

Linearity Enhancement for the RF Class-E Power Amplifiers Using Duty-Cycle Modulation at the Feed-Forward Path

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Abstract— A linearity improved class-E power amplifier using duty-cycle modulation (DCM) is proposed at 2.4 GHz. The main class-E amplifier is combined with the auxiliary duty-cycle modulated class-E amplifier to enhance the linearity with suppressing the harmonics. The duty-cycle modulation is employed for the auxiliary amplifier to generate harmonics which cancel the main amplifier's harmonics at the combiner. It is important to create the harmonics needed to suppress the main amplifier's harmonics by controlling gate voltage of the auxiliary amplifier. The measured maximum output power at the fundamental frequency shows 28.8 dBm, whereas the PAE shows 53 % with 14 dBm input power excited. The ACPR is improved by 12 dB compared to that of the class-E amplifier without duty-cycle modulation.

I. INTRODUCTION

For several decades, a lot of researches have been performed on power amplifiers which play the most important role in the RF subsystem. Among the researches, the efficiency of power amplifiers is more significant than any other performance criteria because that is formed usually under 50%, which is the most significant factor in RF transmitter. Power amplifiers used at mobile devices on service now utilize mostly linear amplifiers of class-A, AB, B or C in order to reduce channel interference of digital mobile communication systems. For that reason, the efficiency which decides the life time of battery is very low. If we use switching-mode (class-D/E/F) power amplifiers that make it possible to obtain 100% drain efficiency theoretically, the life time of battery could be enhanced at once, however it is not realistic because of the low linearity [1-4]. In this paper, we are trying to develop how to improve the linearity of class-E power amplifiers that maintain high efficiency at the same time. We apply the principle of getting rid of the second and third harmonics that enhance the linearity by using duty-cycle modulation (DCM) by connecting two power amplifiers in parallel. It is the only way and breakthrough to improve the efficiency of new mobile applications which need more and more life time of battery so that we make the linearity enhanced up to that of the linear power amplifiers

and also maximize the efficiency. It is even more significant than any other researches that we maximize the linearity by using switching mode power amplifier.

II. DUTY-CYCLE MODULATION

The research on switching-mode power amplifiers over RF band which is used in mobile communication or microwave band was commenced from N.O.Sokal's low frequency band class-E theory amplifier [1]. The DCM technique that we

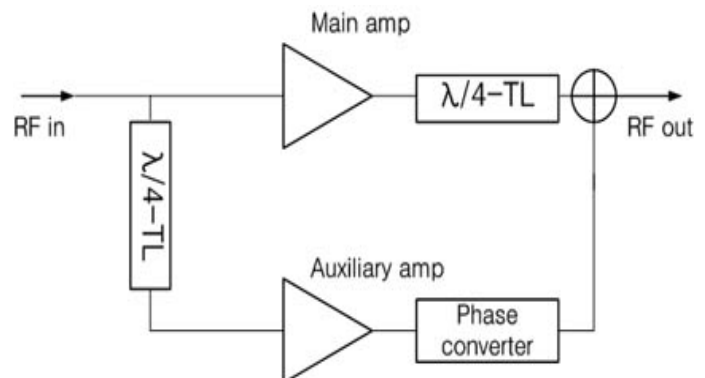


Fig. 1. The block diagram of the proposed class-E power amplifier using the DCM at the feed forward path.

propose in this paper significantly improves the linearity while not much degrading the efficiency based on the operation theory of class-E power amplifiers. In proportion to duty-cycle variation by controlling gate voltage of the auxiliary amplifier, harmonics are suitably created according to the desired performance [5-6]. This shows that harmonics can be controlled by adjusting the duty-cycle. Fig. 1 shows the proposed class-E power amplifier using the DCM amplifier the auxiliary amplifier at the feed forward path. The proposed DCM class-E power amplifier is made up of two amplifiers

which have different duty-cycles. The main power amplifier employs the class-E amplifier that has 50% duty-cycle. However, the auxiliary power amplifier uses a different duty-cycle. In this work, 25% duty-cycle was maintained for the auxiliary amplifier as in Fig. 3. Fig. 2 and Fig. 3 show the

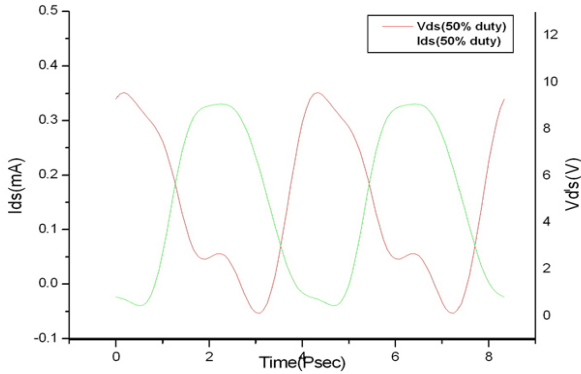


Fig. 2. The voltage and current waveforms of the main class-E power amplifier.

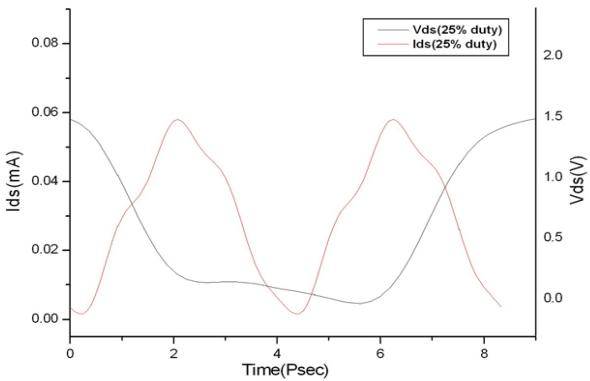


Fig. 3. The voltage and current waveforms of the auxiliary class-E power amplifier using the DCM at the feed forward path.

drain voltage and current waveforms of the main and auxiliary amplifiers. This waveforms tell us how the duty-cycle of main and auxiliary amplifiers affect the time-domain response of the amplifiers. Differences of each amplifier are attributed to controlling the gate voltage. The spectrum of each amplifier is shown as in Fig. 4. Fig. 4 shows the created harmonics due to the variation of duty-cycle. In this work, the second harmonic of main amplifier is as high as about 10 dBm. Therefore, to perfectly suppress the second harmonic of main amplifier, at least 10 dBm output power of second harmonic is needed at the feed forward path. Since DCM is a very powerful technique to obtain harmonics, it is used in the auxiliary power

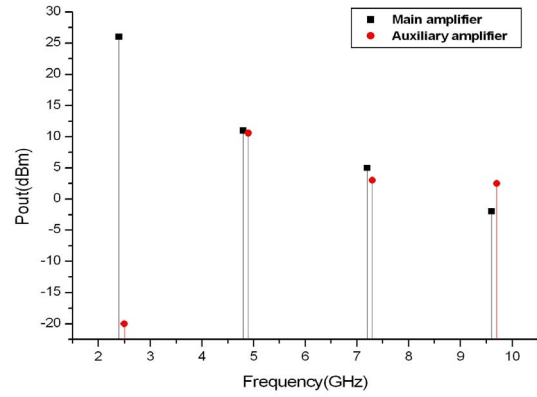


Fig. 4. The spectrums of main and auxiliary amplifiers

TABLE I
THE COMPONENT VALUES OF THE CRLH-TLS

	C_L	L_L	ϕ of RH-TL
CRLH1	1.2 pF	3.3 nH	180°

amplifier. The auxiliary power amplifier adjusts the gate voltage to generate the second and third harmonics. The created harmonics of auxiliary amplifier are used to suppress the sub-harmonics of main amplifier. For this, phase of each harmonic must be anti-phase at the combiner. Therefore, the phase converter is incorporated at the combiner. Fig. 5 shows the

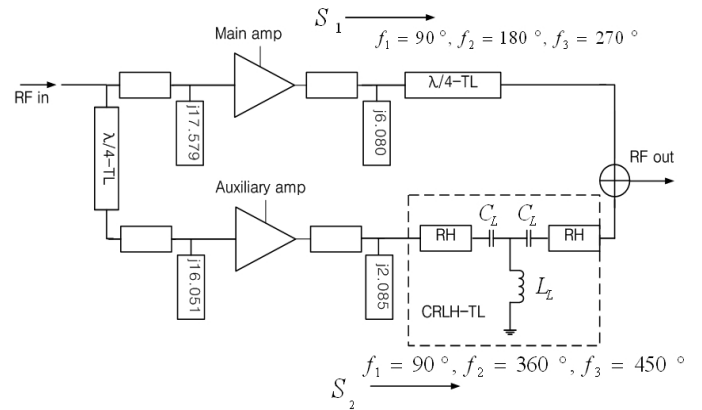


Fig. 5. The proposed duty-cycle modulated class-E power amplifier using CRLH-TL combiner. (f_1 = fundamental frequency, f_2 = second harmonic frequency), f_3 = third harmonic frequency)

overall circuit. For phase converter, the composite right/left-handed transmission line (CRLH-TL) was utilized [7-8]. Table I shows component values of CRLH-TL for this design. In this work, CRLH-TL is employed to convert the phase at the second and third harmonics [7-8]. However, since the auxiliary power amplifier makes overall PAE decrease, it should not have an impact on the fundamental component of main power

TABLE II

THE DC DESIGN PARAMETERS FOR THE PROPOSED AMPLIFIER

	I_{DS}	V_{DS}	V_{GS}
Main amp	0.241 mA	5.2 V	-1 V
Auxiliary amp	0.02 mA	2.5 V	-2.5 V

TABLE III

THE Z_{in} AND Z_{out} OF AMPLIFIERS FOR MAXIMUM POWER AND EFFICIENCY BASED ON LOAD-PULL SIMULATION

	Z_{in}	Z_{out}
Main amp	12.260+j17.579	25.472-j6.080
Auxiliary amp	9.699+j16.051	26.761-j2.085

amplifier and not much consume the DC power. To reduce the DC power consumption of auxiliary power amplifier, the fundamental output of main power amplifier is maintained as high as possible. The fundamental output of auxiliary power amplifier remains as low as possible possible, while the second and third harmonics are to be high. Therefore, if the DC power consumption of auxiliary power amplifier is very low, the overall PAE dose not go down. Nonetheless, a little loss is inevitable. Table II shows the DC design parameters of the proposed class-E power amplifier using DCM applied for the auxiliary amplifier. The result shows that the DC power consumption of auxiliary power amplifier is by far less than that of main power amplifier.

Table III shows the input impedance Z_{in} , and output impedance Z_{out} for maximum power and efficiency which have been characterized using the load-pull simulation for matching network design. With the conjugate matching for the maximum power and efficiency, the input and the output matching networks are realized as shown in Fig. 5.

III. SIMULATED AND MEASURED RESULTS

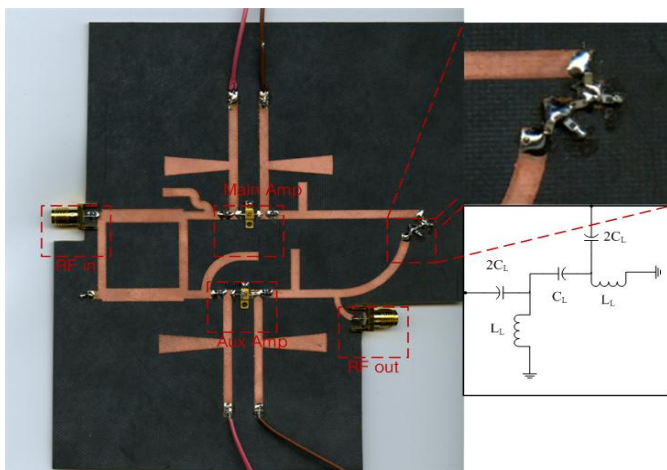


Fig. 6. Layout of the proposed class-E power amplifier using DCM.

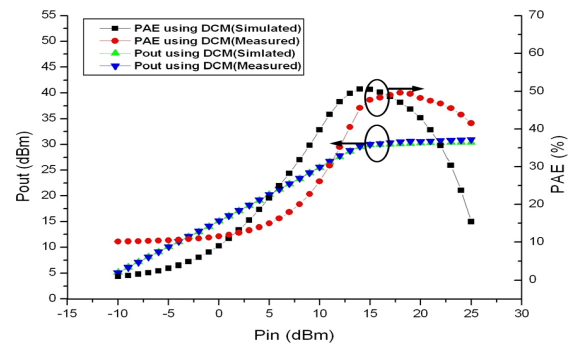


Fig. 7. Simulated and measured results (2.4GHz) of class-E power amplifier using DCM.

Fig. 6 shows the layout of the proposed amplifier. The proposed class-E power amplifier using DCM at feed forward path was simulated with ADS tool. Mitsubishi two of MGF2430A are used for the amplifier. RT Duroid 5880 substrate are used for design. Fig. 7 shows the output powers and PAE of the proposed power amplifier using DCM. The maximum PAE of 53 % at 2.4 GHz is obtained for the proposed amplifier using DCM. The drain efficiency is observed 63 %. When 14 dBm input power was excited, the maximum output was observed 28.8 dBm at 2.4 GHz. Fig. 8 shows that the proposed

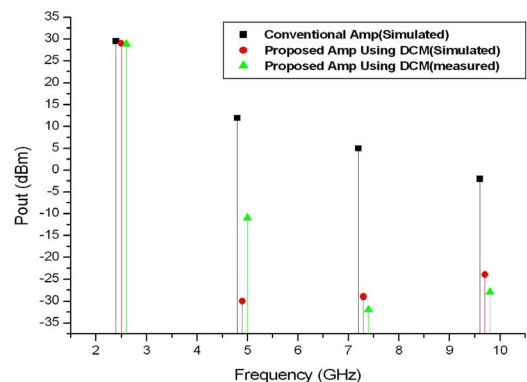


Fig. 8. The spectrums of the proposed class-E power amplifier with DCM and without DCM.

class-E amplifier using DCM applied at the feed-forward path suppresses the harmonics successfully. At the second and third output powers, very little harmonics were confirmed. Fig. 9 shows the IMD3 of the proposed class-E amplifier using DCM was considerably improved compared to that of the class-E amplifier without DCM. It proves the improvement of linearity. Fig. 10 shows that the ACPR performance of the proposed class-E power amplifier using DCM at feed forward path was considerably improved about 12dB compared to that of the conventional class-E power amplifier without DCM. It proves

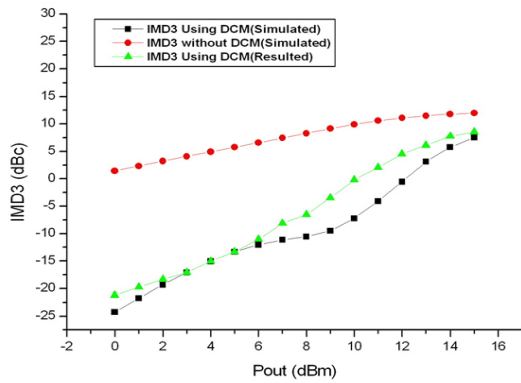


Fig. 9. IMD3 of the proposed class-E amplifier using DCM and the class-E amplifier without DCM.

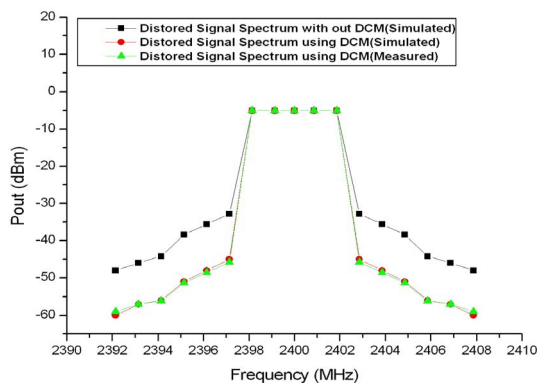


Fig. 10. The ACPRs of the proposed class-E power amplifier with DCM and the class-E amplifier without DCM.

the improvement of linearity. It is because the second and third harmonics were suppressed successfully by incorporating the CRLH-TL and duty-cycle modulated auxiliary power amplifier.

IV. CONCLUSIONS

A class-E power amplifier using DCM at feed forward path was presented at 2.4 GHz. Duty-cycle modulation is validated as one of the powerful techniques to suppress harmonics by controlling gate voltage. The phase converter employing CRLH-TL was shown to suppress the second and third harmonics. The measured output power of the fundamental shows 28 dBm, whereas the PAE shows 53 % at 14 dBm input power. The ACPR is improved by 12 dB compared to that of the class-E amplifier without duty-cycle modulation and CRLH-TL combiner.

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