Development of High-Power Density, 4-kV Pulse Transformers for TWTA

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***Abstract*—Pulse transformers suitable for high-frequency and high-voltage operations in a traveling-wave tube amplifier (TWTA) had been designed, fabricated, and tested. Two transformers with different operation frequency of 100 and 80 kHz were designed, fabricated, and tested. The transformer with 100-kHz switching frequency had input and output voltages of 250 Vdc and −4.1 kV, respectively. Operating power was 3.06 kW. Achieved power density of the 100-kHz transformers was 22.26 W/cm^3. The transformer with 80-kHz switching frequency had input and output voltages of 265 Vdc and −4.1 kV, respectively. Normal operating power of the transformer was 1.67 kW. Achieved power density of the 80-kHz transformer was 12.15 W/cm^3. Three different winding arrangements for the 80-kHz transformer were tested and it was found that the one with a sandwiched primary between secondary windings had the best performance in electrical characteristics. It was possible to reduce the stray capacitance while maintaining low-leakage inductance with the best arrangement. Therefore, the self-resonant frequency was far separated from the operating frequency, and, thus, the new arrangement minimized the self-resonant current that is generally one of source for transformer temperature rise.**

***Index Terms*—High-power density, pulse transformer, traveling-wave tube amplifier (TWTA).**

I. Introduction

MANY applications, such as traveling-wave tube amplifiers (TWTAs), require high-voltage power supplies. Magnetic components in the power supplies contribute about 25% of the power supply volume and more than 30% of the overall weight [1]. Therefore, the magnetic components are a key to achieving a compact and high-power density system. It becomes general to use high-frequency switching technology in designing a high-power density power supplies. Such power supplies can use compact high-power density pulse transformers. To produce a high-voltage output, pulse transformers should have a high stepup ratio. The stepup ratio is generally limited due to stray capacitance and leakage inductance of the pulse transformers. We designed high-voltage, high-frequency pulse transformers for TWT amplifier high-voltage power supplies (HVPSs). Two transformers with different operation frequency of 100 and 80 kHz were designed, fabricated, and tested. For a 100-kHz transformer, required input voltage of the TWT HVPS was 250 Vdc. The HVPS requires two output for cathode and collector, and their voltages are −4.1 and −2.05 kV, respectively. From the fundamental parameters, turn ratios of the transformer are calculated as 16.4 and 8.2 for −4.1 and −2.05 kV secondary outputs, respectively. For a 80-kHz transformer, required input voltage of the TWT HVPS was 265 Vdc. The HVPS requires two output for cathode and collector, and their voltages are −4.1 and −1.9 kV, respectively. From the fundamental parameters, turn ratios of the transformer are calculated as 15.4 and 7.2 for −4.1 and −1.9 kV secondary outputs, respectively. In the case of direct winding of the transformer, turn ratios are relatively large and, thus, increase the values of parasitic elements, such as leakage inductance and parasitic capacitance. Those parasitic elements will induce unacceptably high self-resonance current. We overcome such limit by adapting multisecondary windings with suitable stepup ratios. We also developed a special winding arrangement to optimize the electrical parameters.

TABLE I
Electrical Parameters of 100-kHz Pulse Transformer

Frequency/Efficiency/Duty	100 kHz/90%/0.9	
Primary voltage	253 Vdc	
	240 Vrms	
Secondary voltage (s1/s2/s3/s4)	520 Vrms	
	548 Vdc	
Total power	Input	3,057 W
	Output	2,746 W
Total current	Input	12.74 Arms
	Output	5.28 Arms
Turn ratio(primary = 1)	S1, s2, s3, s4 = 2.167	

II. Transformer Design

A. Electrical Requirements

A full-bridge topology was used at the primary side of the transformer. Input and output requirements of the 100-kHz transformer are listed in Table I. Pulse duty of 0.9 and transformer efficiency of 90% are used. Fig. 1 shows the pulse transformer connection scheme with the load. As shown in Fig. 1, all secondary windings are connected in series to finally produce the required high voltage of −4.1 kV after voltage doublers. Designed minimum insulation of transformer is 6 kVdc. Input and output requirements of the 80-kHz transformer are listed in Table II. We used pulse duty of 0.64 and transformer efficiency of 90%. Fig. 2 shows the pulse transformer connection scheme with the load. As shown in Fig. 2, all secondary windings are connected in series to finally produce the required high voltage of −4.0 kV after rectifiers.

B. Core Selection

Various core materials are reviewed, and Magnetic ferrite EC type core 47 228-EC with R material is selected [6]. The core

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Digital Object Identifier 10.1109/TPS.2004.835953

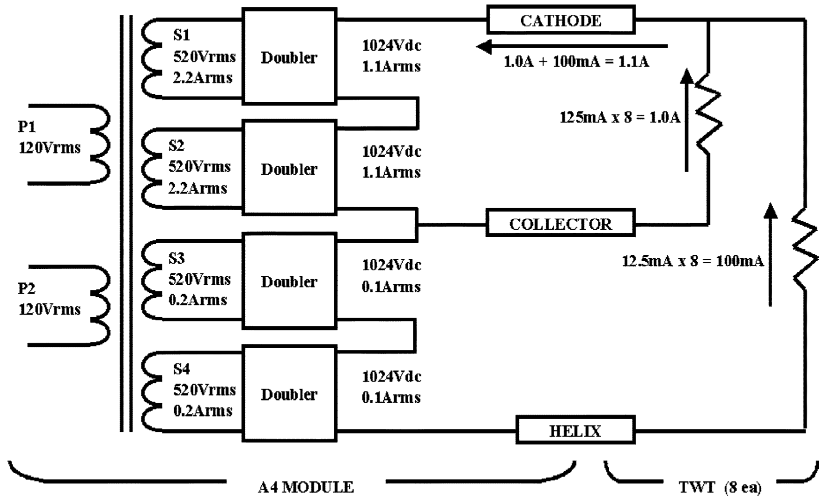

Fig. 1. 100-kHz pulse transformer connection diagram with HV part.

TABLE II
ELECTRICAL PARAMETERS OF 80-kHz PULSE TRANSFORMER

Frequency/Efficiency/Duty	80 kHz/90%/0.64	
Primary voltage	265 Vdc	
	212 Vrms	
Secondary voltage (s1/s2)	1100 Vrms	
	1375 Vdc	
Secondary voltage (s3/s4)	1166 Vrms	
	1458 Vdc	
Total power	Input	1668 W
	Output	1501 W
Total current	Input	7.87 Arms
	Output	1.36 Arms
Turn ratio(primary = 1)	S1, S2 = 5.19	
	S3, S4 = 5.5	

has 50.5 cm^3 volume (V_e). Calculated core losses at 1500 G are 10.2 W for 100 kHz and 6.2 W for 80-kHz operating frequency. Total usable power of the core at 1500 G is respectively 12.4 and 9.9 kW for 100 and 80 kHz. Therefore, the selected core has enough power handle capability than the required transformer power of 3.06 kW for 100 kHz and 1.67 kW at 80 kHz [7].

C. Insulation Film and Wire

To have the required dielectric strength of 6 kV in the transformer, H-type Kapton film (breakdown strength: 275 kV/mm) is used as an insulation film. Layer-to-layer insulation thickness between primary and secondary winding is chosen 2 mil that gives more then 2.3 insulation safety margin between windings. Current density of transformer winding is assumed as 500 Dcma (circular mil/A). The skin depth of copper wire at the operating frequency of 100 kHz is 0.225 mm. To fully occupy the copper area, cross-sectional wire dimension should be smaller than the skin depth. Therefore, at the 100-kHz operation, we used copper foil with 0.2-mm thickness as the primary winding. Two types of Litz wires, which are 35 AWG $\times$ 50 strand and 35 AWG $\times$ 10 strand, are selected for the secondary windings of high-current outputs (S1 and S2 in Fig. 1) and low-current outputs (S3 and S4 in Fig. 1), respectively. For the 80-kHz transformer, we used 35 AWG $\times$ 200 strand Litz as the primary winding. Two types of Litz wires, which are 35 AWG $\times$ 20 strand and 35 AWG $\times$ 10 strand, are selected for the secondary windings of high-current outputs (S1 and S2 in Fig. 2), and low-current outputs (S3 and S4 in Fig. 2), respectively [2]–[5]. Utilization factor of the Litz wires is assumed as 0.64. Tables III and IV summarize wire design values for each transformer.

D. Winding Design and Arrangement

The windings are arranged so that the magnetomotive forces between primary and secondary are balanced. Fig. 3 shows transformer winding design procedure. With the core, insulation film, and wire, the transformer losses are calculated for different flux densities [3]–[5]. Considering available window area of the core, total transformer loss, and temperature rise, operation flux densities are selected as 1500 G for 100 kHz and 1400 G for 80 kHz. Tables V and VI are winding summary of the transformer for 100 and 80 kHz. Fig. 4 shows the winding arrangement of the 100-kHz transformers. It shows a symmetric half of the winding arrangement. The two primary (p1 and p2) are positioned in the middle, and high-current secondary windings (s1 and s2) are arranged near the primary to cancel out as much flux as possible, from which the proximity effect can be minimized. The other two low-current secondary windings (s3 and s4) are positions after the high-current secondary windings since the current is lower than others, and, thus, they have less proximity effects to others. The 80-kHz transformers is tried three different winding arrangements to find an optimum operation condition. Those arrangements are shown in Figs. 5–7. Primary winding is winded on whole length of the core bobbin while secondary windings are separated by half-length of the bobbin. The followings explain the main differences of each type.

1) Type-I: Primary winding is arranged at the most inner side of windings as shown in Fig. 5.
2) Type-II: Primary winding is arranged in the middle of windings as shown in Fig. 6.
3) Type-III: Primary winding is arranged at the most outer side of windings as shown in Fig. 7.

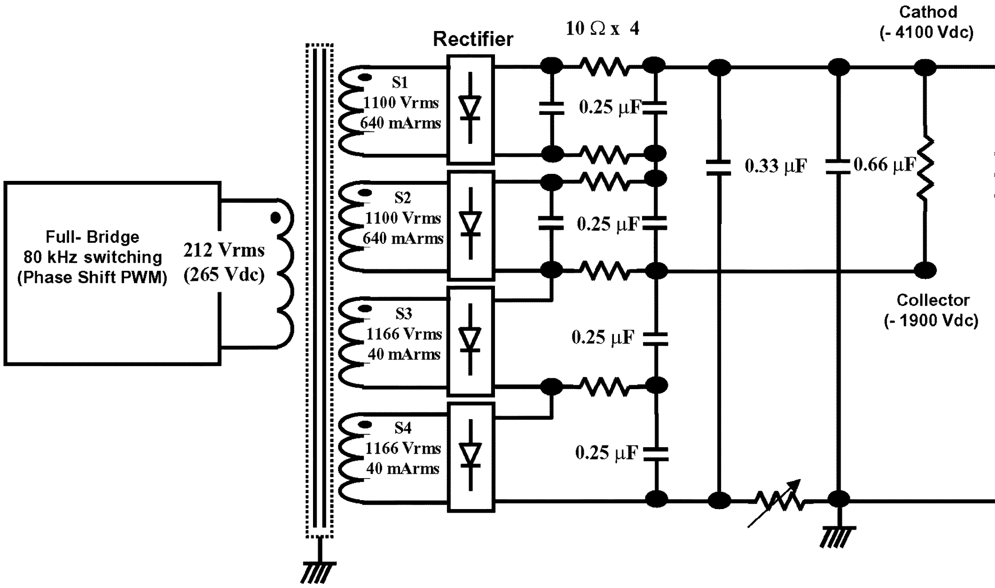

Fig. 2. 80-kHz pulse transformer connection diagram with HV part.

TABLE III
WIRE AND INSULATION DESIGN SUMMARY FOR 100-kHz TRANSFORMER

Wire	Primary(p), Foil	Foil width: 23.46 mm
		Foil thickness: 0.2 mm
	Secondary (s1, s2) Litz (35AWG x 50)	copper area: 0.7697 mm^2
		Copper + insulation area: 1.132 mm^2
		Copper + insulation diameter: 1.2 mm
	Secondary(s3, s4) Litz (35AWG x 10)	copper area: 0.1539 mm^2
		Copper + insulation area: 0.2264 mm^2
		Copper + insulation diameter: 0.537 mm
Insulation		Kapton H-type film Thickness: 2 mil(0.05 mm) Breakdown strength: 275 kV/mm

TABLE IV
WIRE AND INSULATION DESIGN SUMMARY FOR 80-kHz TRANSFORMER

Wi re	Primary(p) Litz (35AWG x 200)	Copper area: 3.079 mm^2
		Copper + insulation area: 4.5276 mm^2
		Copper + insulation diameter: 2.401 mm
	Secondary (s1, s2) Litz (35AWG x 20)	Copper area: 0.3078mm^2
		Copper + insulation area: 0.4528 mm^2
		Copper + insulation diameter: 0.7593 mm
	Secondary(s3, s4) Litz (35AWG x 10)	Copper area: 0.1539 mm^2
		Copper + insulation area: 0.2264 mm^2
		Copper + insulation diameter: 0.537 mm
Insulation		Kapton H-type film Thickness: 2 mil(0.05 mm) Breakdown strength: 275 kV/mm

III. MEASUREMENT

Electrical parameters of the transformers are measured and the results are listed in Tables VII and VIII. Measured parameters are quality factor (Q), leakage inductance (L_l) at the primary side, winding capacitance (C_w), and self-resonant frequency (f_r). The resonant frequency of the transformer is recorded at the instance of maximum primary voltage during frequency scan from 1 kHz to 10 MHz while the secondary is open. Since the resonance occurs with parallel arrangement of primary inductance (L_p) and distributed capacitance (C_d) at the primary side, distributed capacitance can be calculated from the following [8]:

$$C_d = \frac{1}{\lfloor (2 \times \pi \times f_r)^2 \times L_P \rfloor}. \quad (1)$$

As listed in Table VII, the resonance frequencies for 100-kHz transformer is extremely higher than the operating frequency of 100 kHz. The effect of self-resonant current on the transformer operation becomes minimum. Winding capacitance is 88 times higher than distributed capacitance. The quality factor of the winding is also higher than a typical requirement of greater than 40 in pulse transformer design. As shown in Table VIII, Type-II winding arrangement has the lowest leakage inductance of 2 μH, and the highest resonant frequency of 1.4 MHz. With high self-resonant frequency than the operating frequency, the effect of self- resonant current on the transformer operation becomes minimum. Winding capacitance and the quality factor are also high enough to have good electrical characteristics. Therefore, we can conclude from the parameter measurement that the Type-II can be considered the best arrangement among those three.

IV. OUTPUT WAVEFORMS

Output waveforms for each secondary winding are measured. The primary winding is excited from a full bridge FET switching circuit. Typical waveforms are given in Fig. 8. As can be seen in the figure, outputs are perfectly reproducing the 100-kHz switching waveforms without any resonance on the turn-on and turn-off timing. On the flat top of the pulse, there are no signs of oscillation. To test the 80-kHz transformer operation performance, each transformer was connected such as shown in Fig. 2, and output waveforms of each secondary windings are measured. The primary winding was excited from a full bridge FET switching circuit. Switching frequency of

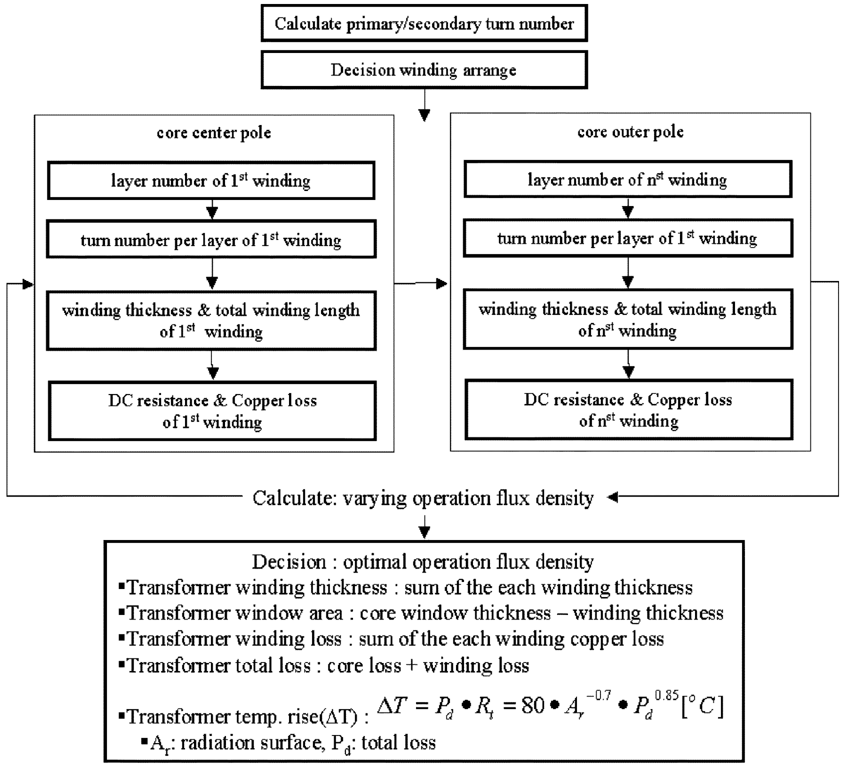

Fig. 3. Transformer winding design procedure.

TABLE V
WINDING DESIGN OF 100-kHz TRANSFORMER

Operation flux density		1500 G
Turn/layer	Primary	12 turn/12 layer
	S1, S2	26 turn/2 layer
	S3, S4	26 turn/1 layer
Winding/window thickness(mm)		10.13/12.01
Transformer loss(W)		12.2
Temperature rise(°C)		44.15

TABLE VI
WIRE AND INSULATION DESIGN SUMMARY FOR 80-kHz TRANSFORMER

Operation flux density		1400 G
Turn/layer	Primary	15 turn/2 layer
	S1, S2	78 turn/9 layer
	S3, S4	83 turn/7 layer
Winding/window thickness (mm)		10.02/12.3
Transformer loss (W)		5.67
Temperature rise (°C)		23.3

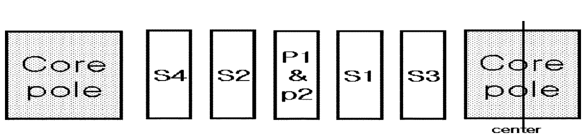

Fig. 4. Winding arrangement of 100-kHz transformer.

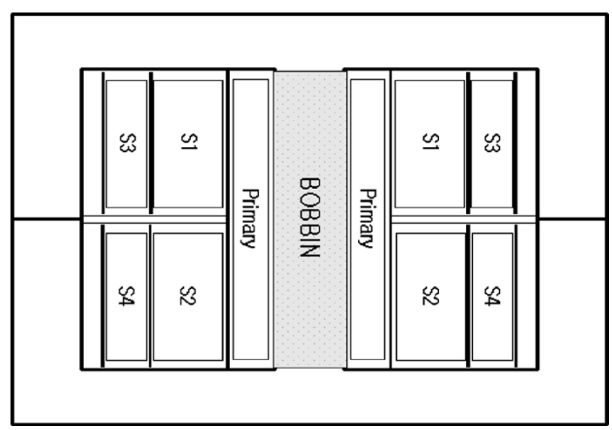

Fig. 5. Type-I winding arrangement of 80-kHz transformer.

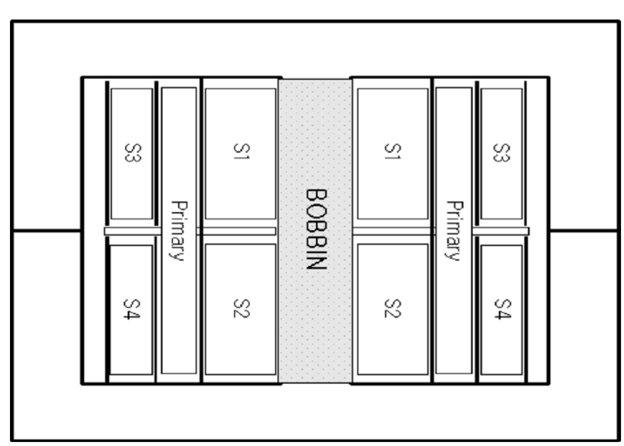

Fig. 6. Type-II winding arrangement of 80-kHz transformer.

the transformer was 80 kHz. The waveforms in Figs. 9–11 are results for the transformers of Type-I, Type-II, and Type-III, respectively. All waveforms shown in the figures are very well reproducing the input 80-kHz switching signals. However, we can see small resonant marks on flat-tops of S3 and S4 outputs of Type-I and S1 and S2 outputs of Type-III. We cannot find

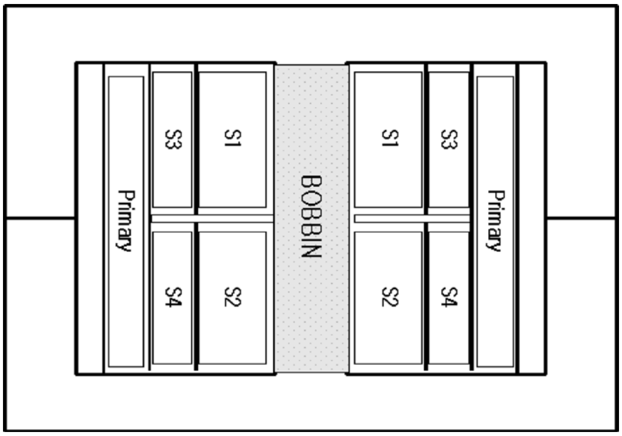

Fig. 7. Type-III winding arrangement of 80-kHz transformer.

TABLE VII
MEASURED PARAMETERS FOR 100-kHz TRANSFORMER(1500 G)

Quality factor, Q, @100 kHz	> 115
Leakage inductance, L_l (μH)	2.04
Winding capacitance, C_W (pF)	277
Resonant frequency, f_r (MHz)	4
Primary inductance, L_p (μH)	505
Distributed capacitance, C_d (pF)	3.13

TABLE VIII
MEASURED PARAMETERS FOR 80-kHz TRANSFORMER (1400 G)

Winding arrangement	Type-I	Type-II	Type-III
Quality factor, Q, @ 80 kHz	> 10	> 45	> 44
Leakage inductance, L_l (μH)	6.03	2	6.23
Winding capacitance, C_W (pF)	116	237	120
Resonant freqequency, f_r (MHz)	0.75	1.4	1
Primary inductance, L_p (μH)	7421	705	890
Distributed capacitance, C_d (pF)	6	18.4	28.5

any such resonant marks for the case of Type-II. This also confirms that the Type-II has the highest resonant frequency and is optimal winding arrangement among three different types.

V. CONCLUSION

High-power density, high-frequency, and high-voltage pulse transformers for TWT HVPSs are designed, fabricated, and tested. Two transformers with different operation frequency of 100 and 80 kHz were designed, fabricated, and tested. The transformer with 100-kHz switching frequency had 250-Vdc primary input voltage and two outputs of −2.05 and −4.1 kV. Operating power was 3.06 kW. Achieved power density of the 100-kHz transformer was 22.26 W/cm^3. The transformer with 80-kHz switching frequency had 265 Vdc primary input voltage and two secondary outputs of −1.9 and −4.1 kV. Normal operating power of the transformer was 1.67 kW. Achieved power density of the 80-kHz transformer was 12.15 W/cm^3. The tested transformers showed good electrical characteristics, such as high-quality factor, low-leakage inductance, low-stray

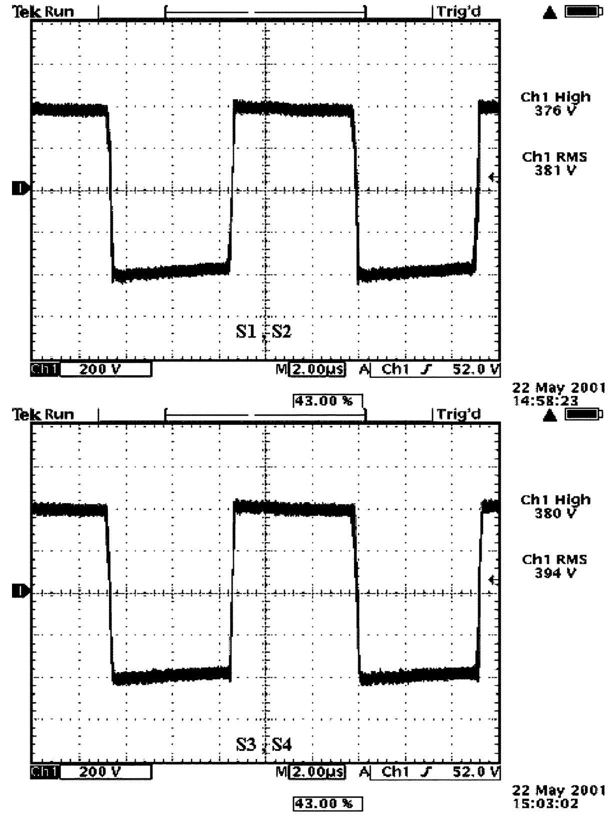

Fig. 8. Output waveforms of 100-kHz transformer.

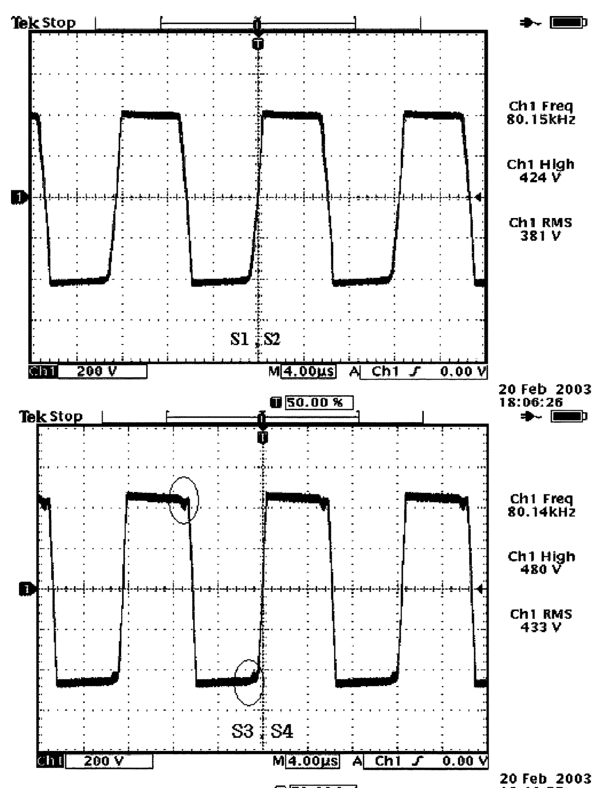

Fig. 9. Output waveforms of 80-kHz type-I transformer.

capacitance, and high self-resonance frequency. The secondary winding was arranged to have four outputs to reduce values

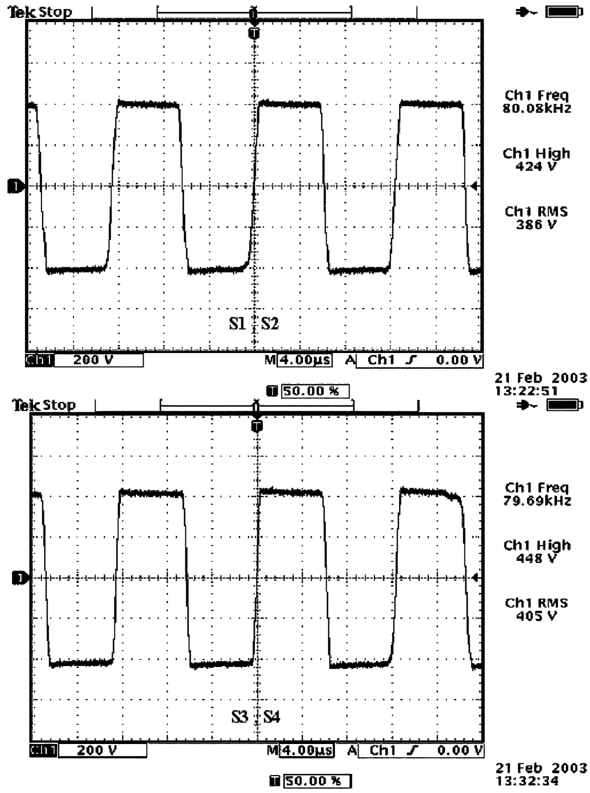

Fig. 10. Output waveforms of 80-kHz type-II transformer.

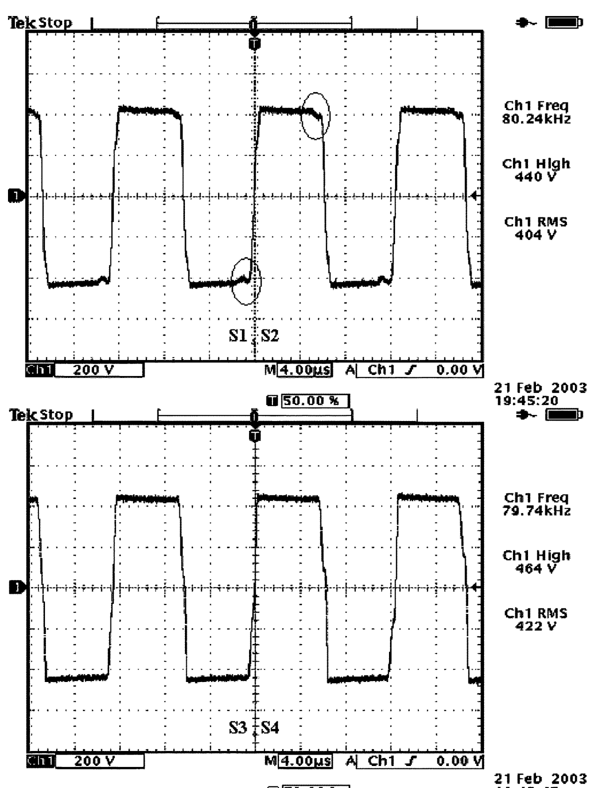

Fig. 11. Output waveforms of 80-kHz type-III transformer.

of stray capacitance and leakage inductance. Large parasitic elements can produce large peak values of self-resonant current and, thus, unacceptably increase the operating temperature of the transformer. Three different winding arrangements for the 80-kHz transformer were tested and found that the one with primary winding, which is arranged in the middle of windings, had the best performance.

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