PAPER

A Dual Band High Efficiency Class-F GaN Power Amplifier Using a Novel Harmonic-Rejection Load Network

Yongchae JEONG[†], **Girdhari CHAUDHARY**[†], *Nonmembers*, *and* **Jongsik LIM**[††a)], *Member*

SUMMARY A class-F high efficiency GaN power amplifier (PA) for dual band operation at 2.14 GHz and 2.35 GHz is proposed. A novel dual band harmonic-rejection load network, which controls the terminating impedances of the second and third harmonics, and contributes greatly to efficiency improvement of PA, is described. In addition, a matching network which guarantees the high efficiency and gain of PA for the desired dual bands is designed. The proposed load network has the harmonic rejection of more than 24 dB which is sufficient for rejecting harmonics, and an insertion loss of less than 0.11 dB. The dual band matching network for the maximum output power results in the measured highest output power for each operating frequency. The fabricated class-F GaN PA has 43 dBm-65.4% and 43 dBm-63.9% of output power - efficiency at the desired dual frequencies.

key words: *power amplifier, class-F, dual band*

1. Introduction

Conventional wireless systems have been designed for mainly low data rate services such as voice and text data. However, recently high density data rate should be transmitted and received according to the integration of lots of required functions in one mobile terminal. So, recent wireless systems should provide various information and multimedia services as well as the conventional voice and text data. In order to perform those complicated multimedia services, multi frequencies, which are very close to each other, are adopted by service providers. Because it takes severely high cost and great efforts to develop individual frequency band wireless equipments, the development of wide band, multi mode, and multi band equipments are strongly recommended. It is well known that the role of power amplifiers (PAs) is critical in the efficiency of overall wireless systems. However, the study to design power amplifiers with high efficiency at multi bands has not been sufficient so far [1]–[6].

Various studies have been performed for enhancing the efficiency of PAs, and class-E and -F PAs are the representative ones. However, although the configuration is not complicated, it is relatively difficult to realize class-E PAs because output power (P_{out}) is so sensitive to the capacitance. In class-F PAs, the method to control harmonic components is often selected hence, in most cases, the maximum output power ($P_{out,max}$) appears when the current and voltage waveforms are not overlapped. Well known advantages of class-F PAs are excellent power density and controllable efficiency by controlling harmonic components with only external networks. However, in practice, it is very difficult to control all harmonics perfectly.

Some study results have been proposed to get high efficiency at dual frequencies using limited design technology for class-E and -F PAs. First, a class-F PA for 1.7 GHz and 2.14 GHz operation has been designed using GaAs MESFET [7]. However in this work, the input impedances for harmonic components were not realized accurately, so the efficiency was not satisfactory. In addition, lots of PAs have been designed recently, such as multi band class-F PAs using composite right/left handed (CRLH) transmission lines [8], [9], a dual band PA with its matching networks realized by dual band filters [10], and a class-E PA using CRLH transmission lines [11]. However, most of them have problems of lower efficiency and output power than expectation.

In this work, a harmonic-rejection load network (HRLN) is proposed to control the second and third harmonic components which mostly contribute to the improvement of efficiency, and ultimately to design a PA which has high efficiency at dual bands. The proposed load network is incorporated to the dual band matching networks which are applied to design the class-F PA with both $P_{out,max}$ and high efficiency simultaneously at dual frequencies.

2. Harmonic-Rejection Load Networks

2.1 Harmonic-Rejection Load Networks for Single Band

Figure 1 illustrates the current and voltage waveforms of ideal class-F PAs. The half period sine wave of current and rectangular wave of voltage should not be overlapped ide-

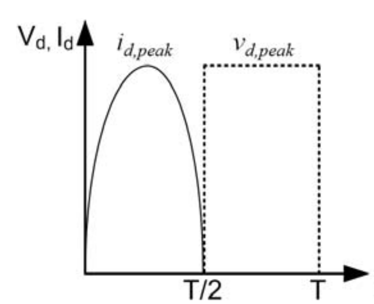

Fig. 1 Current and voltage waveforms of ideal class-F power amplifiers.

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[†]The authors are with Chonbuk National University, Jeonju, Chonbuk, 561-756, Rep. of Korea.
[††]The author is with Soonchunhyang University, Asan, Choongnam, 336-745, Rep. of Korea.
a) E-mail: jslim@sch.ac.kr (Corresponding author)
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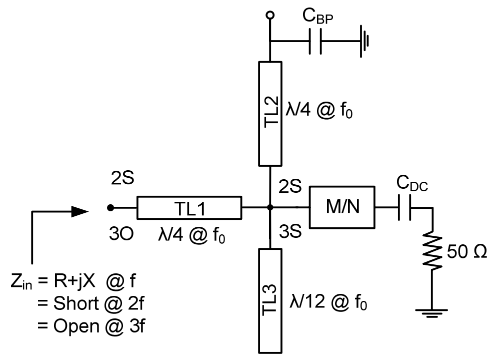

Fig. 2 Proposed HRLN for single band class-F PAs.

ally. The current and voltage waveforms are expressed by Fourier series as (1) and (2).

The current and voltage waveforms consist of even and odd order harmonics in addition to DC component, respectively. If the HRLN is seen as a short-circuit for even harmonics and a open-circuit for odd harmonics, the current and voltage waveforms never overlap to each other and the dissipation of harmonic power may be eliminated. Therefore, the improvement of efficiency is expected.

$$I_d = i_{d,peak}\left(\frac{1}{\pi}+\frac{1}{2}\sin\omega_o t-\frac{2}{\pi}\sum_{n=2,4,6,\ldots}^{\infty}\frac{1}{n^2-1}\cos n\omega_o t\right) \quad (1)$$

$$V_d = v_{d,peak}\left(\frac{1}{2}-\frac{2}{\pi}\sin\omega_o t-\frac{2}{\pi}\sum_{n=3,5,7,\ldots}^{\infty}\frac{1}{n}\sin n\omega_o t\right) \quad (2)$$

Figure 2 shows the proposed HRLN for single band class-F PAs. The network is composed of two shunt stubs which control the second and third harmonic components. Transmission line elements, TL2 and TL3, are short- and open-circuited in order to provide terminating effect for even and odd harmonics, respectively. The physical lengths of TL2 and TL3 are $\lambda/4$ and $\lambda/12$ at the fundamental frequency (f_0). So those of TL2 and TL3 at the harmonic frequencies of $2f_0$ and $3f_0$ are $\lambda/2$ and $\lambda/4$, respectively. Then the input impedances of TL2 and TL3 at the connecting point with TL1 are shorted, which are expressed as "2S" and "3S" in Fig. 2. The short impedances, 2S and 3S, are preserved constantly independent of the connected fundamental matching network (M/N). These short impedances, 2S and 3S, are terminated to TL1 of which physical length is $\lambda/4$ at f_0. The input impedance (Z_{in}) seen by the output stage of PAs is transformed into short (2S) and open (3O) impedances for the second and third-harmonic frequencies, respectively. Here the physical length of TL2 has been determined to be $\lambda/4$ at f_0 because of another mission of DC supply.

In order to suggest the validity of the proposed HRLNs for class-F PA, the designed networks have been simulated electromagnetically (EM) using HFSS v11 from Ansoft, and measured. The proposed HRLNs were simulated and fabricated on substrate Rogers RT/5880 with dielectric constant (ε_r) of 2.2 and thickness (h) of 31 mil. High Q chip capacitors of Tekelec Temex Inc. were used as by-pass capacitor (C_{BP}).

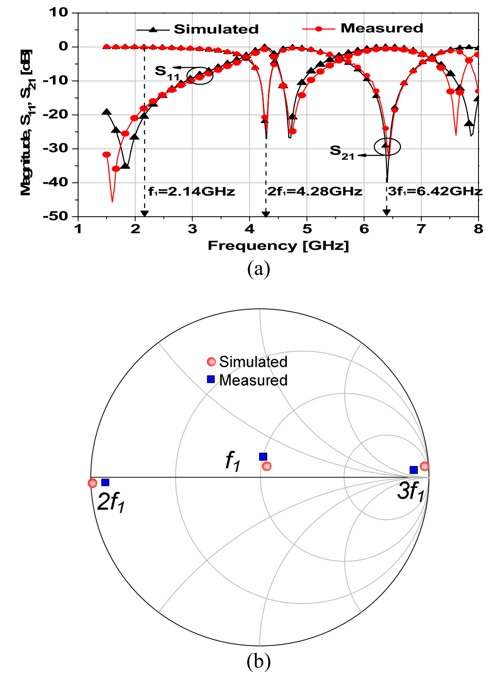

Fig. 3 Simulated and measured transfer characteristics of the proposed HRLN at f_0=2.14 GHz (f_1): (a) S_{11}/ S_{21} and (b) input impedances.

Figures 3(a) and (b) show the simulated and measured transfer characteristics (S_{21}) and input impedances of the proposed HRLN only at the WCDMA frequency (f_1), 2.14 GHz. In Fig. 3(a), the harmonic rejections at $2f_1$ and $3f_1$ are more than 24 dB, which is generally recognized to be sufficient for class-F PAs. In addition, it is clearly observed that the input impedances at $2f_1$ and $3f_1$ frequencies correspond to short and open, respectively. The measured insertion loss at 2.14 GHz is around 0.19 dB.

Figures 4(a) and (b) illustrate the simulated and measured transfer characteristics (S_{21}) and input impedances of the proposed HRLN only at the WiMax frequency (f_2), 2.35 GHz. In the same way, the harmonic rejections at $2f_1$ and $3f_1$ are also more than 24 dB, and the short and open input impedances are shown at the second and third harmonic frequencies with the insertion loss of 0.20 dB at 2.35 GHz. These measurements were based on 50 Ω terminations on both ends without considering the matching network at f_0. Moreover, the required matching network at f_0 can be realized with HRLN by tuning the characteristic impedance of TL1, TL2 and TL3.

2.2 Harmonic-Rejection Load Networks for Dual Band

It is possible to design the dual band harmonic-rejection load network (DBHN) by connecting the above two single band HRLNs with a slightly modification. Figure 5 shows the proposed DBHN for class-F PAs, which is composed of two single band HRLNs for f_1 (=2.14 GHz) and f_2 (=2.35 GHz). TL2 and TL3, transmission line elements, provide short impedance to the second and third harmonics

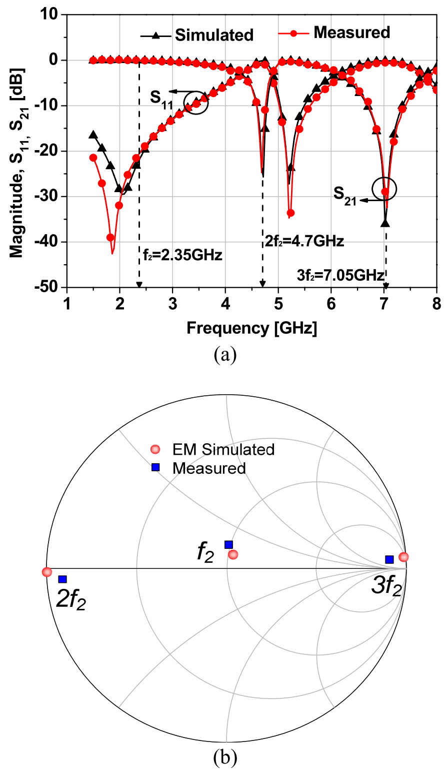

Fig. 4 Simulated and measured transfer characteristics of the proposed HRLN at f_0=2.35 GHz (f_2): (a) S_{11}/S_{21} and (b) input impedances.

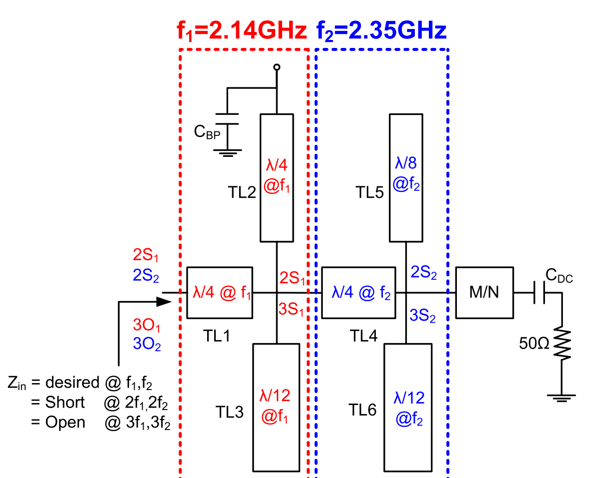

Fig. 5 Proposed dual band harmonic-rejection load network for class-F PAs.

of the first fundamental frequency, f_1. The physical length of TL2 and TL3 are respectively $\lambda/4$ and $\lambda/12$ at f_1. TL2 is also used as a DC bias feeding line in order for an additional bias network not to be adopted. TL1 provides short and open impedances respectively to even and odd harmonics of the fundamental f_1. Similarly, TL5 and TL6 play the same role as TL2 and TL3 for the other fundamental frequency, f_2, i.e. provide short impedance to the second and third harmonics of f_2. The physical length of TL5 and TL6 are $\lambda/4$ at both the second and third harmonic frequencies, or $\lambda/8$ at f_2 (TL5) and $\lambda/12$ at f_2 (TL6). TL1 and TL4 result in the short and open input impedances for the $2f_2$ and $3f_2$.

However, the first stage HRLN has a little effect on the second stage HRLN. To avoid this effect, the characteristic impedances of first stage and second stages are tuned to obtain required load conditions for the class-F amplifier. Since, the second harmonics has higher impact on amplifier efficiency; the impedance at $3f_2$ is compromised to achieve the desired impedance at $2f_2$. Therefore, the impedance at $3f_2$ is not perfectly open impedance condition; however, it provides high reactive termination and provides rejection of harmonic power.

Figures 6(a) and (b) present the simulated and measured S21 and input impedances of the proposed DBHN for dual band class-F PAs at 2.14 GHz (f_1) and 2.35 GHz (f_2). The rejections at the second and third harmonic frequencies ($2f_1$, $2f_2$, $3f_1$, $3f_2$) are more than 29 dB. It is definitely seen that the input impedance exists close to ideal short at $2f_1$ and $2f_2$, and ideal open at $3f_1$ and $3f_2$. It is well known that Fig. 6(b) means good conditions for improving the efficiency of class-F PAs. The insertion losses of the DBHN were 0.45 dB and 0.68 dB at 2.14 GHz and 2.35 GHz from the measurement including the loss of SMA connectors. These measurements results were based on 50 Ω termination impedances at both ends without considering the matching network. Figures 7(a), (b), and (c) show the photographs of fabricated HRLNs and DBHN for 2.14 GHz single band, 2.35 GHz single band, and dual frequencies, respectively.

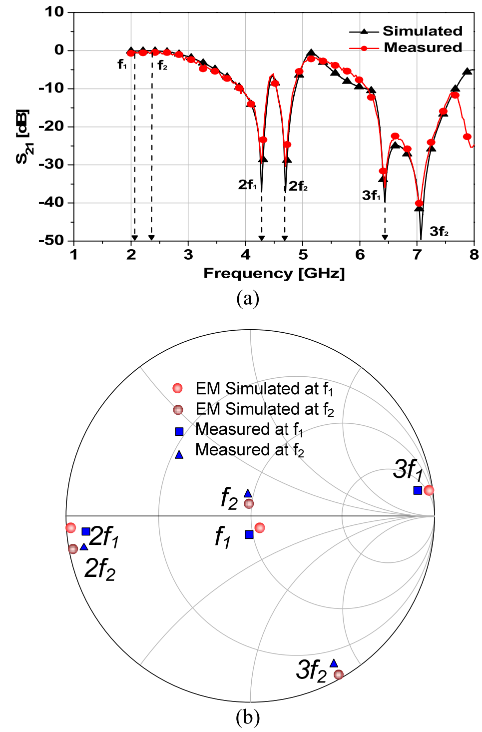

Fig. 6 Simulated and measured transfer characteristics of the proposed DBHN: (a) S_{21} and (b) input impedances.

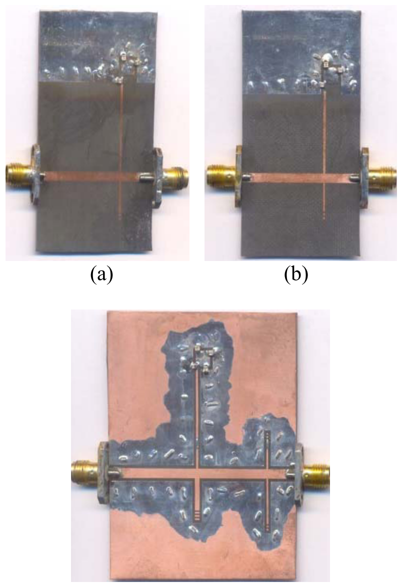

Fig. 7 Photographs of the fabricated HRLNs for (a) 2.14 GHz single band, (b) 2.35 GHz single band, and (c) both frequencies (DBHN).

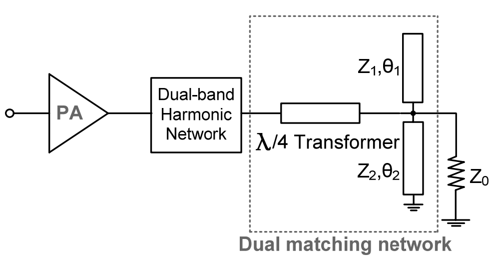

Fig. 8 Proposed dual band matching network (DBMN).

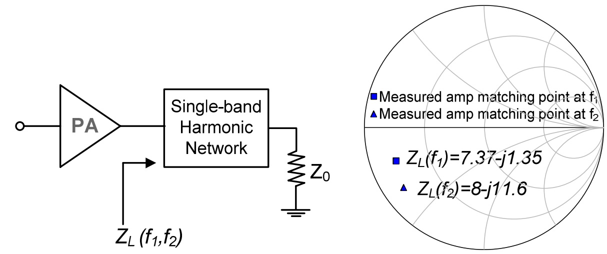

Fig. 9 Measured load matching point for $P_{out.\,max}$ at f_1 (2.14 GHz) and f_2 (2.35 GHz).

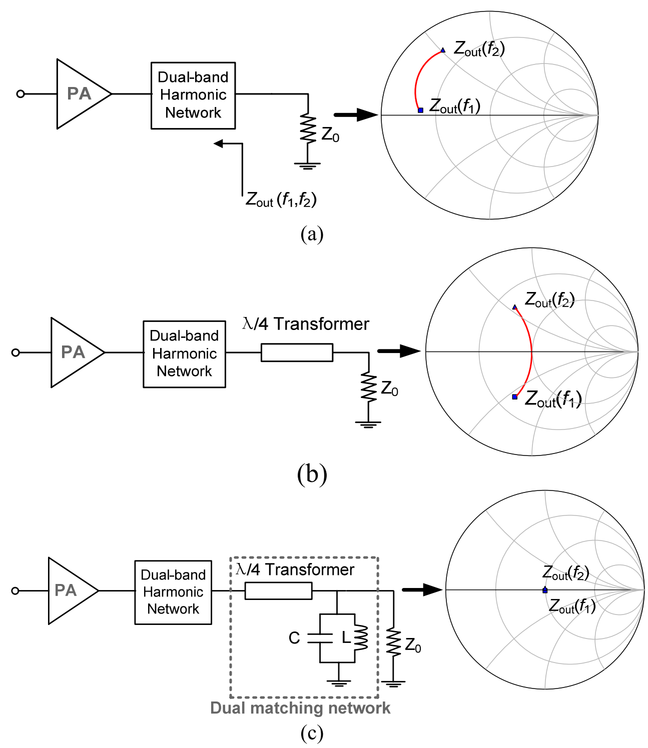

Fig. 10 Graphical description for the proposed DBMN.

3. Dual Band Matching Networks

It is essential to design the dual band matching network (DBMN) to get high efficiency dual band class-F PAs. Figure 8 shows the designed DBMN in this work. The DBMN is located next to the proposed DBHN at the output stage of PA. The design procedure may be described by using Fig. 9 and Figs. 10(a), (b), and (c). Figure 9 shows the measured two load matching points for $P_{out.\,max}$ at f_1 (2.14 GHz) and f_2 (2.35 GHz). First, the matching point for the $P_{out.\,max}$ of the class-F PA with HRLN could be found from the load-pull method at each single band. Figure 10(a) shows the impedance seen by the output port at the end of the DBHN, Z_{out}.

After then, in Fig. 10(b), an impedance transform was performed using a $\lambda/4$ transmission line in order to place the measured output matching points to near the normalized unity conductance circle. Finally, a parallel LC resonator has been adopted to match the network to the center of the smith chart as depicted in Fig. 10(c). The resonant frequency has been determined in the mid of f_1 and f_2. The short and open stub transmission lines were used to implement LC resonator in distributed transmission line. The characteristic impedance must be optimized to fit unity conductance circle.

The proposed DBMN has been fabricated, measured, and compared to the EM simulation results for verifying the design procedure. Figure 11(a) shows the simulated and measured S21 of the output network including DBHN and DBMN. It is observed that the second and third harmonics are well rejected with the low loss for the fundamental signals at f_1 and f_2. Figure 11(b) shows the input impedances of the output network including DBHN and DBMN, Z_L, for the dual band. One can recognize easily that the power transistor and output network are well matched for $P_{out.\,max}$ at the desired dual band from both simulation and measurement.

4. Fabrication and Measurement of the Single and Dual Band Class-F PA

The single and dual band class-F PAs adopting the pro-

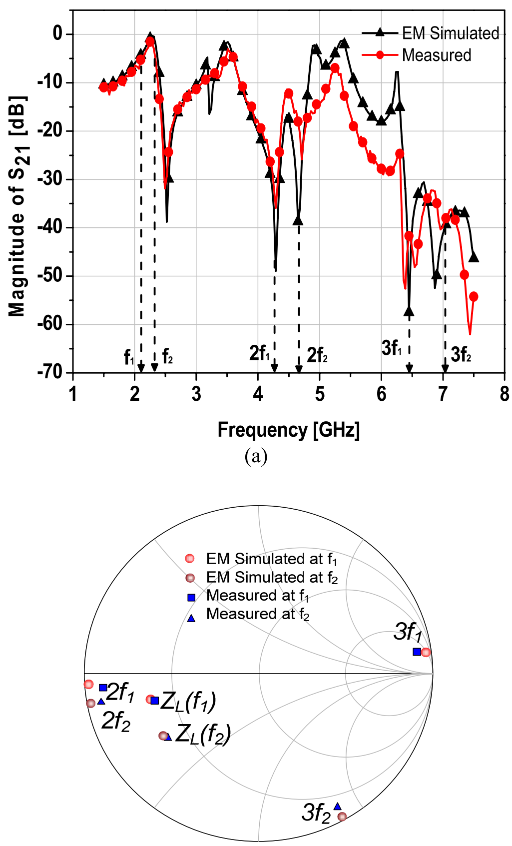

Fig. 11 Simulated and measured transfer characteristics of the DBMN with the proposed DBHN: (a) S_{21} and (b) input impedances (Z_L).

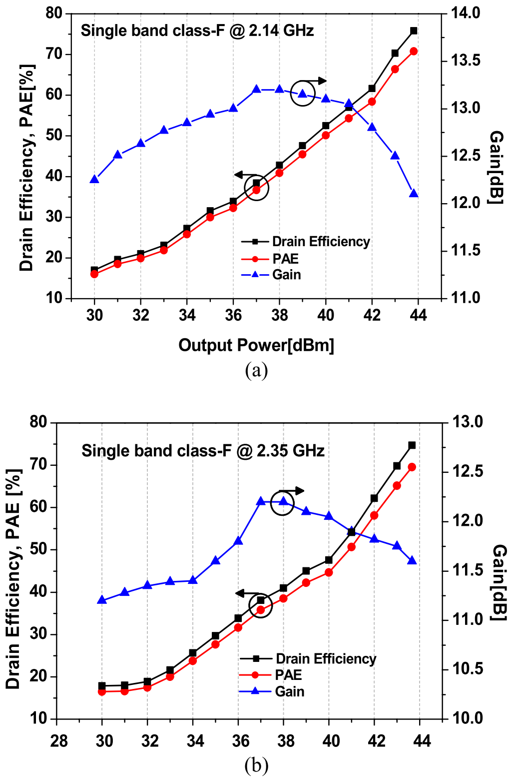

Fig. 12 Measured performance of single band class–F PA at (a) 2.14 GHz and (b) 2.35 GHz.

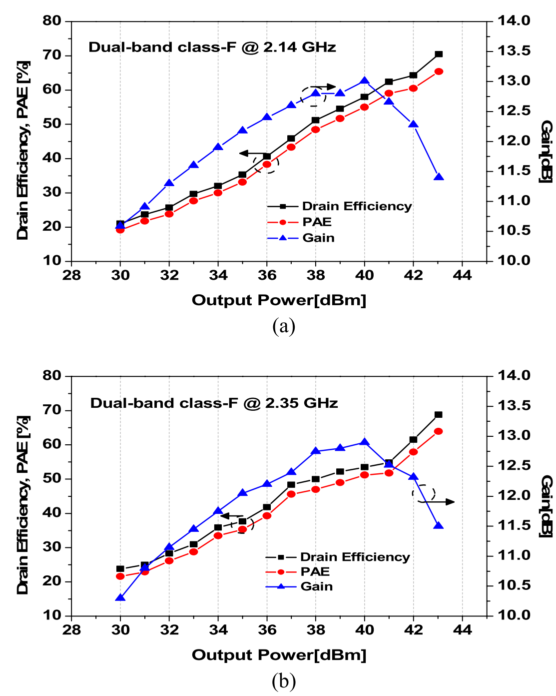

Fig. 13 Measured performances of the dual band class-F PA at (a) 2.14 GHz and (b) 2.35 GHz.

posed single band HRLN and DBHN and DBMN have been fabricated and measured. The selected power transistor is NPTB00025, a GaN HEMT from Nitronex in both case.

Figure 12 shows the measured output power, power gain, drain efficiency and power added efficiency (PAE) of the single band class-F PA for a 2.14 GHz and 2.35 GHz CW signal. The device gate and drain biases were set at $V_{gs} = -2.5$ V and $V_{ds} = 28$ V. Saturated output power was 43.8 dBm with saturated gain of 12.1 dB at 2.14 GHz. The maximum drain and power added efficiency (PAE) at this frequency were 75.82% and 71.42% respectively. Similarly, the maximum drain and PAE were 74.73% and 69.56% respectively, with saturated output power and gain of 43.66 dBm and 11.6 dB at 2.35 GHz.

Figure 13 shows the measured performances of the dual band class-F PA at 2.14 GHz and 2.35 GHz with the second and third harmonics terminated properly. The device gate and drain biases were set at $V_{gs} = -1.8$ V and V_{ds}=28 V. The $P_{out,max}$, drain efficiency, and power added efficiency (PAE) at 2.14 GHz are 43 dBm, 70.5%, and 65.4%, respectively. The power gain is 11.4 dB for the condition of $P_{out,max}$

The $P_{out,max}$, drain efficiency, and power added efficiency (PAE) at 2.35 GHz are 43 dBm, 68.8%, and 63.9%, respectively. The power gain is 11.5 dB when $P_{out,max}$ appears. Figure 14 shows the prototype of the dual band class-F PA fabricated using in house facilities. These results were comparable to the single band class-F PA at 2.14

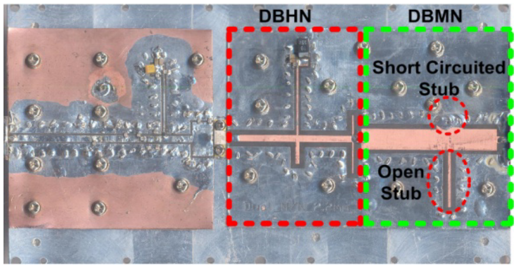

Fig. 14 Photograph of the fabricated dual band class-F PA.

Table 1 Performance comparison of the proposed dual band class-F PA to previous studies.

Reference	f_0 [GHz]	PAE [%]	P_{sat} [dBm]	Gain [dB]	Device	Topology
[7]	1.70 2.14	44.0 61.3	32.80 34.40	5.0	GaAs FET	Class-F
[8]	0.70 0.80 1.80 2.14	58.2 50.3 48.6 56.6	41.50 39.70 37.70 40.70	11.5 9.7 7.7 10.7	LDMOS FET	Class-F
[9]	0.80 1.70	42.5 42.6	22.40 22.20	X	GaAs FET	Class-E
[10]	0.80 1.50	51.6 51.9	30.90 28.20	10.0	GaAS FET	X
[11]	0.80 1.70	64.8 61.4	45.60 48.07	13.0 11.0	GaN HEMT	Class-E
This work	**2.14 2.35**	**65.4 63.9**	**43.04 43.02**	**11.4 11.5**	**GaN HEMT**	**Class-F**

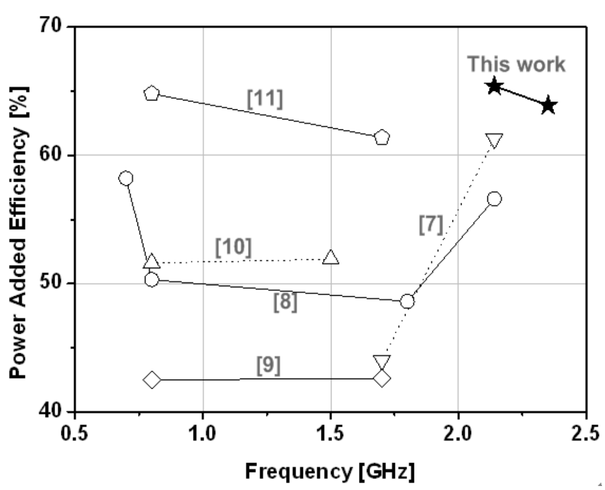

Fig. 15 Comparison of efficiency and frequency of the proposed dual band class-F PA to previous studies.

and 2.35 GHz respectively.

Table 1 and Fig. 15 summarize the measured performances of the proposed dual band class-F PA, and compare them to those of previous studies designed using various design technologies. It is well observed that a remarkable improvement has been obtained in this work in the operating frequency, efficiency, gain, and output power unlikely to previous class-F PAs.

5. Conclusion

A new dual band harmonic-rejection load network (DBHN) and dual band matching network (DBMN) have been described in this work for dual band class-F PAs at 2.14 GHz and 2.35 GHz which are the frequencies for WCDMA and WiMax systems. The proposed DBHN could attenuate the second and third harmonics at both bands simultaneously by more than 24 dB which is generally sufficient for rejecting those harmonic components. It has been shown that the proposed harmonic rejection load network provided the short and open impedances for the second and third harmonic frequencies, at both bands, which are key conditions for improving the efficiency of class-F PAs. In addition, the proposed DBMN also satisfied the matching conditions for the maximum output power for both bands. The fabricated dual band class-F power amplifier has proved the validity of the proposed design by showing the 66.4% and 63.9% of PAE at f_1 and f_2 with 43 dBm of output power and 11.4 dB of power gain from measurement. It is understood that the proposed design in this work can be adopted as a solution for existing problems such as relatively low efficiency, power gain and operating frequency in dual band power amplifiers.

Acknowledgments

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Yongchae Jeong received BSEE, MSEE and Ph.D. degree in Electronic Engineering from Sogang University in Seoul, Republic of Korea in 1989, 1991, and 1996, respectively. From 1991 to 1998, worked as a senior engineer with Samsung Electronics. From 1998, joined Division of Electronic Engineering, Chonbuk National University, in Jeonju, South Korea. From July 2006 to December 2007, he joined at Georgia Institute of Technology as a visiting research professor. Now he is a professor in Division of Electronic Engineering, vice dean of College of Engineering, and member of IT Convergence Research Center in Chonbuk National University. He is currently teaching and conducting research in the area of microwave devices, base-station amplifiers, nonlinear device & system linearization technology, and RFIC design. Prof. Jeong is a senior member of IEEE and member of KIEES (Korea Institute of Electromagnetic Engineering and Science).

Girdhari Chaudhary received the B.E. and M.Tech. in Electronics and Communication Engineering from Nepal Engineering College (NEC), Kathmandu, Nepal and Malaviya National Institute of Technology (MNIT), Jaipur, India in 2004 and 2007, respectively. He is currently working towards Ph.D. at Chonbuk National University, Jeonju, Republic of Korea. His research interests include multiband passive circuits, negative group delay filters, high efficiency power amplifiers and RF energy harvesting systems. He has authored and co-authored over 10 papers in international journals and conference proceedings. Mr. Chaudhary is a student member of IEEE and KIEES (Korea Institute of Electromagnetic Engineering and Science).

Jongsik Lim received the B.S. and M.S. degrees in Electronic Engineering from Sogang University in Seoul, Republic of Korea in 1991 and 1993, and Ph.D. degree in the School of Electrical Engineering and Computer Science from Seoul National University in 2003. In 1993, he joined Electronics and Telecommunications Research Institute (ETRI) and worked in the Satellite Communications Division as a senior member of research staff. From March to July in 2003, he worked in Division of Information Technology, Brain Korea 21 Project in Seoul National University as a post doctoral fellow. He has experiences as a patent examiner in the Korean Intellectual Property Office (KIPO) through July 2003 to September 2004. Since March 2005, he has been with the Department of Electrical Engineering, Soonchunhyang University in Asan, Chungnam, Korea, as a faculty member. His current research interests include design of the passive and active circuits for RF/microwave and millimeter-wave with MIC/MMIC technology, modeling of active device, design of high power amplifiers for mobile communications, applications of periodic structure to the RF/microwave circuits and modeling of passive structure having periodic structures. Prof. Lim is a senior member of IEEE, and member of KIEES (Korea Institute of Electromagnetic Engineering and Science).