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RESEARCH ARTICLE

60 W Class-E/F_3 Switching Power Amplifier With an Improved Second Harmonic Distortion of −49 dBc

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ABSTRACT This paper presents a Class-E/F_3 switching power amplifier (SPA) with reduced second harmonic leakage using parallel resonant circuit in series for the second harmonics. The proposed Class-E/F_3 SPA has a structure utilizing a series resonant circuit in shunt for the third harmonic, designed to function as a shunt capacitor for the fundamental, and an additional parallel resonant circuit for the second harmonic, designed to operate as a series inductor for the fundamental. Using the proposed scheme, a Class-E/F_3 SPA was designed and implemented for 6.78 MHz, and was evaluated with various supply voltages. It exhibited output power levels ranging from 10.26 to 59.98 W (40.11 to 47.78 dBm) with supply voltages ranging from 10 to 24 V. The efficiency was maintained at over 89.25%. Additionally, it demonstrated very low second and third harmonic distortion levels, each not exceeding −49.98 dBc, while the total harmonic distortion (THD) ranged from 1.54% to 2.15%.

INDEX TERMS Class-E/F_3 switching power amplifier, SPA, Class-E, switching amplifier, resonant circuit, total harmonic distortion, harmonic distortion.

I. INTRODUCTION

Recently, wireless power transmission (WPT) technology has been used in various fields to provide user the convenience of charging. Class-E switching power amplifiers (SPAs) have been popularly used in the transmitter of the WPT systems [1], [2], [3], [4], [5], [6], [7], [8]. The Class-E SPA has a simple structure consisting of a shunt capacitor, series resonant circuit, and matching network, and ideally, has 100% efficiency. The ideal series resonant circuit of the Class-E SPA passes only the fundamental components, and completely rejects all other harmonics. However, the practical series resonant circuit of the Class-E SPA cannot completely reject all harmonics, causing degradation in total harmonic distortion (THD), and possibly reducing efficiency. To achieve high efficiency and low THD, additional resonant circuits could be deployed to reduce harmonic leakage.

Class-EF_n or Class-E/F_n are based on a Class-E SPA with resonant circuits for harmonic control. Class-EF_2 and Class-E/F_3 SPAs are the representative examples [9], [10], [11], [12], [13], [14], and [15]. The Class-EF_2 SPA has a series resonant circuit for the second harmonics in shunt. In [10] and [11], design parameters of the Class-EF_2 SPA, such as the maximum output capability, maximum switching frequency, and maximum output power were analyzed using the ratio (k) between the capacitor in the series resonant

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circuit for the second harmonics and the shunt capacitor, and the duty cycle (D). Despite achieving very high efficiency of 91% at 6.78 MHz, the Class-E SPA in [11] still has a high THD of 37.61%. References [12] and [13] proposed a series resonant circuit for the third harmonic that satisfies zero voltage switching (ZVS) / zero derivative voltage switching (ZDVS) through analysis of the Class-E/F_3 SPA that includes nonlinear parasitic capacitance. The Class-E/F_3 SPAs in [12] and [13] showed high efficiency of 93.45% and 95.45%, and moderately low THD of 4.35% and 5.1% at 4 MHz, respectively. Reference [14] proposed a Class-E/F_3 SPA that has decreased maximum switching voltage by analyzing the gate-to-drain and drain-to-source parasitic capacitors. The Class-E/F_3 SPA showed high efficiency of 95% with a moderately low THD of 4.86% at 4 MHz.

To achieve even lower THD, there have been SPAs that use multiple series resonant circuits to reject more than single harmonics and/or use push-pull structure to reject the even harmonics [16], [17], [18], [19], [20]. The SPAs consist of multiple series resonant circuits for more than single harmonics [16], [17]. Reference [16] presented the Class-$EF_{2,3}$ and Class-E/$F_{3,2}$ SPAs using series resonant circuits for the second and third harmonics. Reference [17] proposed an SPA that includes a multi-resonant-frequency (MRF) filter composed of series resonant circuits for the third, fifth, and seventh harmonics. The SPA in [17] showed low THD of 4.23% at high output power of 300 W and a frequency of 390 kHz. References [18], [19], and [20] proposed the push-pull SPAs. Reference [20] introduced a symmetrically driven push-pull Class-E SPA that exhibited output power levels of 50 to 270 W with very low THD of 0.78% at 1.2 MHz. However, these multiple resonant circuits of push-pull structures significantly increase the complexity and cost of the overall circuits.

In this paper, a Class-E/F_3 SPA with reduced second harmonic leakage using an additional parallel resonant circuit for the second harmonic is proposed. The proposed Class-E/F_3 SPA has a structure with a series resonant circuit in shunt for the third harmonic, which is used as a shunt capacitor for the fundamental, while the parallel resonant circuit to reject the second harmonic is also used as an inductor in the fundamental resonant circuit. Using the proposed scheme, a Class-E/F_3 SPA was designed and implemented to have low THD for the 6.78 MHz frequency. Its performances are presented in comparison table to those of the previously published SPAs.

II. PROPOSED CLASS-E/F_3 SPA WITH REDUCED SECOND HARMONIC LEAKAGE

Fig. 1(a) and (b) show circuit diagrams of the conventional Class-E SPA and the proposed Class-E/F_3 SPA, respectively. The conventional Class-E SPA consists of a choke inductor of L_{CHK}, a shunt capacitor of C_p, and a series resonant circuit for the fundamental with L_1 and C_1. In contrast, the proposed Class-E/F_3 SPA incorporates additional resonant circuits, including a shunt network with a series resonant circuit for

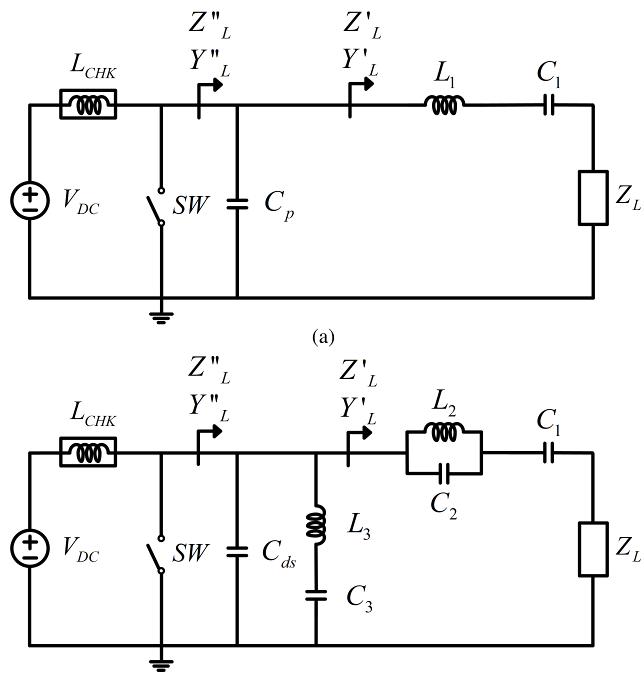


FIGURE 1. Circuit diagrams of (a) the conventional Class-E SPA, and (b) the proposed Class-E/F_3 SPA.

the third harmonics with L_3 and C_3, and series network with a parallel resonant circuit for the second harmonics with L_2 and C_2. C_{ds} is an internal parasitic capacitance for the transistor between drain and source, and C_1 is a capacitor for the series resonance for the fundamental signal.

For the Class-E/F_3 operation, the admittance on the current generator plane(or the SW plane) must be close to infinity for the third harmonic frequency. The shunt components of the proposed Class-E/F_3 SPA should be designed to have the same optimum admittance on the current generator plane for the fundamental frequency as the Class-E SPA has. To determine the values of the shunt elements right after the SW, the relationships for the shunt components of the proposed Class-E/F_3 SPA were derived as follows.

$$Y''_L(\omega) - Y'_L(\omega) = j\omega C_{ds} + \frac{1}{j\omega L_3 + \frac{1}{j\omega C_3}}, \quad (1)$$

where $Y''_L(\omega) - Y'_L(\omega)$ is an admittance of the shunt elements including C_{ds}, C_3, and L_3. Then, (1) should have the following relations at the third-harmonic and the fundamental frequency:

$$Y''_L(3\omega_0) - Y'_L(3\omega_0) = \infty, \quad (2)$$

$$Y''_L(\omega_0) - Y'_L(\omega_0) = j\omega_0 C_p, \quad (3)$$

where C_p is an optimum shunt capacitance for Class-E operation. Since C_{ds} is given as a parasitic element of transistor, the component values of L_3 and C_3 can be calculated using the relations (2) and (3) as functions of C_p

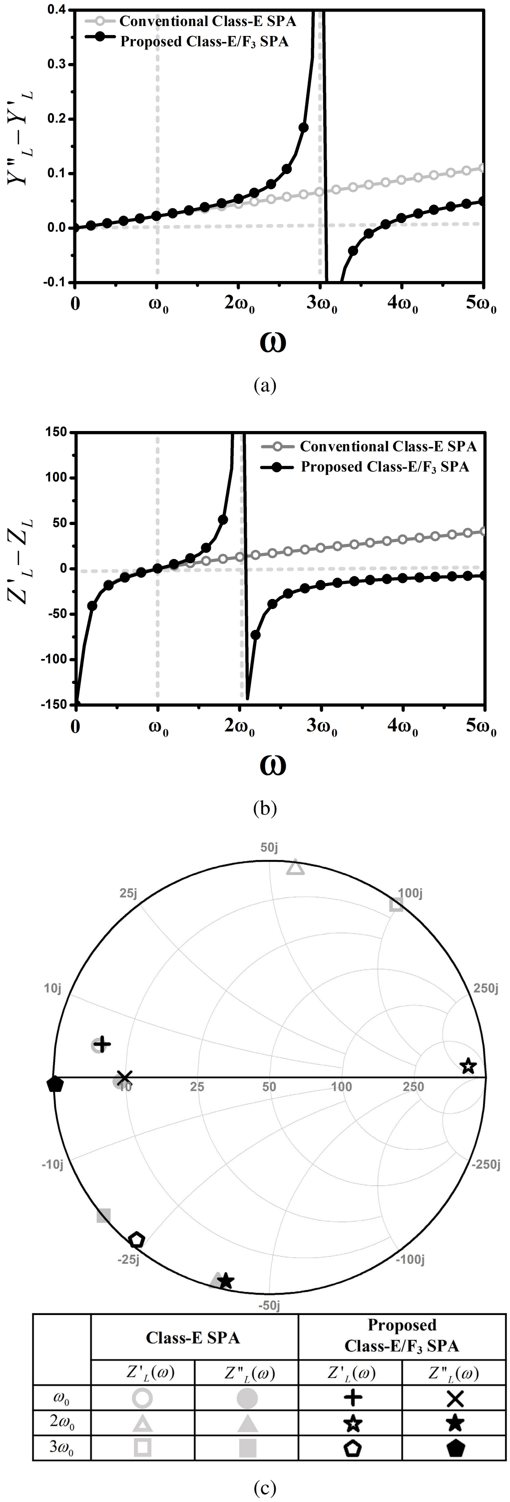


FIGURE 2. (a) $Y''_L(\omega)$-$Y'_L(\omega)$ and (b) $Z'_L(\omega)$-$Z_L(\omega)$ of the conventional Class-E and proposed Class-E/F3 SPAs as a function of frequency. (c) Simulated impedances at each reference plane on Simth chart.

and C_{ds}, as follows.

$$L_3 = \frac{1}{8\omega_0{}^2(C_p - C_{ds})}, \quad (4)$$

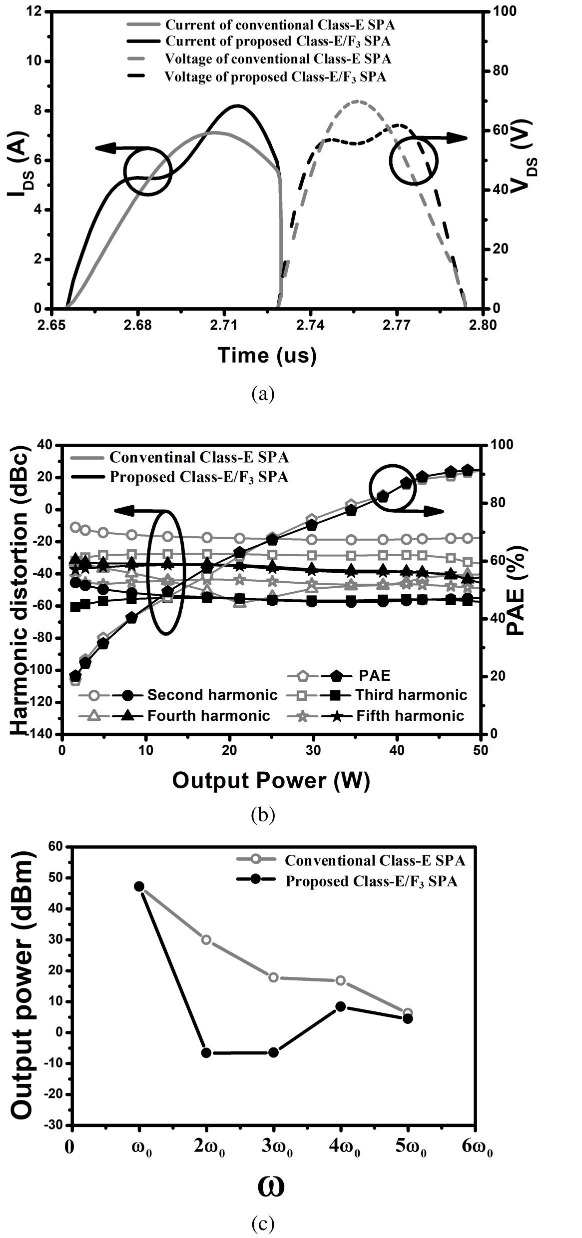


FIGURE 3. (a) Simulated current and voltage waveforms, (b) harmonic distortion and PAE, and (c) output power levels for each harmonic frequency of the conventional Class-E and the proposed Class-E/F3 SPAs.

$$C_3 = \frac{8}{9}(C_p - C_{ds}). \quad (5)$$

To suppress the second harmonic leakage to the load, the impedance of the parallel resonant circuit using L_2 and C_2 should be close to infinity at the second harmonic frequency. In addition, the impedance of the overall series circuits including the second-harmonic resonance circuit and C_1 for the proposed Class-E/F3 SPA should be the same as the series resonant circuit of the Class-E SPA at the fundamental frequency. To find the values of the series components, the impedance relationship for the series components of the

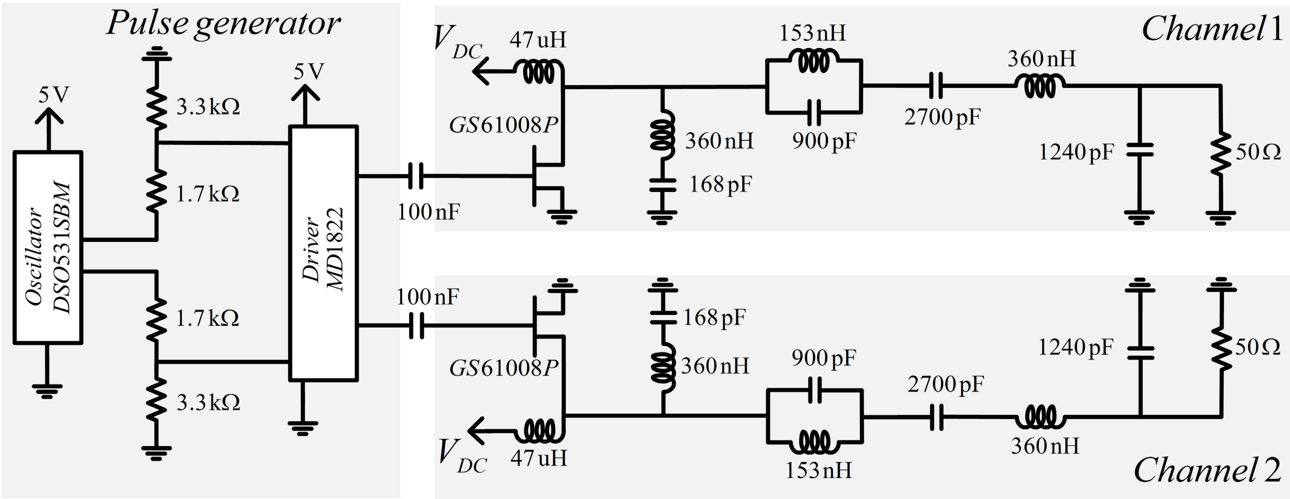
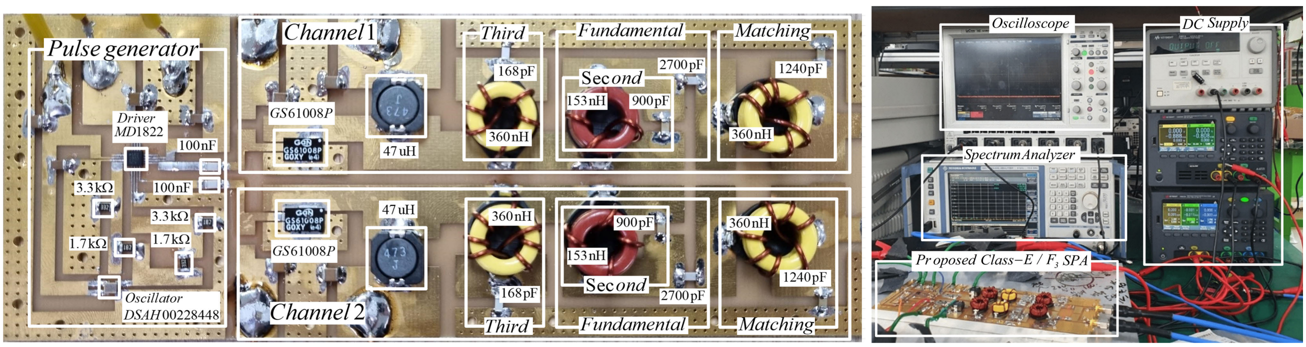


FIGURE 4. Overall schematic of the proposed Class-E/F_3 SPA.



(a) (b)

FIGURE 5. (a) Photographs of the implemented Class-E/F_3 SPA and (b) the measurement setup for the proposed Class-E/F_3 SPA.

proposed Class-E/F_3 SPA can be derived as follows.

$$Z'_L(\omega) - Z_L(\omega) = \frac{1}{\frac{1}{j\omega L_2} + j\omega C_2} + \frac{1}{j\omega C_1}, \tag{6}$$

where $Z'_L(\omega) - Z_L(\omega)$ is an impedance of the series elements including C_2, L_2, and L_1. Then, (6) should have the following relations at the second harmonic and the fundamental frequency:

$$Z'_L(2\omega_0) - Z_L(2\omega_0) = \infty, \tag{7}$$
$$Z'_L(\omega_0) - Z_L(\omega_0) = 0. \tag{8}$$

Then, the values of L_2 and C_2 can be derived using the capacitance of C_1 as follows.

$$L_2 = \frac{3}{4{\omega_0}^2 C_1}, \tag{9}$$
$$C_2 = \frac{1}{3} C_1, \tag{10}$$

where C_1 is the capacitance of the series resonant circuit of the Class-E SPA. The value of C_1 can be appropriately selected. For general cases, since the value of inductor is more discrete and the performance of an inductor becomes more critical, C_1 should be selected to have an appropriate value of L_2.

GaN systems's GaN HEMT, GS61008P, was used to design and implement the proposed Class-E/F_3 SPA at the 6.78 MHz. Its C_{ds} is 325.4 pF. For Class-E SPA, the value of C_p was obtained as 514.4 pF, while the series resonant circuit for the fundamental frequency constitutes L_1 and C_1 of 200 nH, and 2,700 pF, respectively. Z_L was obtained as 4.7 + j4.3 Ω to have an output power of 50 W using the load-pull simulation. Since the component values of the conventional Class-E SPA are found, the component values of the proposed Class-E/F_3 SPA can be calculated using (4), (5) and (9), (10). The values of L_3 and C_3 are obtained as 360 nH and 168 pF, while the values of L_2 and C_2 are obtained as 153 nH and 900 pF, respectively.

Fig. 2 shows $Y''_L(\omega)$ - $Y'_L(\omega)$ and $Z'_L(\omega)$ - $Z_L(\omega)$ of a conventional Class-E SPA and the proposed Class-E/F_3 SPA as a function of frequency and simulated impedances at each reference plane on Simth chart. Both SPAs should satisfy (3) for the fundamental frequency, while the proposed Class-E/F_3 SPA satisfies (2) at the third harmonic using the additional

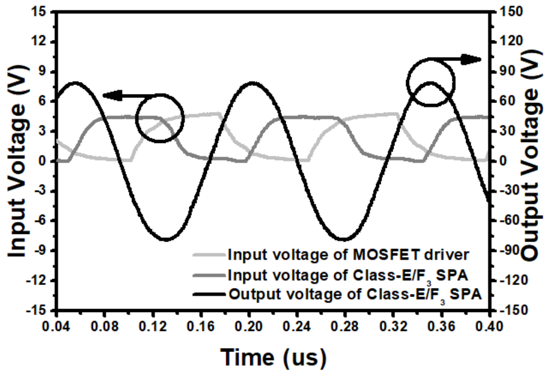


FIGURE 6. Measured voltage waveforms of the proposed Class-E/F_3 SPA and the MOSFET driver.

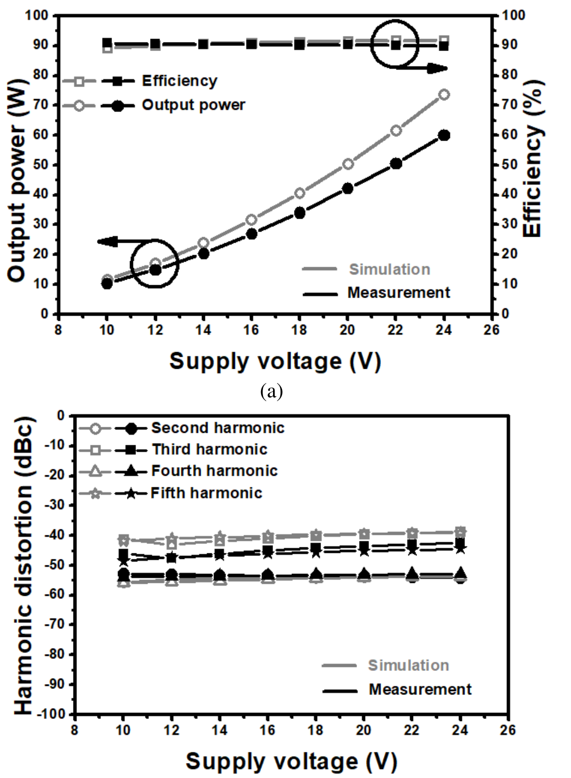


FIGURE 7. Simulated and measured results according to the supply voltage level of 10 - 24 V: (a) output power and efficiency, (b) harmonic distortion level.

resonant circuit shown in Fig. 2(a). Since the impedance at the third harmonic at the terminal of the transistor approaches zero, Class-E/F_3 operation can be achieved. As shown in Fig. 2(b), both SPAs satisfy (8) for the fundamental frequency, while the Class-E/F_3 SPA satisfies (7) with high impedance at the second harmonic using the parallel resonant circuit, which significantly suppress the second harmonic leakage current to the load. Fig. 2(c) shows the simulated impedances of the proposed Class-E/F_3 SPA compared to the conventional Class-E SPA. As shown, the proposed SPA has its third harmonic impedance close to zero for the $Z''_L(\omega)$ plane. The simulated impedances are almost the same as the theoretical ones.

Fig. 3(a) shows the simulated voltage and current waveforms of the conventional Class-E and the proposed Class-E/F_3 SPAs. With a supply voltage of 20 V, the peak voltage of the proposed Class-E/F_3 SPA is 61.8 V, slightly lower than that of the conventional Class-E SPA, which is 69.8 V. In return, the peak current of 8.2 A for the proposed Class-E/F_3 SPA becomes slightly higher than that of 7.1 A for the conventional Class-E SPA. Fig. 3(b) shows the simulated harmonic distortion level and PAE of the conventional Class-E and the proposed Class-E/F_3 SPAs according to the output power with a supply voltage of 20 V. The efficiency at the saturation power of both SPAs is greater than 90.7%. When the output power is changed from 0 to 50 W, the second and third harmonic distortion levels of the proposed Class-E/F_3 SPA were obtained from −45.4 to −60.7 dBc, while those of the conventional Class-E SPA were obtained from −11.0 to −32.7 dBc. Fig. 3(c) shows the simulated output power levels of the conventional Class-E and the proposed Class-E/F_3 SPAs for each harmonic frequency. The fundamental output power of both SPAs is the same at 47 dBm with a supply of 20 V, while the second and third harmonic distortion levels become significantly lower at −53.7 and −53.6 dBc at the proposed Class-E/F_3 SPA, thanks to the additional parallel resonant circuit for the second harmonic, and to the series resonant circuit for the third harmonic.

III. IMPLEMENTATION AND EXPERIMENTAL RESULTS

Fig. 4 shows the overall schematic of the proposed Class-E/F_3 SPA, which was implemented with two identical amplifier channels. The proposed Class-E/F_3 SPA includes a signal generator using an oscillator, Dasishinku Corp.'s DSO531SBM, and a MOSFET driver, Microchip's MD1822. The load network of the proposed Class-E/F_3 SPA is composed of a Wurth Electronic's choke inductor of 47 μH as a dc feeder, and an impedance matching network using a self-made series inductor of 360 nH and a Murata's shunt capacitor of 1,240 pF. Other component values are the same as introduced in the previous section for analysis.

Fig. 5(a) shows a photograph of the implemented two-channel Class-E/F_3 SPA. The implemented board has a thickness of 40 mil, and a size of 195.3 × 62.8 mm^2. The measurement setup in Fig. 5(b) consists of a dc power supply, a spectrum analyzer, and an oscilloscope. A supply voltage of 5 V was applied to the oscillator and driver, while a supply voltage of 10 - 24 V was applied to the Class-E/F_3 SPA. The spectrum analyzer was used to measure the spectral power levels for each frequency component. Voltage waveforms were measured using the oscilloscope. Fig. 6 shows the measured voltage waveforms of the proposed Class-E/F_3 SPA and the MOSFET driver, MD1822. Since the supply voltage to the oscillator and the MOSFET driver is 5 V peak-to-peak pulses, they were generated and supplied to the Class-E/F_3 SPA.

TABLE 1. Performance comparison with previous works.

Ref.		Topology	Frequency (MHz)	Supply voltage (V)	Efficiency (%)	Output power (W)	THD (%)
[11]		Class-EF_2	6.78	30	91.1	22.67	37.61
[12]		Class-E/F_3	4.00	25	93.45	10.0	4.35
[13]		Class-E/F_3	4.00	25	95.45	10.5	5.1
[14]		Class-E/F_3	4.00	25	95.0	5.54	4.86
[21]		Class-E	1.80	12	86.5	10.53	2.2
This work	Simulation	Proposed Class-E/F_3	6.78	10 - 24	89.25 - 91.86	11.62 - 73.68	1.52 -2.30
	Measurement		6.78	10 - 24	89.77 - 90.93	10.26 -59.98	1.54 - 2.15

Fig. 7(a) and (b) show the simulation and measurement results of the proposed Class-E/F_3 SPA according to the various supply voltages of 10 - 24 V. In Fig. 7(a), it can be observed that the output power steadily increases from 10.26 to 59.98 W (40.11 to 47.78 dBm) with increasing supply voltage while maintaining high efficiency of 89.25 to 90.93% during the measurement. Fig. 7(b) presents the harmonic distortion levels corresponding to the supply voltages. Both simulation and measurement results for supply voltages ranging from 10 to 24 V indicate that the second and third harmonic distortion levels do not exceed −49.98 dBc, whereas the fourth and fifth harmonic distortion levels remain below −39.04 dBc. The THD from the second to fifth harmonic was obtained in the range 1.54 to 2.15%. Table 1 summarizes and compares the simulation and measurement results. Compared to other previous works, this work shows a significantly improved THD performance, attributed to the resonant circuits for both the second and third harmonics.

IV. CONCLUSION

This paper proposed a Class-E/F_3 SPA with reduced second harmonic leakage to achieve low total harmonic distortion (THD) using a parallel resonant circuit for the second harmonic. For the third harmonic, a series resonant circuit was employed after the transistor in shunt. The parallel resonant circuit for the second harmonic is equivalently used as a series inductor for the fundamental resonant circuit, while the series resonant circuit for the third harmonic is used as a shunt capacitor for the fundamental frequency. Therefore, the proposed Class-E/F_3 SPA has a simple structure. The proposed Class-E/F_3 SPA was designed and implemented for the 6.78 MHz, and was evaluated with various supply voltages. As a result of the measurements, when the supply voltage of 10 - 24 V is applied, the output power was obtained from 10.26 - 59.98 W (40.11 - 47.78 dBm) with efficiency of no less than 89.25%. The second and third harmonic distortion levels were maintained with no higher than −49.98 dBc, while the THD levels were achieved as low as from 1.54 - 2.15%.

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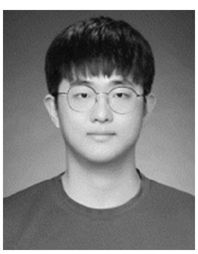

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