Copper Track Separation	1mm
Copper Track Thickness	70µm (2 Oz/ft^2)
Number of Primary Turns	10
Number of Secondary Turns	10
Dimensions of Ferrite Plates	25mm × 25mm 0.4mm
PCB Laminate Thickness	0.4mm
Insulating Layer Thickness	0.228mm
Transformer Radius	23.5mm

coating a layer of copper sheet on the surface of each ferrite plate as shown in Fig. 3. The modified transformer and the ferrite-shielded transformer are of the same dimensions as shown in Table I. The area and thickness of the copper sheets are 25 mm $\times$ 25 mm and 70 μm, respectively.

III. Magnetic Field Analysis of PCB Transformer With Various Kinds of Shielding Techniques

The magnetic field intensity generated from the shielded PCB transformers is simulated with a 2-D field simulator [8] using finite-element-method (FEM). Cylindrical coordinates system is chosen in the magnetic field simulation. The structure in R–Z plane, of the PCB transformer shown in Fig. 4 is applied in the field simulator. The z-axis is the axis of symmetry, which passes through the center of the transformer windings. In the 2-D simulation, the spiral circular copper tracks are approximated as concentric circular track connected in series [9]. Besides, the ferrite plates and the insulating layers adopted in the simulation model are in circular shape, instead of in square shape in the transformer prototype.

A. Transformer Shielded With Ferrite Plates

The use of the ferrite plates helps to confine the magnetic field generated from the transformer windings. The high relative permeability, μ_r, of the ferrite material guides the magnetic field along and inside the ferrite plates. In the transformer prototype, 4F1 ferrite material is used. The relative permeability of the 4F1 material is about 80.

Based on the Maxwell equation that the net magnetic flux density flowing out of a closed surface is zero

$$\oint_S \vec{B} \cdot d\vec{S} = 0 \tag{1}$$

the normal component of the magnetic flux density is continuous across the boundary between the ferrite plate and free space. Thus, at the boundary

$$B_{1n} = B_{2n} \tag{2}$$

where B_{1n} and B_{2n} are the normal component (in z-direction) of the magnetic flux density in the ferrite plate and free space, respectively.

From (2)

$$\mu_r \mu_0 H_{1n} = \mu_0 H_{2n} \Rightarrow H_{2n} = \mu_r H_{1n}. \tag{3}$$

From (3), at the boundary between the ferrite plate and free space, the normal component of the magnetic field intensity in free space can be much higher than that in the ferrite plate when the relative permeability of the ferrite material is very high. Therefore, when the normal component of the H-field inside the ferrite plate is not sufficiently suppressed (e.g., when the ferrite plate is not thick enough), the H-field emitted from the surface of the ferrite plates can be enormous. Fig. 5 shows the magnetic field intensity vector plot of the transformer shielded with ferrite plates. The primary is excited with a 3 MHz 3 A current source and the secondary is left open. The size of the arrows indicates the magnitude of the magnetic field intensity in dB A/m. Fig. 5 shows that the normal component of the H-field inside the ferrite plate is not suppressed adequately and so the H-field emitted from the ferrite plate to the free space is very high.

The tangential (H_r) and normal (H_z) components of magnetic field intensity near the boundary between the ferrite plate and free space, at $R = 1$ mm, are plotted in Fig. 6. The tangential H-field (H_r) is about 23.2 dB and is continuous at the boundary. The normal component of the H-field (H_z) in free space is about 31.5 dB and that inside the ferrite plate is about

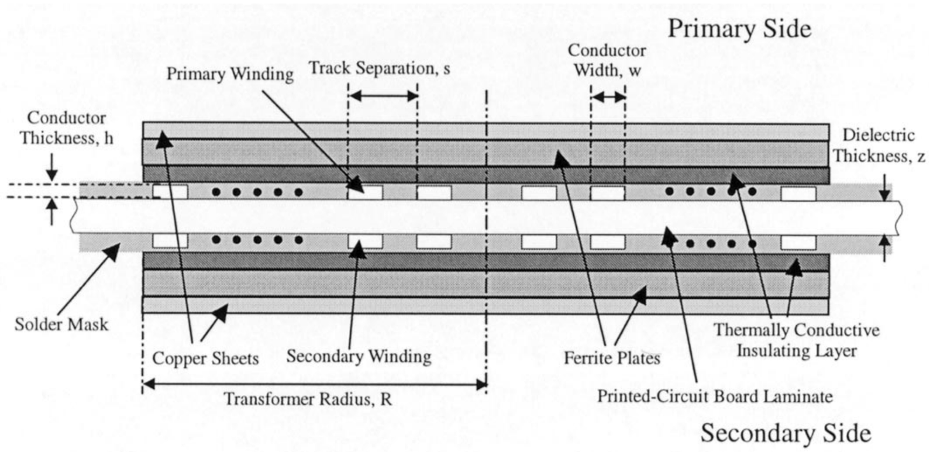

Fig. 3. Proposed cross-sectional structure of a PCB transformer shielded with ferrite plates and copper sheets.

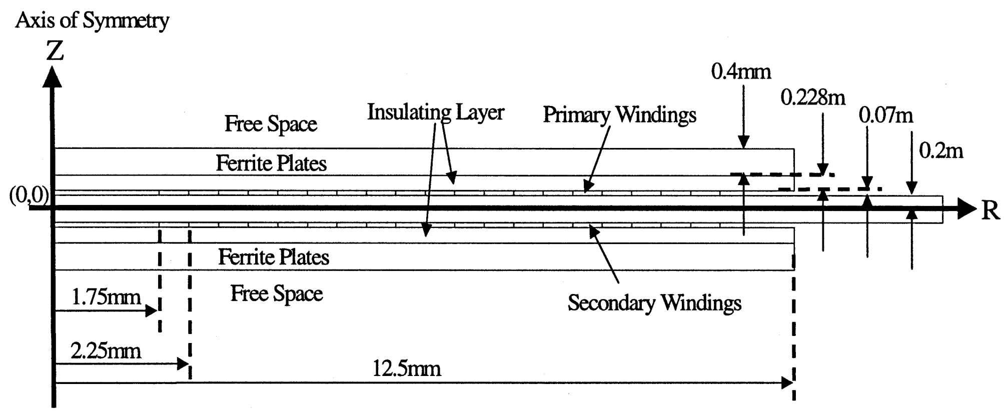

Fig. 4 R–Z plane of the PCB transformer shielded with ferrite plates.

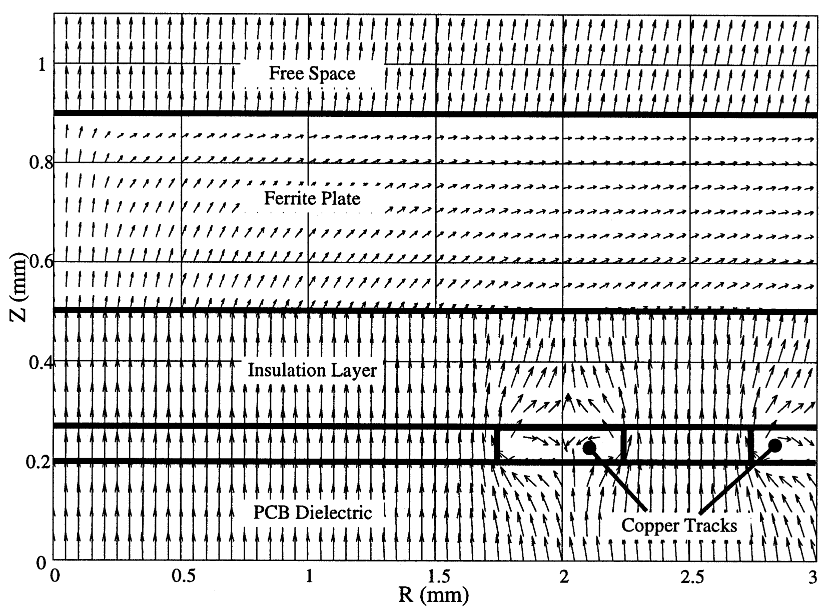

Fig. 5. Magnetic field intensity vector plot of the PCB transformer shielded with ferrite plates.

12.5 dB at the boundary. The normal component of the H-field is, therefore, about 8% of the resultant H-field inside the ferrite plate at the boundary. Thus, using thin ferrite plate alone cannot completely guide the H-field in the tangential direction. As described in (3), the normal component of the H-field in free space is 80 times larger than that in the ferrite plate at the boundary.

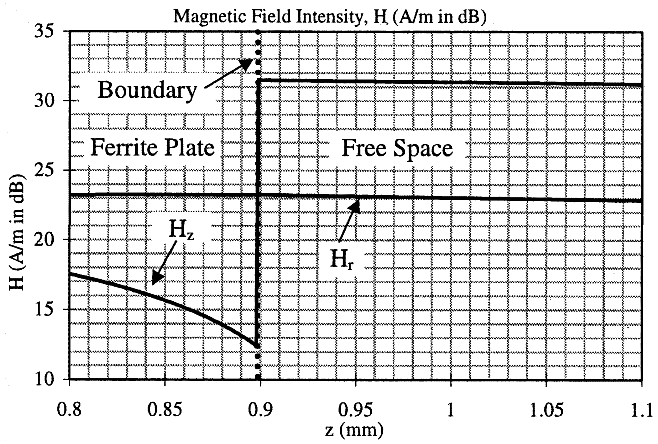

Fig. 6. Tangential (H_r) and normal (H_z) components of magnetic field intensity near the boundary between the ferrite plate and free space.

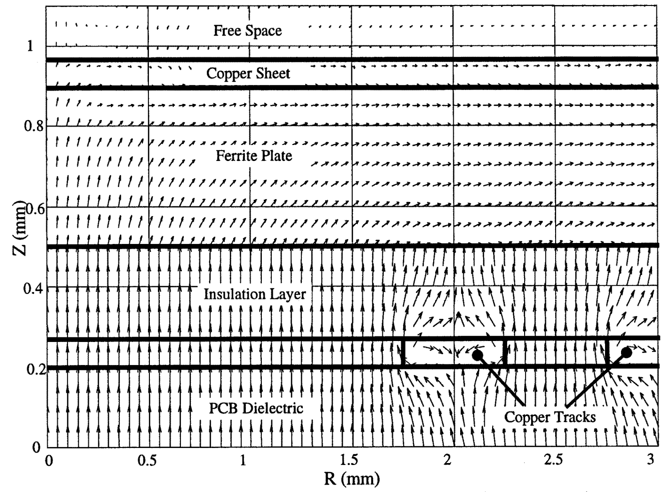

Fig. 7. Magnetic field intensity vector plot of the PCB transformer shielded with ferrite plates and copper sheets.

From the simulated results in Fig. 6, the normal component of the magnetic field intensity in free space is about 19 dB, i.e., 79.4 times, higher than that inside the ferrite plate. Thus, both simulated results and theory described in (3) show that using ferrite plates only is not an effective way to shield the magnetic field generated from the planar transformer.

B. Transformer Shielded With Ferrite Plates and Copper Sheets

The PCB transformer using ferrite plates coated with copper sheets as a EM shield(Fig. 3) has been fabricated. The size of the copper sheets is the same as that of the ferrite plates but its thickness is merely 70 μm. Thin copper sheets are required to minimize the eddy current flowing in the z-direction, which may diminish the tangential component of the H-field.

Based on Maxwell equation that the net current flowing out of a closed surface is zero

$$\oint_C \vec{H}\cdot d\vec{l} = \oint_S \left(\vec{J} + \frac{\partial \vec{D}}{\partial t}\right)\cdot d\vec{S} \tag{4}$$

and assuming that the displacement current is zero and the current on the ferrite–copper boundary is very small and negligible, the tangential component of the magnetic field intensity is continuous across the boundary between the ferrite plate and the copper sheet. Thus, at the boundary

$$H_{1t} = H_{2t} \tag{5}$$

where H_{1t} and H_{2t} are the tangential component (in r-direction) of the magnetic field intensity in the ferrite plate and copper, respectively. Because the tangential H-field on the surfaces of the copper sheets and the ferrite plates are the same at the boundary, thin copper sheets have to be adopted to minimize eddy current loss.

Consider the differential form of the Maxwell equation at the ferrite–copper boundary

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{6}$$

the magnetic field intensity can be expressed as

$$\vec{H} = -\frac{1}{j\omega\mu\sigma}\nabla \times \vec{J} \tag{7}$$

where ω, μ and σ are the angular frequency, permeability and conductivity of the medium, respectively. Because copper is a good conductor ($\sigma = 5.80 \times 10^7$ S/m) and the operating frequency of the PCB transformer is very high (a few megahertz), from (7), the magnetic field intensity, H, inside the copper sheet is extremely small. Accordingly, the normal component of the H-field inside the copper sheet is also small. Furthermore, from (3), at the ferrite–copper boundary, the normal component of the H-field inside the ferrite plate is 80 times less than that inside the copper sheet. As a result, the normal component of the H-field inside the ferrite plate can be suppressed drastically.

By using FEM [8], the magnetic field intensity vector plot of the PCB transformer shielded with ferrite plates and copper sheets has been simulated and is shown in Fig. 7. The tangential (H_r) and normal (H_z) components of magnetic field intensity near the copper sheet, at $R = 1$ mm, are plotted in Fig. 8. From Fig. 8, the tangential H-field (H_r) is about 23 dB and approximately continuous at the boundary. The normal component of the H-field (H_z) in copper sheet is suppressed to about 8 dB and that inside the ferrite plate is about -7.5 dB at the boundary. Therefore, the normal component of the H-field is, merely about 0.09% of the resultant H-field inside the ferrite plate at the boundary. Accordingly, at the ferrite–copper boundary, the H-field is nearly tangential and confined inside in the ferrite plate. Besides, the normal component of the H-field emitted into the copper sheet and free space can be neglected practically. Since the normal component of the H-field emitted into the copper is very small, the eddy current loss due to the H-field is also very small. This phenomenon is verified by the energy efficiency measurements of the ferrite-shielded PCB transformers with and without copper sheets in Section IV. As a result, the use ferrite plates coated with thin copper sheets is an effective way to shield the magnetic field generated from the transformer windings without diminishing the transformer energy efficiency.

Since the displacement current inside the copper sheet is negligible, the differential form of the Maxwell equation in (4) becomes

$$\nabla \times \vec{H} = \vec{J} \Rightarrow \nabla \times \nabla \times \vec{H} = \nabla \times \left(\sigma \vec{E}\right). \tag{8}$$

Substituting (6) and $\nabla \cdot \vec{H} = 0$ into (8), a second order Maxwell equation describing the magnetic field inside the copper sheet is

$$\nabla^2 \vec{H} = j2\pi f \sigma \mu \vec{H}. \tag{9}$$

By solving (9), the attenuation factor α of the magnitude of the tangential magnetic field intensity inside a good conductor is given by

$$\alpha = \sqrt{\pi f \sigma \mu}. \tag{10}$$

As the thickness of the copper sheet is 70 μm and the operating frequency is 3 MHz, the magnitude of the tangential magnetic field intensity attenuates to about 16% of its value at the ferrite–copper boundary. As a result, the attenuation of the tangential magnetic field attributed to the copper sheet is $20 \log_{10}(0.16) = 16$ dB. From the simulated magnetic field intensity in Fig. 8, the tangential H-field in the ferrite–copper and copper–air boundaries are about 23 dB and 5.5 dB respectively. The attenuation of the tangential magnetic field due to the copper sheet is therefore about 17.5 dB, which is close to the computed result.

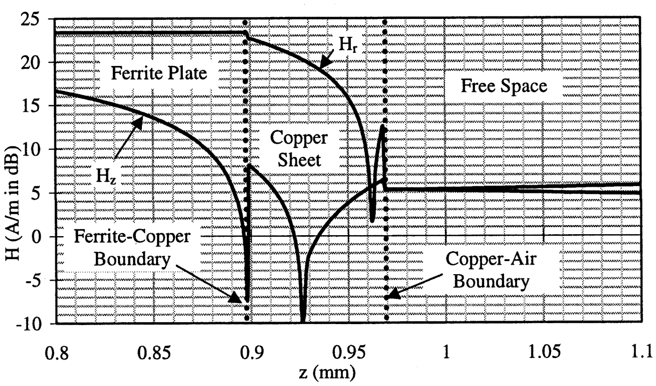

Fig. 8. Tangential (H_r) and normal (H_z) components of magnetic field intensity near the copper sheet at $R = 1$ mm.

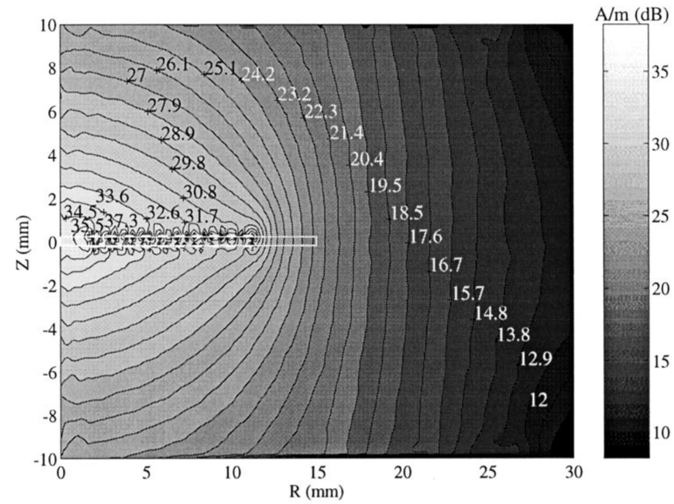

Fig. 9. Simulated magnetic field intensity magnitude of the PCB transformer without shielding in no load condition.

IV. Shielding Effectiveness of PCB Transformer With Various Kinds of Shielding Techniques

The shielding effectiveness (SE) of a barrier for magnetic field is defined as [10]

$$SE = 20 \log_{10} \left| \frac{\vec{H}_i}{\vec{H}_t} \right|$$

or

$$SE = 2 \times 10 \log_{10} \left| \frac{H_i}{\vec{H}_t} \right| = 2 \times \left(\left| \vec{H}_i \text{ (in dB)} \right| - \left| \vec{H}_t \text{ (in dB)} \right| \right) \tag{11}$$

where $\vec{H}_i$ is the incident magnetic field intensity and $\vec{H}_t$ is the magnetic field intensity transmits through the barrier. Alternatively, the incident field can be replaced with the magnetic field when the barrier is removed.

Magnetic field intensity generated from the PCB transformers with and without shielding has been simulated with FEM 2D simulator [8] and measured with a precision EMC scanner. In the field simulation, the primary side of the transformer is excited with a 3 MHz 3 A current source. However, the output of the magnetic field transducer in the EMC scanner will be clipped when the amplitude of the high-frequency field intensity is too large. Thus, the 3 MHz 3 A current source is approximated as a small signal (0.1 A) 3 MHz source superimposed into a 3 A dc source because the field transducer cannot sense the dc component. In the measurement setup, a magnetic field transducer for detecting vertical magnetic field is located at 5 mm below the PCB transformer.

A. PCB Transformer Without Shielding

Magnetic field intensity of the PCB transformer without shielding and loading has been simulated and its R–Z plane is shown in Fig. 9. From the simulated result, the magnetic field intensity, at $R = 0$ mm and $Z = 5$ mm, is about 30 dBA/m. The measured magnetic intensity, in z-direction, is shown in Fig. 10. The white square and the white parallel lines in Fig. 10 indicate the positions of transformer and the current carrying leads of the transformer primary terminals, respectively. The output of the magnetic field transducer, at 5 mm beneath the center of the transformer, is about 130 dBμV.

B. PCB Transformer Shielded With Ferrite Plates

The simulated magnetic field intensity of the PCB transformer shielded with ferrite plates, under no load condition, is shown in Fig. 11. The simulated result shows that the magnetic field intensity, at $R = 0$ mm and $Z = 5$ mm, is about 28 dBA/m. The measured magnetic intensity, in z-direction, is shown in Fig. 12. The output of the magnetic field transducer, at 5 mm beneath the center of the transformer, is about 128 dBμV.

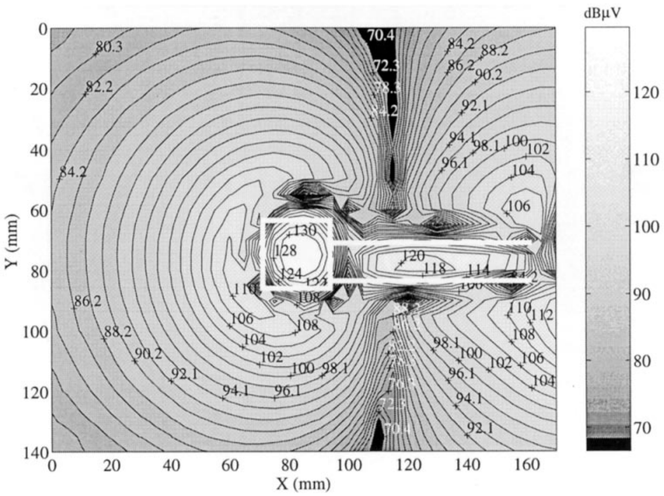

Fig. 10. Measured magnetic field intensity, in z-direction, of the PCB transformer without shielding in no load condition.

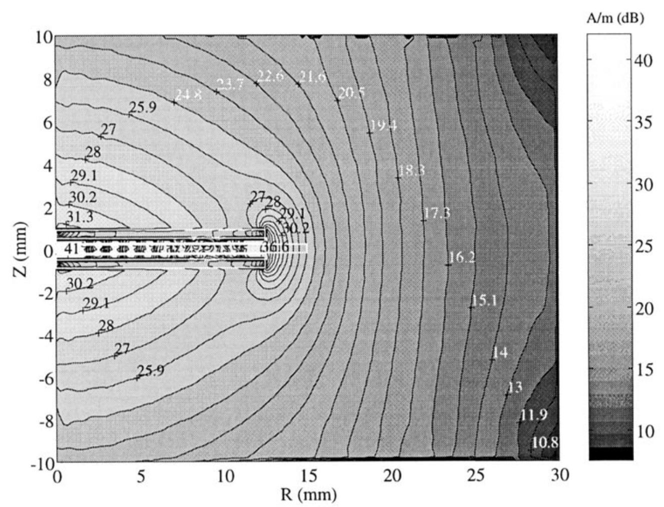

Fig. 11. Simulated magnetic field intensity magnitude of the PCB transformer shielded with ferrite plates in no load condition.

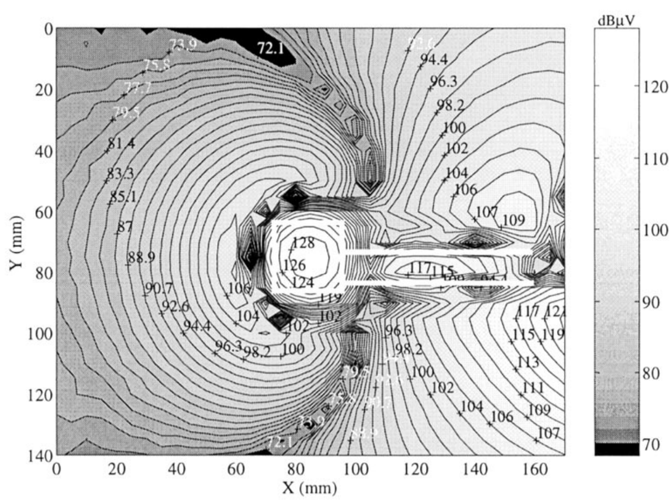

Fig. 12. Measured magnetic field intensity, in z-direction, of the PCB transformer shielded with ferrite plates in no load condition.

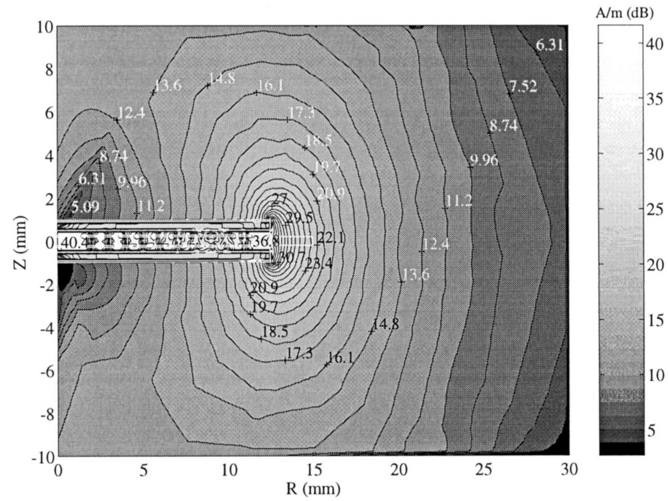

Fig. 13. Simulated magnetic field intensity magnitude of the PCB transformer shielded with ferrite plates and copper sheets in no load condition.

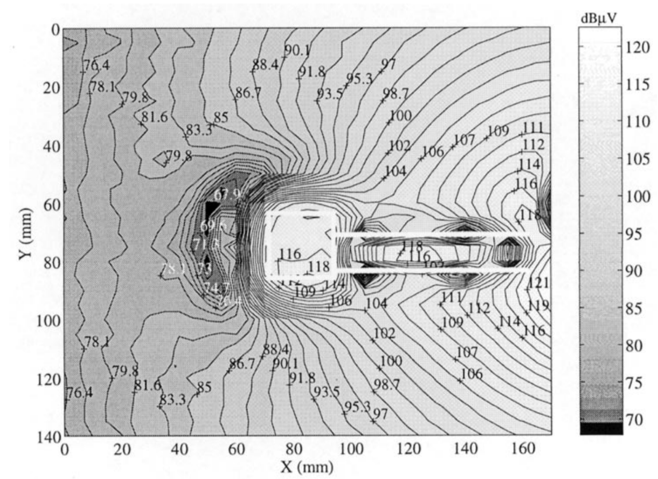

Fig. 14. Measured magnetic field intensity, in z-direction, of the PCB transformer shielded with ferrite plates and copper sheets in no load condition.

Therefore, with the use of 4F1 ferrite plates, the shielding effectiveness (SE), from the simulated result, is

$$SE = 2 \times (30 - 28) = 4 \text{ dB}.$$

The shielding effectiveness obtained from measurements is

$$SE = 2 \times (130 - 128) = 4 \text{ dB}.$$

Both simulation and experimental results shows that the use of the 4F1 ferrite plates can reduce the magnetic field emitted from the transformer by 4 dB (about 2.5 times).

C. PCB Transformer Shielded With Ferrite Plates and Copper Sheets

Fig. 13 shows the simulated magnetic field intensity of the PCB transformer shielded with ferrite plates and copper sheets under no load condition. From the simulated result, the magnetic field intensity, at $R = 0$ mm and $Z = 5$ mm, is about 13 dBA/m. Fig. 14 shows the measured magnetic intensity in z-direction.

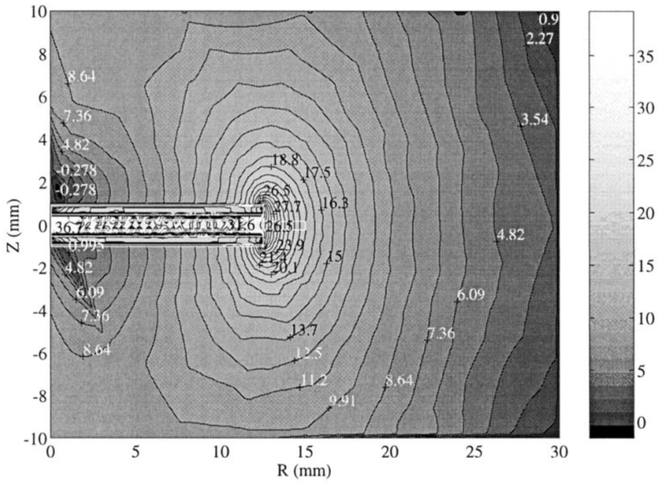

Fig. 15. Simulated magnetic field intensity magnitude of the PCB transformer shielded with ferrite plates and copper sheets in 20 Ω load condition.

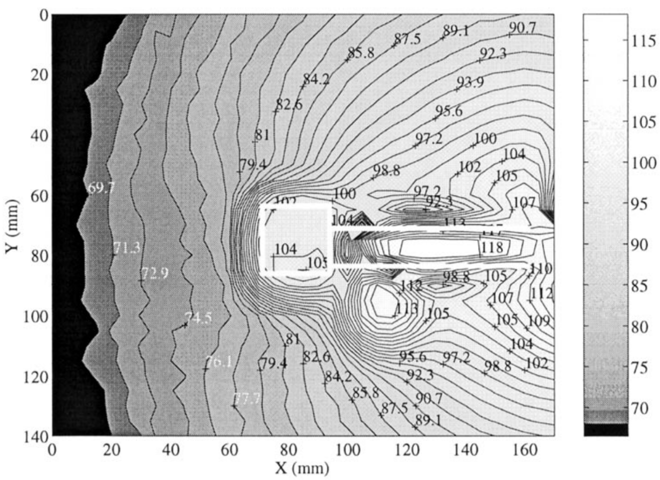

Fig. 16. Measured magnetic field intensity, in z-direction, of the PCB transformer shielded with ferrite plates and copper sheets in 20 Ω load condition.

The output of the magnetic field transducer, at 5 mm beneath the center of the transformer, is about 116 dBμV. With the use of 4F1 ferrite plates and copper sheets, the shielding effectiveness (SE), from the simulated result, is

$$SE = 2 \times (30 - 13) = 34 \text{ dB}.$$

The shielding effectiveness obtained from measurements is

$$SE = 2 \times (130 - 116) = 28 \text{ dB}.$$

As a result, the use of ferrite plates coated with copper sheets is an effective way to shield magnetic field generated from PCB transformer. The reduction of magnetic field is 34 dB (2512 times) from simulation result and 28 dB (631 times) from measurement. The SE obtained from the measurement is less than that obtained from the simulated result. The difference mainly comes from the magnetic field emitted from the leads of the transformer. From Fig. 14, the magnetic field intensity generated from the leads is about 118 dB, which is comparable with

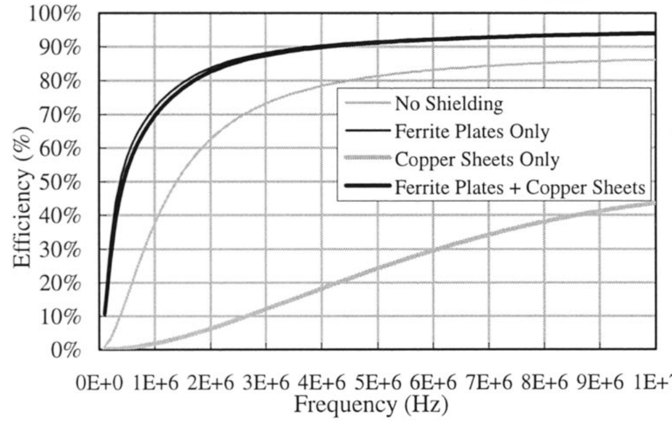

Fig. 17. Efficiency of planar transformers with various shielding techniques in 100 Ω load condition.

the magnetic field generated from the transformer. Therefore, the magnetic field transducer beneath the center of the transformer also picks up the magnetic field generated from the lead wires.

D. PCB Transformer in Loaded Condition

When a load resistor is connected across the secondary of the PCB transformer, the opposite magnetic field generated from secondary current cancels out part of the magnetic field setup from the primary. As a result, the resultant magnetic field emitted from the PCB transformer in loaded condition is less than that in no load condition. Fig. 15 shows the simulated magnetic field intensity of the PCB transformer shielded with ferrite plates and copper sheets in 20 Ω load condition. From the simulated result, the magnetic field intensity, at $R = 0$ mm and $Z = 5$ mm, is about 4.8 dBA/m, which is much less than that in no load condition (13 dBA/m). Fig. 16 shows the measured magnetic intensity in z-direction. The output of the magnetic field transducer, at 5 mm beneath the center of the transformer, is about 104 dBμV and that in no load condition is 116 dBμV.

V. Efficiency Comparison of PCB Transformer With Various Kinds of Shielding Techniques

Energy efficiency of the PCB transformers shielded with i) ferrite plates only, ii) copper sheets only, and iii) ferrite plates covered with copper sheets has been measured and is compared with that of the PCB transformer with no shielding. Fig. 17 shows the measured energy efficiency of the four PCB transformers with 100 Ω resistive load. In the PCB transformer shielded with only copper sheets, a layer of insulating sheet of 0.684 mm thickness is used to isolate the transformer winding and the copper sheets. From Fig. 17, energy efficiency of the transformers increases with increasing frequency. The transformer shielded with copper sheets only has the lowest energy efficiency among the four transformers. The energy loss in the copper-shielded transformer mainly comes from the eddy current, which is induced by the normal component of the H-field generated from the transformer windings, circulating in the copper sheets.

TABLE II
INDUCTIVE PARAMETERS OF THE PCB TRANSFORMERS

Transformers	Self-inductance of Primary Winding	Self-inductance of Secondary Winding	Mutual-inductance between Primary and Secondary Windings	Leakage-inductance of Primary Winding
No Shielding	1.22 μH	1.22 μH	1.04 μH	0.18 μH
Shielded with Ferrite Plates Only	3.92 μH	3.92 μH	3.74 μH	0.18 μH
Shielded with Ferrite Plates and Copper Sheets	3.80 μH	3.80 μH	3.62 μH	0.18 μH

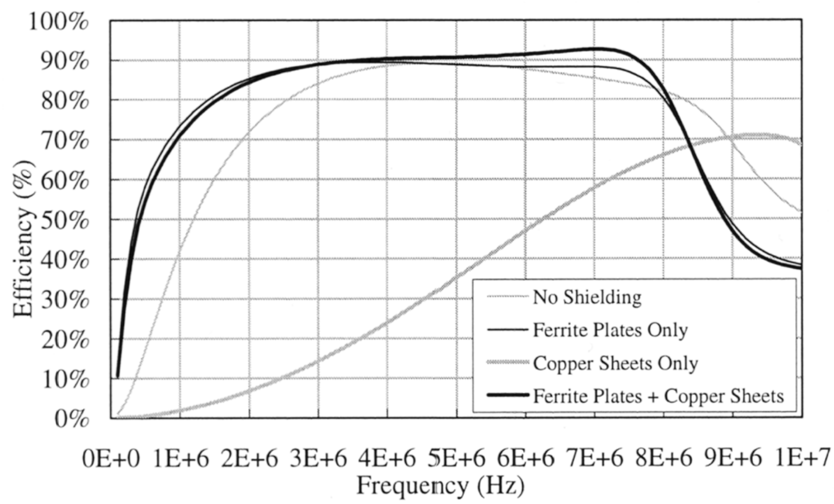

Fig. 18. Efficiency of planar transformers with various shielding techniques in 100 Ω//1000 pF load condition.

The energy efficiency of the transformer with no shielding is lower than that of the transformers shielded with ferrite plates. Without ferrite shielding, the input impedance of coreless PCB transformer is relatively low. The energy loss of the coreless transformer is mainly due to its relatively high i^2R loss (because of its relatively high input current compared with the PCB transformer covered with ferrite plates). The inductive parameters of the transformers with and without ferrite shields are shown in Table II. However this shortcoming of the coreless PCB transformer can be overcome by connecting a resonant capacitor across the secondary of the transformer [11]. The energy efficiency of the 4 PCB transformers with 100 Ω//1000 pF capacitive load is shown in Fig. 18. The energy efficiency of the coreless PCB transformer is comparable to that of the ferrite-shielded transformers at the maximum efficiency frequency (MEF) of the coreless PCB transformer.

The ferrite-shielded PCB transformers have the highest energy efficiency among the four transformers, especially in low frequency range. The high efficiency characteristic of the ferrite-shielded transformers is attributed to their high input impedance. In the PCB transformer shielded with ferrite plates and copper sheets, even though a layer of copper sheet is coated on the surface of each ferrite plate, the eddy current loss in the copper sheets is negligible as discussed in Section III. The H-field generated from the transformer windings is confined in the ferrite plates. The use of thin copper sheets is to direct the magnetic field in parallel to the ferrite plates so that the normal component of the magnetic field emitting into the copper can be suppressed significantly. The energy efficiency measurements of the ferrite-shielded transformers with and without copper sheets confirm that the addition of copper sheets on the ferrite plates will not cause significant eddy current loss in the copper sheets and diminish the transformer efficiency. From Figs. 17 and 18, the energy efficiency of both ferrite-shielded transformers, with and without copper sheets, can be higher than 90% at a few megahertz operating frequency.

VI. CONCLUSION

A simple and effective technique of magnetic field shielding for PCB transformers is proposed. Performance comparison, including shielding effectiveness and energy efficiency, of the PCB transformers shielded with the proposed method, copper sheets and ferrite plates has been accomplished. Both simulation and measurement results show that the use of ferrite plates coated with thin copper sheets has the greatest shielding effectiveness (SE) of 34 dB (2512 times) and 28 dB (631 times) respectively, whereas the SE of using only ferrite plates is about 4 dB (2.5 times). Addition of thin copper sheets on the surfaces the ferrite plates does not diminish the transformer energy efficiency. Unlike the "copper only" shielding approach, the "ferrite–copper" shielding method under investigation offers a low-loss solution to planar PCB transformers. Experimental results show that the energy efficiency of both ferrite-shielded transformers can be higher than 90% at operating frequency in the Megahertz range.

ACKNOWLEDGMENT

The authors want to thank G. Sauerlander and T. Duerbuam, Philips Research, Aachen, for helpful discussions on the properties of ferrite sheets.

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S. C. Tang (M'98) was born in Hong Kong in 1972. He received the B.Eng. degree (with first class honors) and the Ph.D. degree in electronic engineering from the City University of Hong Kong, Kowloon, in 1997 and 2000, respectively.

When he was an undergraduate student at the City University of Hong Kong, he obtained the Li Po Chun Scholarships and Intertek Testing Services (ITS) Scholarships. After graduation, he worked as a Research Fellow at the same university and then joined the National University of Ireland, Galway, as a Post-Doctoral Research Fellow in 2001. He is presently a Visiting Scientist in the Laboratory for Electromagnetic and Electronic Systems, Massachusetts Institute of Technology, Cambridge. His research interests include electromagnetics and high-frequency low-profile power converters.

Dr. Tang won the Championship of the HKIE Young Member Paper Contest in 2000. In 1997, he received the First Prize Award from the IEEE Hong Kong Section Student Paper Contest and was the second winner in the Hong Kong Institution of Engineers (HKIE) 50th Anniversary Electronic Engineering Project Competition. He also received Certificates of Merit in the IEEE Paper Contests (Hong Kong Section) in 1998 and 1999.

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, U.K., in 1984, and the D.I.C. and Ph.D. degrees from the Imperial College of Science and Technology, University of London, 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 took up a lectureship at the University of Technology, Sydney, Australia, where he became a Senior Lecturer in 1991. He joined the University of Sydney in 1993 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 an Associate Dean of the Faculty of Science and Engineering at the City University of Hong Kong. He has published over 150 technical papers, including over 80 refereed journal publications. His research interests include all aspects of power electronics.

Dr. Hui received the Teaching Excellence Award in 1999 and the Grand Applied Research Excellence Award in 2001 from the City University of Hong Kong. He has been appointed an Honorary Professor by the University of Sydney, Australia since 2000.

Henry Shu-hung Chung (S'92–M'95) received the B.Eng. (with first class honors) degree in electrical engineering and the Ph.D. degree from The Hong Kong Polytechnic University, 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-domain and frequency-domain analysis of power electronic circuits, switched-capacitor-based converters, random-switching techniques, digital audio amplifiers, soft-switching converters, and electronic ballast design. He has authored four research book chapters, and over 140 technical papers including 65 refereed journal papers in the current research area, and holds two U.S. patents.

Dr. Chung received the Grand Applied Research Excellence Award in 2001 from the City University of Hong Kong. He is currently IEEE student branch counselor and was Track Chair of the Technical Committee on Power Electronics Circuits and Power Systems, IEEE Circuits and Systems Society, from 1997 to 1998. He is presently an Associate Editor of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—PART I: FUNDAMENTAL THEORY AND APPLICATIONS.