Design of Coreless printed circuit board (PCB) Step-Down Transformer –An Assessment of the Optimal Operation Frequency

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Abstract : *Coreless PCB transformers are one of the most efficient transformers due to their zero core losses, low cost and simplicity of the fabrication. In this paper, a novel two layers PCB transformer is designed and simulated using CST Studio 3D software. In addition, since the optimal operating frequency has a profound impact on the efficiency of the circuit, this parameter is identified using simulation in this work.*

Keywords - *Coreless PCB transformer, maximum coupling frequency, coupling coefficient, resonant frequency*

I. INTRODUCTION

For over a century, transformers have been used for electrical isolation and energy/signal transfer. In traditional transformers, ferrite cores have been employed to provide the magnetic path for signal and energy transfer. High manufacturing/labour cost, large size and high weight are serious challenges of manually-wound transformers and inductors. Skin and proximity effects, leakage inductance and unbalanced magnetic flux distribution are other problems involved in high frequency magnetic which generate localized hot spots and reduce the coupling coefficient. Recently, planar technology has been employed to reduce cost, weight, and size maintaining high power density (at least 24 W/cm^2). Coreless printed circuit board (PCB) transformers have the benefits of low cost, very high power density, no limitation due to magnetic cores, no magnetic loss and ease of manufacturing [1]. Owing to the low cost and simple transformer construction, a coreless PCB step-down transformer can be applied for industrial applications such as DC-DC converters for applications like WLAN Access-points, Power over Ethernet, IP phones, Switch Mode Power Supply (SMPS) and for a wide variety of telecom applications. This paper presents the design, simulation, and theory of coreless PCB step-down transformer.

II. PROPOSED DESIGN

In order to design coreless PCB, step down transformer have been used from three spiral windings which are etched on the two layers of the FR-4 PCB laminate with approximate breakdown voltage 50kv/mm. In this design, there are two primary windings (P1 and P2) in two different layers being connected by via hole and one secondary winding (S) in between the primary windings on the opposite side of the one doubled-side PCB laminate aiming to minimize the leakage inductances. In [2], the inductive characteristics of coreless PCB transformers with different geometric parameters includes: i) outermost radius, ii) number of turns, iii) conductor width, iv) laminate thickness and v) conductor thickness are investigated. Figure1 shows the designed coreless PCB transformer. The geometrical parameters play an important role in operation of transformer. The electrical parameters such as resistance, capacitance and inductance depend on geometrical parameters. The dimensions of the coils, the PCB layout, the copper thickness and the track width must be selected with respect to the maximum allowable power losses [3].The geometrical parameters of multilayer coreless PCB step-down transformer are presented in table.

Table.1. Geometrical parameters of transformer

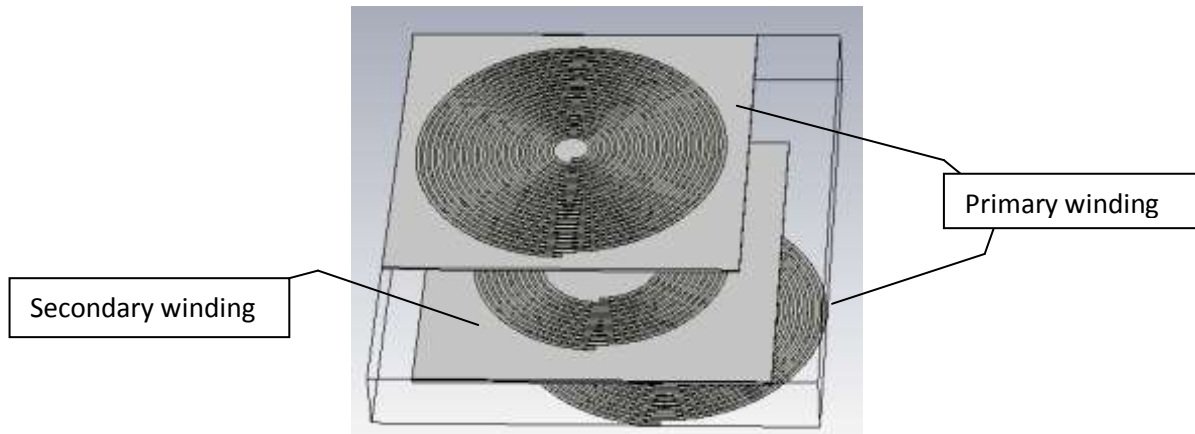| S. No	Parameters	Value
1	No. of primary/secondary turns	20/10
2	Track separation [mm]	0.4
3	Width of conductor [mm]	0.6
4	Outermost Diameter [mm]	42
5	Height of conductor [μm]	35
6	Board Thickness [mm]	0.4
7	Air gap between two layers PCB [mm]	0.4

Figure 1.Three dimensional (3-D) structure of coreless PCB transformer
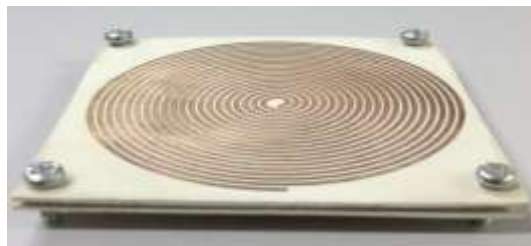

Figure 2. Prototype of Coreless PCB Step-down Transformer

III.   OPERATION OF CORELESS PCB TRANSFORMER PARAMETERS

In order to evaluate parameters such as voltage gain, input impedance and resonant frequency in this kind of transformers we have used a high frequency equivalent circuit of transformer as it is presented in Fig 3. A parallel load across the secondary winding has been employed.
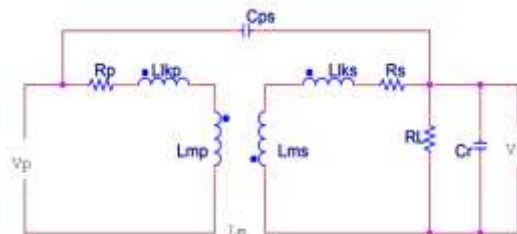

Figure 3. High frequency model of coreless PCB transformer

In this step, the electrical and initial parameters of coreless PCB step-down transformer have been calculated and measured at 100 KHz by employing a LCR meter 4263B. The electrical parameters such as the leakage/self inductance of the primary 'L_{lkp}'/'L_P' is obtained by short and open circuiting the secondary winding respectively and vice versa. The precise initial parameters of transformers are gained by passing them into the high frequency model.

Table.2. Electrical Parameters of the Transformer

S.NO	Parameters	Value
1	Primary/Secondary self inductance [μH]	46.3/11.5
2	Primary/Secondary leakage inductance [μH]	0.56/0.13
3	Primary/Secondary Mutual inductance [μH]	42.1/9.5
4	Primary/Secondary DC resistance [Ω]	0.48/0.29
5	Inter winding capacitance [pF]	21

Regarding to high frequency model of transformer, the resonant frequency (f_o), voltage gain (V_S/V_P) and the input impedance (Z_{in}) can be calculated as follows [4]-[5]-[6]:

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

where

$$L_{eq} = L_{lks}' + L_{mp} \; ?? \; L_{lkp} \qquad (2)$$

Here, L_{mp} and L_{lkp} are mutual and primary leakage inductance respectively. And L_{lks}' is secondary leakage inductance referred to the primary.

$$C_{eq} = C_r' + C_{ps}' \qquad (3)$$

Where, C_r' is sum of the secondary winding capacitance and an externally connected capacitance referred to the primary and C_{ps}' Capacitance between primary and secondary winding referred to the primary. It determines that the resonant frequency can be limited by equivalent capacitance and inductance of the circuit model. The value of resonant capacitors across the secondary winding will play an important role in the bandwidth of the transformer. The intra-winding capacitances of transformer are very small and can be ignored according to [7].

$$H(f) = \frac{V_s}{V_p} = \frac{\frac{1}{X_1} + j(2\pi f)C_{ps}'Y1}{nY} \qquad (4)$$

$$Z_{in} = \frac{1}{sC_{ps}'\left(1 - n \times \frac{V_s}{V_p}\right) + \frac{(1-A)}{X_1} + sC_{pp}'} \qquad (5)$$

Where 'n' is number of turns

$$R_s' = n^2 R_s \qquad (6)$$

$$L_{lks}' = n^2 L_{lks} \qquad (7)$$

$$C_{PP}' = C_{PP} + \frac{n-1}{n} C_{ps} \qquad (8)$$

$$C_r' = \frac{1}{n^2} C_r + \frac{1-n}{n} C_{ps} \qquad (9)$$

$$C_{ps}' = \frac{1}{n} C_{ps} \qquad (10)$$

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

$$X_2 = R_s' + sL_{lks}' \qquad (11)$$

$$Y_1 = X_2\left[\frac{1}{X1} + \frac{1}{sL_{mp}}\right] + 1 \qquad (12)$$

$$Y_2 = \frac{1}{X2} + sC_{ps}' + sC_r' + \frac{1}{n^2 R_L} \qquad (13)$$

$$Y = -\frac{1}{X_2} + Y_1 Y_2 \qquad (14)$$

$$A = \frac{sC_{ps}' + \frac{X_2}{X_1}Y_2}{Y} \qquad (15)$$

The coupling coefficient is given by [8]

$$K = \frac{L_m}{\sqrt{L_p \cdot L_s}} \qquad (16)$$

$$L_{mp} = L_p - L_{lkp} \qquad (17)$$

$$L_{ms} = L_s - L_{lks} \qquad (18)$$

$$L_m = \sqrt{L_{mp} - L_{lks}} \qquad (19)$$

Where, L_m is the mutual inductance between the primary and secondary winding and 'L_p' and 'L_s' are primary and secondary self inductance of winding.

In order to increase the input impedance, voltage gain, and the energy efficiency of the transformer, a resonant capacitor across the secondary winding has been employed.

IV. ASSESSING OPTIMAL OPERATING FREQUENCY

In this section, frequency of maximum coupling, input impedance and phase of a coreless PCB step-down transformer for operating at or near this frequency has been investigated. Finding the optimal operating frequency, results in having a better assessment, and prediction of the transformer's bandwidth. Same

parameters as shown in Table 1 are used for simulation in this section. A parallel RC load is coupled on secondary winding for simulating. In addition, the transformer is tested within the frequency range of 10KHZ-100MHz. The simulated maximum coupling input impedance and phase angle using CST Microwave Studio are plotted in Fig 4 to Fig 6. Fig 4, shows that the maximum coupling frequency (MCF) occurs at 17.848MHz. From Fig 5, it can be seen that the maximum impedance frequency (MIF) occurs at 17.848 MHz and phase angle is placed between 18 and 20.3 MHz.
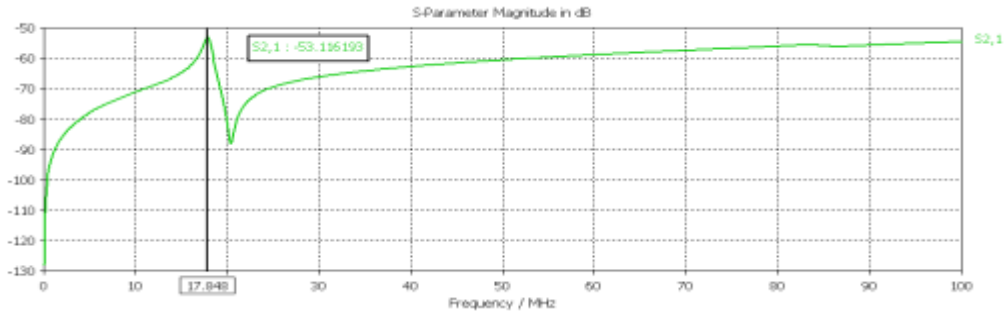
Figure. 4.The maximum coupling frequency (MCF) with C_r= 12 nF and R_L=100 Ω
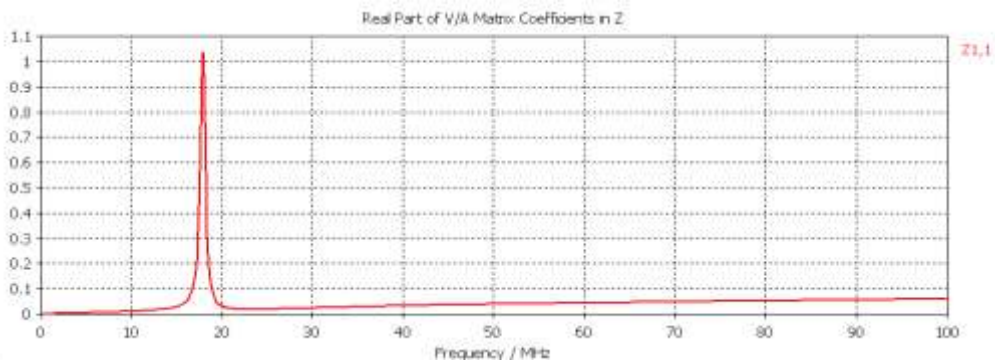

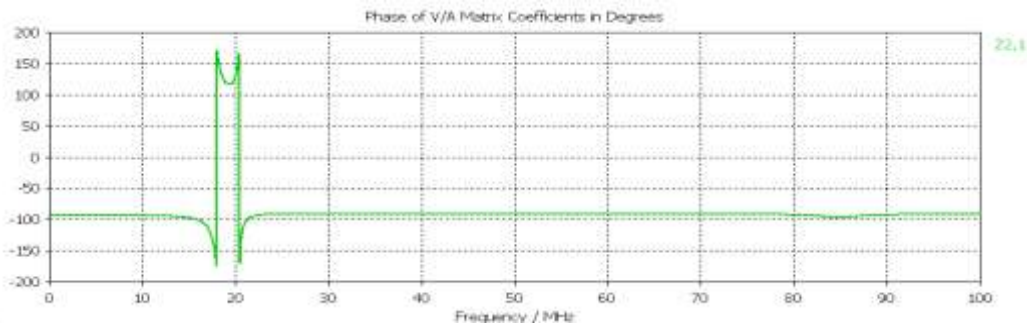Figure. 5. Simulated result of input impedance of the transformer at C_r= 12 nF and R_L=100 Ω

Figure 6. Simulated results of the phase angle of transformer at C_r= 12 nF and R_L=100 Ω

Fig. 5 shows the values of maximum coupling frequency for different load capacitance with a constant load resistance (R_L =100 Ω).
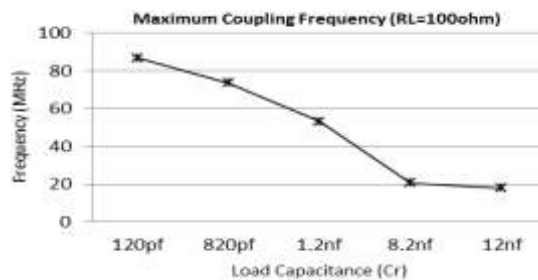

Figure 7. The values of maximum coupling frequency at different load capacitance

In order to minimize the input current and as a result, the power dissipated at the gate drive circuits, the operating frequency of the transformer should be near or at the high frequency end of the usable operating region. It also shows the output capacitance plays significant role in the bandwidth of the transformer.

V. CONCLUSION

In this paper the design, simulation and analysis of a novel coreless PCB step-down transformer were presented. The simulation results were used to evaluate the maximum coupling and the optimal operating frequency of the proposed transformer. We found that the maximum coupling frequency is almost 17.8MHz. In addition, the obtained results showed that the load capacitance across the secondary winding has an important effect on the maximum coupling frequency.

Acknowledgment

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