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Coreless Printed Circuit Board (PCB) Step-down Transformers for DC-DC Converter Applications

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***Abstract*—**In this paper, multilayered coreless printed circuit board (PCB) step-down power transformers for DC-DC converter applications have been designed, manufactured and evaluated. A set of two different circular spiral step-down transformers were fabricated in the four layered PCB. These transformers have been modelled with the assistance of high frequency equivalent circuit and characterized with both sinusoidal and square wave excitation. This paper provides the comparative results of these two different transformers in terms of their resistances, self, leakage, mutual inductances, coupling coefficient and also their energy efficiencies. The operating regions for optimal performance of these transformers for power transfer applications are determined. These transformers were tested for the output power levels of about 30 Watts within the input voltage range of 12-50 Vrms. The energy efficiency for these step down transformers is observed to be in the range of 90%-97% in MHz frequency region.

***Keywords*—**Coreless Step down Transformer, DC-DC Converter applications, High frequency transformer, MHz operating frequency, Multilayered PCB transformers, Power Transfer Applications.

I. Introduction

THIS In this modern era, where we can find miniaturized electronic circuits, planar technology plays a prominent role because of their small size and reduced weight with high power density [1], [2]. As some of the applications demand electrical isolation and multiple outputs, transformers have become the irreplaceable components in modern power supplies. The switching frequencies of isolated power supplies are limited to few hundreds of kHz because of the increased hysteresis and eddy current losses of core based transformers and the switching losses of the Power MOSFET at higher operating frequencies. The other major problems involved in high frequency magnetics are leakage inductance, skin and proximity effects and unbalanced magnetic flux distribution, which generate localized hot spots and reduce the coupling coefficient [3]. The drawbacks of the core type transformer at higher frequencies and also the advancements in the semiconductor technology such as introduction of SiC, GaN devices strongly demands the high frequency, high power density transformers. Thus, the research is made to focus on the high frequency coreless transformers. The investigation regarding the coreless PCB transformers provided the useful information that it is possible to use them as an isolation transformer for both signal and energy transfer applications [4]. Since in these type of transformers, the magnetic flux is not confined, there exists a delusion of high radiated EMI but according to antenna theory, these transformers are not considered as good antenna/receiver and therefore can be suitable for the energy transfer applications [4].

In DC/DC converters for applications such as Power over Ethernet, WLAN Access-points, IP phones and for a wide variety of telecom applications, a step down power transformer of different turn's ratio is required. Two different coreless PCB step down (2:1) multilayered transformers were manufactured suitable for high frequency DC/DC converters. In this paper these transformers performance characteristics for power transfer applications have been studied and application potentials of these transformers were addressed.

II. Structure of the Multilayered PCB Transformers

In these coreless PCB transformers, the primary and secondary copper windings of the transformers are etched on the FR4 PCB laminate whose breakdown voltage is of approximately 50kV/mm [5]. In order to have better coupling and for the high power density of the transformer, the 2:1 transformers are designed in a four layered PCB. Here, there are two primary windings (P1 and P2) in two different layers and one secondary winding (S) in between the two primary windings. The two primaries P1 and P2 are connected in series externally using the fourth layer of the PCB. The dimensions of the two transformers are shown in fig. 1. It is mentioned in [6], increasing the area of the transformer by increasing the number of turns without changing the track separation of the conductors, the rate of increase of self and mutual inductances are greater with respect to that of the leakage inductances. As a result the coupling coefficient of the transformer is going to be increased. Therefore, a series consisting of two different transformers of the

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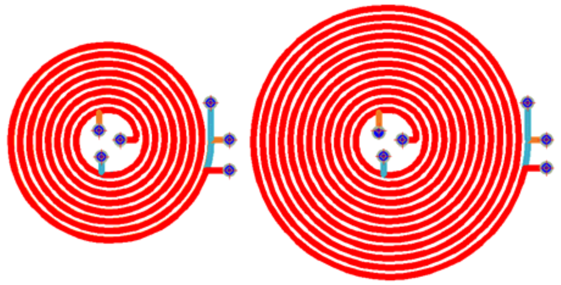

Fig. 1. Dimensions of coreless PCB Transformers Tr1 (20mm) and Tr2 (30mm)

same width, track separation and height have been designed for the DC/DC Converter applications. The width, track separation and height of the conductor are 0.6mm, 0.4mm and 70µm respectively. The number of turns relating to the primary and secondary winding for these transformers is different, while at the same time the other geometrical parameters remain constant. The number of primary/secondary turns of Tr1 and Tr2 are 16/8 and 24/12 respectively. The outer diameter of the designed transformers Tr1 and Tr2 are 20mm and 30mm respectively and the corresponding height of the transformers is 1.48mm.

III. High Frequency Model of Multilayered Step Down PCB 2:1 Transformers

In this section the resistive, inductive and capacitive parameters relating to the transformer using high frequency equivalent circuit are presented. The performance characteristics such as the transfer function H(*f*) and input impedance *(Z_{in})* of the transformer with two different resonant capacitors 'Cr' of 1.5nF and 2.2nF at a load resistance of 470 Ω are measured for matching the high frequency model of the transformer. The initial parameters such as the primary self inductance 'Lp', secondary self inductance 'Ls' and the resistances of the windings are measured with the assistance of HP4284A precision LCR meter at 1MHz frequency by open circuiting the opposite winding of the transformer. The preliminary primary and secondary leakage inductances of the transformers are obtained by using the four-wire measuring method [7]. The leakage inductances of the transformers which are less than 1µH are obtained by (1)

$$L_{lk} = \frac{50}{2\pi f}\frac{V_{dut}}{V_{50\Omega}} \quad (1)$$

Where, L_{lk} - Leakage Inductance
f - Excitation frequency, [Hz]
V_{dut} - Voltage across the device under test
$V_{50\Omega}$ - Voltage across the 50Ω resistor

The actual parameters such as self inductance, mutual inductance and leakage inductance of the transformers are obtained by fitting the above measured parameters in high frequency model of the transformer shown in fig.2.

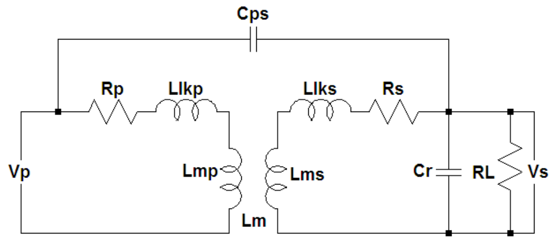

Fig.2. High frequency model of coreless PCB step down transformer

Here,

R_p Primary winding resistance;
R_s Secondary winding resistance;
L_{lkp} Leakage inductance of primary;
L_{lks} Leakage inductance of secondary;
R_L Load resistance;
C_r Resonant Capacitor;
L_{mp} Primary Mutual inductance;
L_{ms} Secondary Mutual inductance;
L_m Mutual inductance;
C_{ps} Interwinding capacitance;

The intrawinding capacitances of both the windings are very small and can be ignored in the analysis. The above measured parameters at 1MHz frequency are passed into this high frequency model and are fine tuned in order to match the measured performance characteristics over the full frequency range and hence the correct model parameters are obtained. The model parameters such as self, mutual, leakage inductances, interwinding capacitance of the primary and secondary windings, and the corresponding DC resistances are shown in table II. Here, the primary /secondary mutual inductance of the transformer is given as

$$Lmp = Lp - Llkp \quad (2)$$

$$Lms = Ls - Llks \quad (3)$$

The mutual inductance 'L_m' between the primary and secondary of the transformer is the geometric mean of the primary and secondary mutual inductances 'L_{mp}' and 'L_{ms}' [8]

$$Lm = \sqrt{Lmp * Lms} \quad (4)$$

From Table I, it can be verified that the rate of increase of leakage inductance of primary/secondary with respect to their corresponding self inductance is low when the area of the transformer is increased with the increased number of turns as mentioned earlier. Therefore, the comparative leakage inductance to self inductance of the transformer Tr2 is lower compared to that of the transformer Tr1.
The DC resistances of the transformers are shown in the table I.

TABLE I

ELECTRICAL PARAMETERS OF THE DESIGNED TRANSFORMERS

PARAMETERS	TR1	TR2
$R_p(\Omega)$-DC	0.62	0.84
$R_s(\Omega)$-DC	0.30	0.41
$L_p(\mu H)$	2.86	8.25
$L_s(\mu H)$	0.78	2.20
$L_{lkp}(\mu H)$	0.35	0.40
$L_{lks}(\mu H)$	0.09	0.18
$L_m(\mu H)$	1.29	3.98
C_{ps}(pF)	30.0	48.0
$\%L_{lkp}/L_p(\mu H)$	12.2	4.85
$\%L_{lks}/L_s(\mu H)$	11.5	8.18

The winding resistance of the above transformers increases as the operating frequency of the current increases due to skin effect. These AC resistances of the primary and secondary windings of the two transformers are calculated by using the following expression and by approximating the model to a circular spiral inductor [9].

$$R_{AC} = \frac{R_{DC} h}{\delta(1-\exp(-h/\delta))} \tag{5}$$

Where
R_{DC} - DC resistance of the winding
h - Height of the conductor
δ - Skin depth

The equation of the skin depth [10] is given as follows

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{6}$$

Here,
f - Operating frequency
μ - Permeability of the medium
σ - Conductivity

The measured and calculated AC resistance of the primary winding of the two transformers is illustrated in fig. 3. The AC resistance of the secondary windings of the transformer follows the same behaviour as shown in fig. 3 but is twice as low, as it consists of one winding as compared to two for the primary. The AC resistances of the primary are obtained by measuring the voltage, current and phase angle between the voltage and current while open circuiting the secondary winding of the transformer.

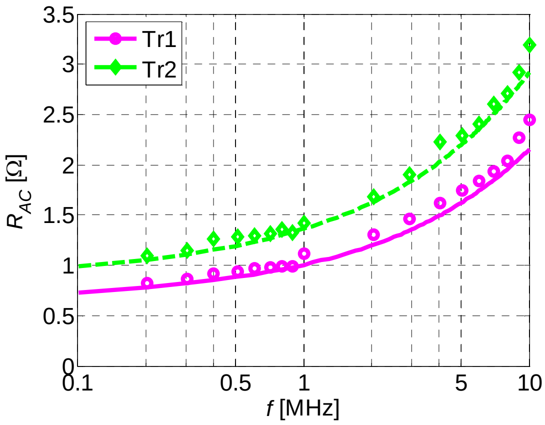

Fig.3. Calculated (solid line) and measured (symbols) AC resistances of the primary winding of the designed transformers

Coupling Coefficient: The coupling coefficient is the ratio of the mutual inductance to the geometric mean of primary and secondary self inductances according to [10]:

$$K = \frac{L_m}{\sqrt{L_p \times L_s}} \tag{7}$$

where, L_m is the mutual inductance between the primary and secondary windings and L_p/L_s the self inductance of the primary/secondary winding. The coupling coefficient of transformer Tr1 is 0.875 and for the transformer Tr2 it is 0.93. We observe that, the coupling coefficient 'K' enhances as the area of transformer increases with the increase of number of turns as discussed earlier. In these transformers also by placing an external resonant capacitor the problem of low voltage gain because of low coupling factor can be eliminated. This is due to the partial resonant phenomena of the leakage inductance of the transformer and the external resonant capacitor [11]. Therefore, the energy efficiency of the transformer increases and can actually be greater than the coupling coefficient which also makes the smallest transformers energy efficient and thus useful for power supplies.

IV. PERFORMANCE CHARACTERISTICS OF THE MULTILAYERED PCB TRANSFORMERS

The performance characteristics such as transfer function of the coreless PCB transformers under load condition $H(f)$, input impedance (Z_{in}) and the phase angle (φ) of the transformers determine the operating frequency of these transformers. These expressions are obtained from the high frequency equivalent circuit of the transformers shown in fig. 4 and are derived in [4], [6], and [11] as follows:

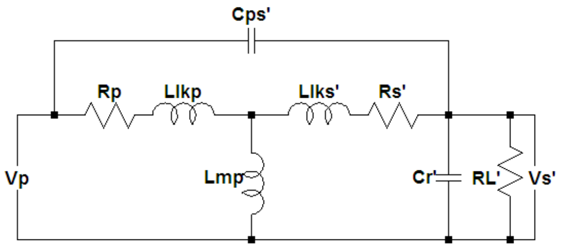

Fig. 4. High frequency equivalent circuit of the transformer referred to primary

$$H(f) = \frac{V_s}{V_p} = \frac{\frac{1}{X_1} + j(2\pi f)C_{ps}'Y_1}{nY} \tag{8}$$

$$Z_{in} = \frac{1}{sC_{ps}'(1 - n \times \frac{V_s}{V_p}) + \frac{(1-A)}{X_1} + sC_{pp}'} \tag{9}$$

where 'n' is the turn's ratio of the transformer

$$R_s' = n^2 R_s$$

$$L_{lks}' = n^2 L_{lks}$$

$$C_{pp}' = C_{pp} + \frac{n-1}{n} C_{ps}$$

$$C_r' = \frac{1}{n^2} C_r + \frac{1-n}{n^2} C_{ps}$$

$$C_{ps}' = \frac{1}{n} C_{ps}$$

$$X_1 = R_p + sL_{lkp}$$

$$X_2 = R_s' + sL_{lks}'$$

$$Y_1 = X_2 \left[\frac{1}{X_1} + \frac{1}{sL_{mp}} \right] + 1$$

$$Y_2 = \frac{1}{X_2} + sC_{ps}' + sC_r' + \frac{1}{n^2 R_L}$$

$$Y = -\frac{1}{X_2} + Y_1 Y_2$$

$$A = \frac{sC_{ps}' + \frac{X_2}{X_1} Y_2}{Y}$$

A. Transfer Function H (f) of the Coreless PCB Transformer:

The transfer functions of designed transformers are determined by using two different resonant capacitors. The magnitudes of the transfer functions, referred to the primary side with resonant capacitors of 1.5nF and 2.2nF at a load resistance of 470Ω, are plotted and are shown in fig. 5 and 6 respectively. From fig.5 and 6 we observe that the measured transfer functions of the transformers are in good agreement with those calculated by using the model equations. The transfer function *H (f)* is maximum at a frequency known as maximum gain frequency of the transformer. Theoretically the resonant frequency [11] of the transformer can be calculated by using (10)

$$f_r = \frac{1}{2\pi\sqrt{L_{eq} \times C_{eq}}} \tag{10}$$

where

$$L_{eq} = L_{lks}' + L_{mp} \parallel L_{lkp} \tag{11}$$

$$C_{eq} = C_r' + C_{ps}' \tag{12}$$

The resonant frequency of the transformer decreases for larger value of resonant capacitors across the secondary winding of the transformers. For example in fig. 5 it can be observed that the maximum gain frequency of the transformer Tr1 with C_r=1.5nF is close to 9.8MHz where as in fig.6 it is 8.0MHz with C_r=2.2nF.

B. Input Impedance (Z_{in}) and phase angle (φ):

With an external resonant capacitor of 1.5nF connected across the secondary winding of the transformers (Tr1 and Tr2), the measured and the calculated input impedance *(Z_{in})* and phase angle *(φ)* are plotted in fig. 7 and 8 respectively. In this case the load resistance is 470Ω. From fig. 5 the maximum gain frequency of the transformer Tr1 is approximately 9.8MHz as discussed in the previous section. For the same transformer Tr1, from fig. 7 it can be observed that the input impedance peaks at 4.8MHz approximately. This frequency, at which the impedance of the transformer is maximum, is known as the Maximum Impedance Frequency (MIF). From fig. 5 and 7, the maximum impedance frequency of the transformer is less than the maximum gain frequency. From fig. 8 it can be observed that before MIF, the transformer is highly inductive in nature and at MIF, the phase angle of the transformer Tr1 is very small. The operating frequency region is the region where the transformer possesses sufficient input impedance and also where it is highly inductive in nature.

The input impedance of the transformer Tr1 at 3MHz is reasonably high and thus the corresponding operating frequency region of this transformer lies approximately in the frequency range of 3-4.8MHz. After this frequency region, the input impedance of the transformer is decreasing as shown in

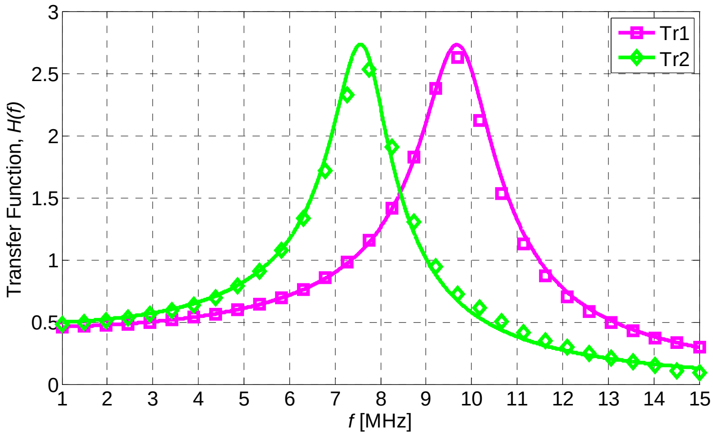

Fig. 5. Calculated (solid line) and measured (symbols) transfer function *H (f)* of the transformers with C_r=1.5nF and RL=470 Ω.

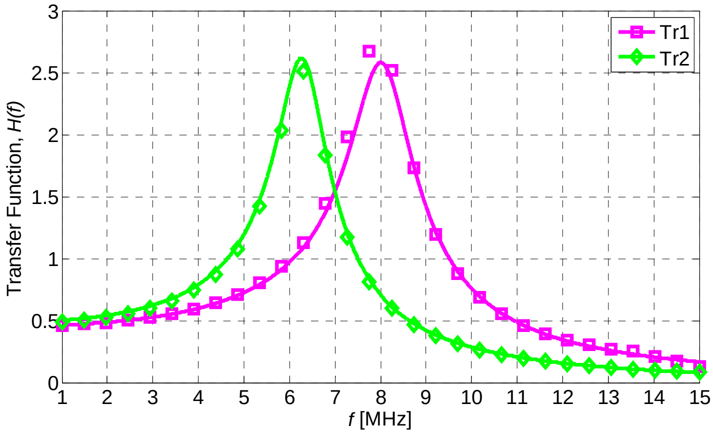

Fig. 6. Calculated (solid line) and measured (symbols) transfer function *H (f)* of the transformers with C_r=2.2nF and R_L=470 Ω.

fig.7 and additionally the transformer is not inductive in nature as illustrated in fig. 8, hence we cannot operate the transformer after MIF. Therefore, for power transfer applications, MIF determines the maximum limit on the operating frequency region of the transformer. The same phenomenon i.e., the maximum impedance frequency, operating frequency region is observed for the other transformer Tr2. The input impedance of the transformers Tr1 and Tr2 is observed to be increasing in nature as the number of turns of the transformer increases because of the increased inductance of the transformer as shown in fig.7.The effect of the resonant capacitor on the input impedance and phase angle is also observed by connecting a 2.2nF resonant capacitor across the secondary winding of the transformers Tr1 and Tr2 and the results are plotted in fig. 9 and 10 respectively. From fig. 6 and 9, the maximum gain frequency and the maximum impedance frequency of the transformer Tr1 are 8 and 4MHz respectively. It can be observed that these frequencies were shifted towards the lower operating frequencies when the resonant capacitor value is increased. Here, the input impedance of the transformer is sufficiently high at a frequency of 2.75MHz and thus, the operating frequency region of the transformer Tr1 is observed to be in the frequency range of 2.75-4MHz. However, as it has been previously discussed, the operating frequency region of transformer Tr1 with the resonant capacitor C_r=1.5nF is 3-4.8MHz. From this we can say that the wide operating frequency region is obtained with the assistance of lower value of resonant capacitors. Also, we can say that for the given transformer, with the help of larger value of resonant capacitor, the optimal operating frequency region moves towards the lower frequencies whereas with the lower value of capacitor it moves towards the higher operating frequencies while maintaining the similar characteristic curves. The same criterion is observed for the transformer Tr2. For SMPS applications, since the switching losses of the power mosfet are dominant in nature, the maximum impedance frequency of the transformer can be shifted further towards the lower operating frequencies with the help of resonant capacitor so that maximum energy efficiency of the converter can be

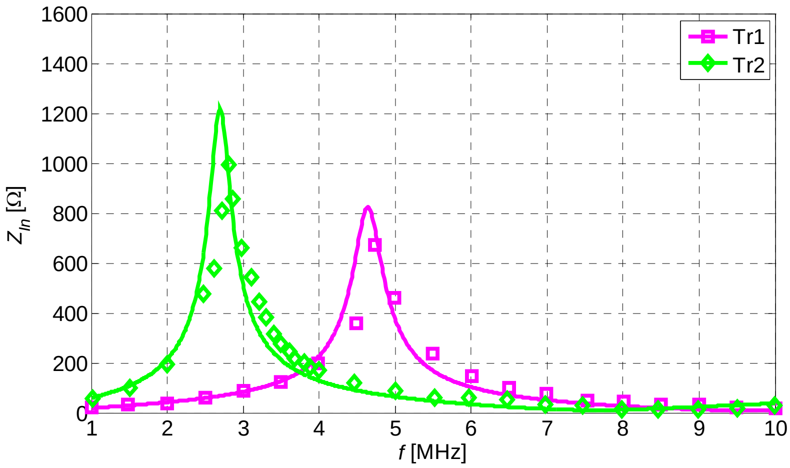

Fig. 7. Calculated (solid line) and measured (symbols) input impedance of transformers with C_r=1.5nF and R_L=470 Ω

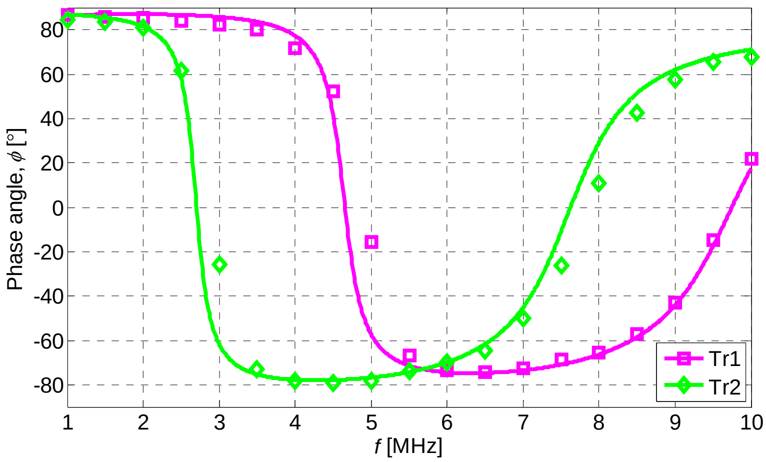

Fig. 8. Calculated (solid line) and measured (symbols) phase angle of transformers with C_r=1.5nF and R_L=470 Ω

attained at a frequency known as maximum energy efficiency frequency. From fig. 7 and 9, we can observe that the magnitude of the

input impedance becomes reduced when the resonant capacitor value is increased which also agrees with (6).

C. Energy Efficiency (η): Since no magnetic core exists, there is no magnetic core loss involved in these transformers. The power loss in the primary and secondary windings of the 2:1 step down transformer [12] is given by (13).

$$P_{loss} = \frac{1}{2}\left(i_p i_p^* R_{ac}(p) + i_s i_s^* R_{ac}(s) + R_{ac}(ps)\left(i_p i_s^* + i_p^* i_s\right)\right) \quad (13)$$

where,

i_p/i_s- RMS currents through primary/secondary winding
i_p*/i_s*- Complex conjugate RMS currents through primary/secondary winding
$R_{ac}(p)$ / $R_{ac}(s)$ - Primary/secondary winding ac resistance

The measured average input and output powers per cycle of these transformers are obtained from (14) and (15) respectively.

$$P_{in} = \frac{1}{T}\int_0^T v_p(t) \times i_p(t)dt \quad (14)$$

$$P_{out} = \frac{1}{T}\int_0^T v_s(t) \times i_s(t)dt \quad (15)$$

Where, v_p - Instantaneous primary voltage across the primary winding

v_s - Instantaneous secondary voltage across the secondary winding

i_p - Instantaneous current through the primary winding of the transformer

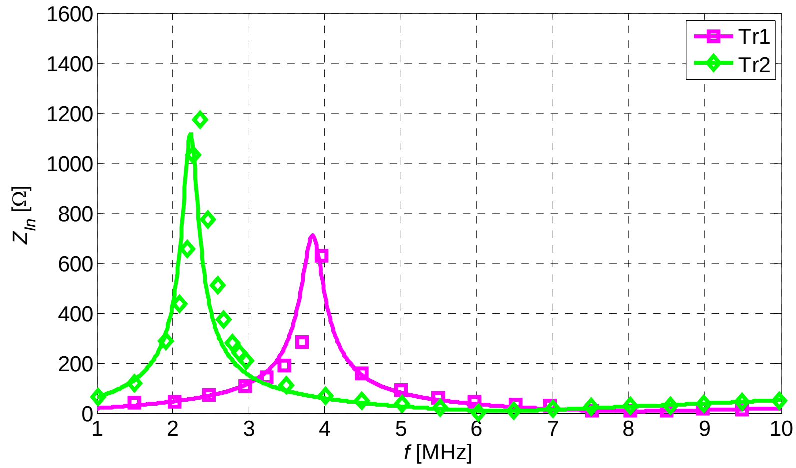

Fig. 9. Calculated (solid line) and measured (symbols) input impedance of transformers with C_r=2.2nF and R_L=470 Ω

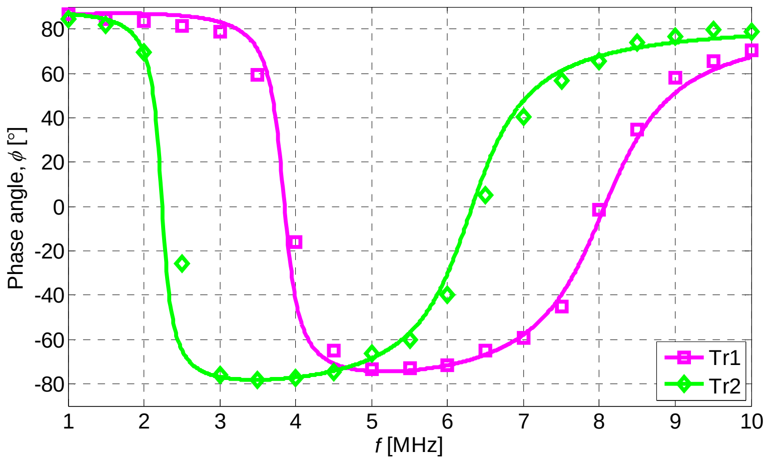

Fig. 10. Calculated (solid line) and measured (symbols) phase angle of transformers with C_r=2.2nF and R_L=470 Ω

i_s - Instantaneous current through the secondary winding of the transformer

T - Period of a cycle where T=1/f

f - Operating frequency of the transformer

Hence, the measured energy efficiency of the transformer is

$$\eta_{meas} = \frac{P_{out}}{P_{in}} \times 100\% \tag{16}$$

V. Power Tests of the Transformers

The power tests of the transformers Tr1 and Tr2 are carried out with the help of EMPOWER BBM0A3FKO Radio Frequency Power Amplifier whose frequency range is given as 0.01MHz - 230MHz and with a power delivering capacity of 100Watts. Here, the transformers primary winding is subjected to the variable voltage in the frequency range of 1-10MHz. The type of the waveform i.e., sinusoidal/square wave and the excitation voltage fed to the power amplifier is varied with the help of HP33120A signal generator. The measurements are fetched from the Tektronix oscilloscope TPS2024 with the help of Lab view 8.5. The primary/secondary voltages of the transformer are measured with the help of high voltage probes P5120 and the current through the primary/secondary windings are taken by using Tek-CT2 Current transformers.

(A) Energy Efficiency of the transformers Tr1 and Tr2 with different loaded conditions

The energy efficiency of the transformer Tr1 with C_r=1.5nF is measured for different loaded conditions and is shown in fig. 11. With this external resonant capacitor, the maximum impedance frequency of the transformer is found to occur at 4.8MHz and from fig. 11 we can observe that the efficiency is maximum at a frequency of 4MHz for all the loads. This means that the maximum energy efficiency frequency of the transformer does not change with respect to different loaded conditions. From this we can also observe that the maximum energy efficiency frequency is less than maximum impedance frequency. The energy efficiency of the transformer Tr1 is about 97% at the frequency of 4MHz with the load resistance of 50 Ω. Here, the output power of the transformer is approximately 12 Watts and with the load current of 0.5Amp, fed with an input voltage of 43Vrms. Under the same voltage excitation, with the load resistance of 20 Ω, the efficiency of the transformer is approximately 93.8% at an output power of 23Watts with the load current carrying capacity of 1.07Amp.

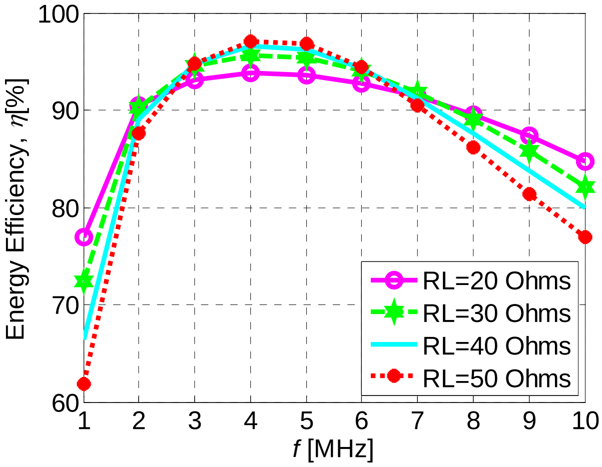

Fig.11. Efficiency of the transformer Tr1 with different loads at C_r=1.5nF

Similarly, the energy efficiency of the transformer Tr2 with different loaded conditions and with an external resonant capacitor of 1.5nF is illustrated in fig. 12. For this transformer, the maximum input impedance frequency is observed to be at 2.8MHz from fig (7).Hence, the maximum energy efficiency of this transformer can be in the range of 2-2.8MHz.

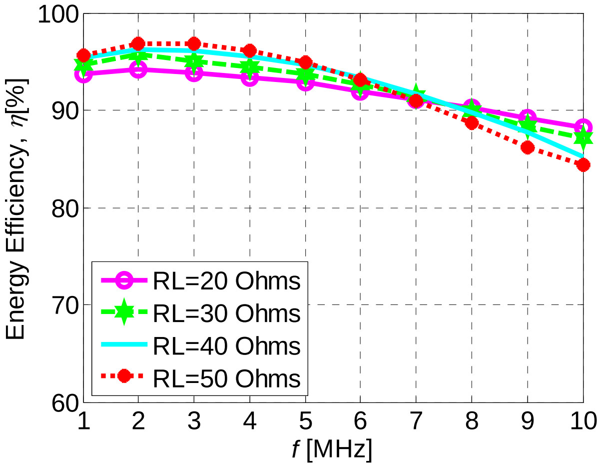

Fig.12. Efficiency of the transformer Tr2 with different loads at C_r=1.5nF

The energy efficiency of the transformer is approximately 97% at load resistance of 50 Ω with a load power of about 10Watts at a frequency of 2MHz which can be observed from fig (12). Here, the input voltage is 40Vrms with an output load current of 0.459Amp. At the load resistance of 20 Ω the efficiency is approximately 94.5% with an output power from the transformer is of about 20 Watts and with the load current of 0.98 Amp. At this instant the input voltage fed to the primary winding of the transformer is 40Vrms.

(B) *Energy Efficiency of the transformers Tr1 and Tr2 with different resonant capacitors*

The measured energy efficiency of the transformers Tr1 and Tr2 with different resonant capacitors at the resistive load of 30 Ω is illustrated in fig. 13 and 14 respectively.

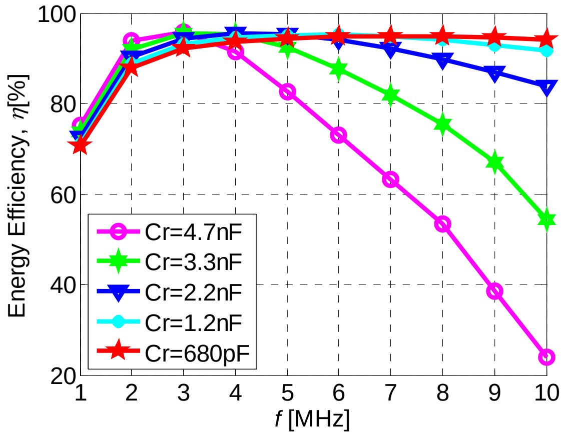

Fig. 13. Measured energy efficiency of the transformer Tr1 with different resonant capacitors and at RL=30Ω.

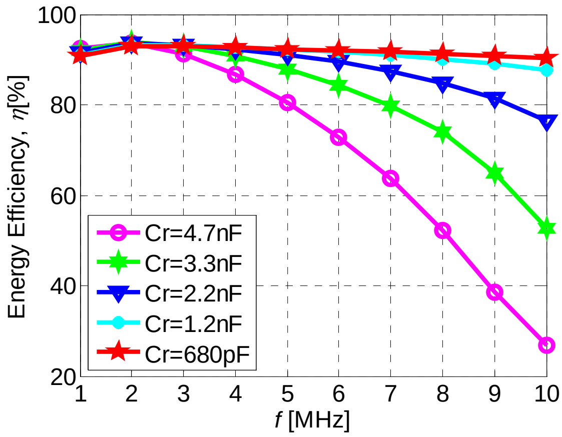

Fig. 14. Measured energy efficiency of the transformer Tr2 with different resonant capacitors and at R_L=30Ω.

As the resonant capacitor value across the secondary winding of the transformer increases, the maximum energy efficiency frequency moves towards the lower operating frequencies which can be observed from fig. 13 and 14.This is because their corresponding maximum gain frequency and maximum impedance frequency are decreased with the increased value of the capacitors. Hence, with the proper selection of resonant capacitor across the transformer, it can be operated at the desired lower frequencies by still maintaining the high energy efficiency.

(C) *Energy Efficiency of the transformers Tr1 and Tr2 with Sinusoidal and Square wave excitation*

For most of the SMPS applications the input voltage fed to the power transformer is of square wave in nature. Therefore, the power tests were carried out for both the sinusoidal and square wave excitations for these two transformers Tr1 and Tr2 and the energy efficiencies are shown in fig. 15.

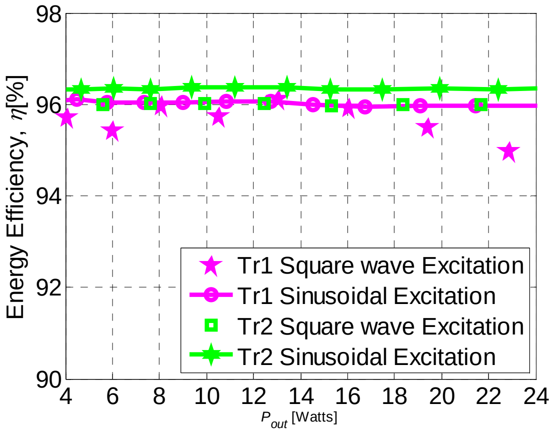

Fig. 15. Efficiency of the transformer Tr1 and Tr2 for different excitations with R_L=30Ω and C_r=1.5nF at 4 and 2MHz respectively.

The energy efficiency of the transformer Tr1and Tr2 is measured at a load resistance of 30Ω with an external resonant capacitor of 1.5nF and is shown in fig.15. The maximum impedance frequency of the transformer Tr1 is at 4.8MHz and the energy efficiency is found to be approximately 96% at 4MHz with the output power range of 4-24Watts for both the excitations. The efficiency of transformer Tr2 is found to be approximately 96.3% at the frequency of 2 MHz for both sinusoidal excitation.The efficiency of the transformers Tr1 and Tr2 for square wave excitation is not varied significantly with respect to sinusoidal excitation, hence these transformers can be utilized well in the SMPS applications together with mosfets which has low rise and fall times in order to reduce mosfet switching losses.

The waveforms were captured at maximum energy efficiency frequency of Tr1 at 4MHz are illustrated in fig.16. The load resistance considered is of 30 Ohms and the external resonant capacitor is 1.5nF. Here, the RMS values of the primary voltage, V_{pri}, secondary voltage, V_{sec}, primary current, I_{pri} and the secondary current, I_{sec}, of coreless PCB step down transformer are illustrated. In this case, the load power is approximately 12.5 watts and energy efficiency is of about 96%.

VI. Application Potential of the Designed Transformers

The designed two transformers Tr1 and Tr2 are compared with existing transformers of coil craft in terms of their dimensions for various output power levels of about 8, 15 and 30 Watts. For these different applications the required input

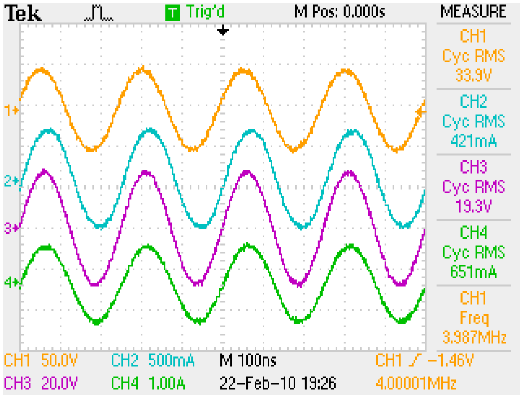

Fig. 16. Measured waveforms with Cr=1.5nF and RL=30 Ω. CH1 – V_{pri} (50V/div), CH2 – I_{pri} (500mA/div), CH3 – V_{sec} (20V/div), CH4 – I_{sec} (1A/div)

voltage range, output voltage, output current, dimensions and percentage volume reduction of designed transformers are listed in table II.

TABLE II

EXISTING CORE BASED TRANSFORMERS DIMENSIONS, PART NUMBER AND ELECTRICAL CHARACTERISTICS

V_{in} (Volts)	V_{in} (Volts)	I_{out} (Amps)	Power (Watts)	Dimensions in mm & part number(Coil craft)	%Volume reduction of Tr1, Tr2
18-36	15	0.53	8	15.24x12.7x11 FCT1-150L2SLB	72, 37
18-36	15	1.00	15	17.7x13.4x12 FCT1-150M2SLB	79, 53
36-72	24	1.25	30	30x20.5x11.4 FCT1-150M2SLB	91, 81

For the 8 Watt application mentioned in the table II, the transformer Tr1 and Tr2 are fed with an input voltage of about 30Vrms and the energy efficiency of Tr1 and Tr2 are 95.7% and 96.3% respectively. Similarly, for 15 Watt application the input voltage applied to the transformers is 35Vrms and the energy efficiency of these transformers is of about 92.4% and 93.5% respectively. For 30 Watt application the input voltage given to the transformers is approximately 56Vrms and the measured energy efficiency of the transformers are 93.7% and 94.8% respectively. In all the cases i.e., for 8, 15 and 30watt applications we can observe that the energy efficiency of the transformer Tr2 is slightly greater when compared to that of the transformer Tr1. In this case, even though the AC resistance of the transformer Tr2 is greater than Tr1, the efficiency is higher because of the high coupling coefficient. With these designed multilayered coreless PCB transformers the height of the transformers used in converters gets reduced significantly from 12mm to 1.48mm and in some cases the size of the converter can be the size of the transformer. Therefore, for the SMPS applications which require very tight restrictions on the height of the transformer, transformers Tr1 and Tr2 can be utilized when compared to the existing transformers.

VII. Conclusions

In this paper the design, analysis and the application potential of multilayered coreless PCB 2:1 step down transformers for DC/DC converter applications has been presented. The transformer primary and secondary windings are etched on the Fr4 PCB laminate. The high coupling coefficient of the transformers is achieved by increasing the number of turns of the transformer and also by sandwiching the secondary winding between the two primary windings. The high frequency equivalent circuit model has been verified for these multilayered coreless PCB step down transformers. These fabricated transformers have been tested for the output power levels upto 30Watts and the energy efficiency is found to be within the range of 90-97% for both the transformers. Transformer Tr2 has higher energy efficiency with respect to Tr1 and can be utilized for the abovementioned applications. From the observations we can conclude that these step down 2:1 multilayered PCB transformers are highly energy efficient and can be used in SMPS for power transfer applications in MHz region.It was proven that the high energy efficiency of the step down transformers is possible by increasing the step down ratio for higher power ratings and reduced voltages which was not possible with just two layered 1:1 transformer [11].This provides the scope for further increase of step down ratio of the transformer for different SMPS applications.

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