

Split Slant-End Stubs for the Design of Broadband Efficient Power Amplifiers

Youngcheol Park* · Taeggu Kang

Abstract

This paper suggests a class-F power amplifier with split open-end stubs to provide a broadband high-efficiency operation. These stubs are designed to have wide bandwidth by splitting wide open-end stubs into narrower stubs connected in shunt in an output matching network for class-F operation. In contrast to conventional wideband class-F designs, which theoretically need a large number of matching lines, this method requires fewer transmission lines, resulting in a compact circuit implementation. In addition, the open-end stubs are designed with slant ends to achieve additional wide bandwidth. To verify the suggested design, a 10-W class-F power amplifier operating at 1.7 GHz was implemented using a commercial GaN transistor. The measurement results showed a peak drain efficiency of 82.1% and 750 MHz of bandwidth for an efficiency higher than 63%. Additionally, the maximum output power was 14.45 W at 1.7 GHz.

Key Words: Broadband, Class-F, Efficiency, Power Amplifier.

I. INTRODUCTION

Recently, power amplifiers (PAs) have been studied extensively for better efficiency and bandwidth, as communication devices need to support various technologies and exhibit a longer battery time. In an effort to address the issue of efficiency, architectures that exploit harmonic waveforms, such as class-F, have been widely studied from many perspectives [1, 2]. Although the theoretical efficiency of class-F amplifiers approaches 100% and their implementation results are very close to the ideal values, the circuit implementations of class-F amplifiers are necessarily bulky in general, because they require high-order harmonic control circuits, even though some techniques have been suggested to overcome these practical issues [3–6]. Furthermore, the need to control harmonic impedances necessarily results in a relatively narrow bandwidth. For these reasons, class-F amplifiers have

not been used for the latest commercial applications that require a wide bandwidth. Therefore, this paper suggests a power amplifier design with split transmission lines to realize wide bandwidth while maintaining a small circuit area. In addition, in order to further improve the performance obtained in the previous work [7], this paper redesigned the slant-end architecture using split slant-end transmission lines and impedance optimization.

II. STEPPED TRANSMISSION LINE FOR BROADBAND OPERATION

Fig. 1 shows the steps for broadening the bandwidth of transmission lines in matching networks. In transmission lines, physical parameters such as length, width, height, and the dielectric constant all influence the electrical length at a certain frequency. As such, the conventional transmission

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Department of Electronics Engineering, Hankuk University of Foreign Studies, Yongin, Korea.

*Corresponding Author: Youngcheol Park (e-mail: ycpark@hufs.ac.kr)

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line in Fig. 1(a) results in a narrow bandwidth. In other words, amplifiers that rely on transmission lines for harmonic matching networks necessarily show limited operational bandwidth.

The input impedance of a transmission line is approximated as follows [8]:

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)}, \quad (1)$$

where β , Z_0 , l are the propagation constant, characteristic impedance, and length of a transmission line, respectively.

This impedance can be expressed as a function of frequency, f .

$$\begin{aligned} Z_{in}(f) &= Z_0 \frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)} \\ &= Z_0 \frac{Z_L + jZ_0 \tan(2\pi \times f \times l \times \sqrt{\epsilon_{eff}}/c)}{Z_0 + jZ_L \tan(2\pi \times f \times l \times \sqrt{\epsilon_{eff}}/c)}, \end{aligned} \quad (2)$$

where ϵ_{eff} is the effective permittivity of the transmission line, and c is the speed of light.

Assuming that the efficiency is mainly affected by the output impedance, the bandwidth of the transmission lines can be found from $BW = |f_2 - f_1|/f_0$, where f_2 and f_1 are the nearest frequencies that meet the following condition:

$$|Z_{in}(f) - Z_{in,TARGET}| \leq \epsilon_{max}, \quad (3)$$

where ϵ_{max} is the maximum allowable error.

In the case of a conventional transmission line, particularly, the bandwidth can be analytically found from (2) and (3):

$$\begin{aligned} BW &= \frac{c}{2\pi fl \sqrt{\epsilon_{eff}}} \\ &\times \left\{ \begin{aligned} &\tan^{-1} \left[\frac{1}{j} \frac{Z_0 (Z_L - Z_{in,TARGET} + \epsilon_{max})}{(Z_{in,TARGET} - \epsilon_{max}) Z_L - Z_0^2} \right] \\ &- \tan^{-1} \left[\frac{1}{j} \frac{Z_0 (Z_L - Z_{in,TARGET} + \epsilon_{max})}{(Z_{in,TARGET} + \epsilon_{max}) Z_L - Z_0^2} \right] \end{aligned} \right\} \end{aligned} \quad (4)$$

When two transmission lines of different lengths are connected in shunt, as shown in Fig. 1(b), the combined line will have a “stepped” shape at the end (Fig. 1(c)), resulting in a combined impedance as follows:

$$\begin{aligned} Z_{in,stepped} &\cong \\ &\left(Z_{02} \frac{Z_L + jZ_{02} \tan(\beta l_1)}{Z_{02} + jZ_L \tan(\beta l_1)} \right) \parallel \left(Z_{02} \frac{Z_L + jZ_{02} \tan(\beta l_2)}{Z_{02} + jZ_L \tan(\beta l_2)} \right) \end{aligned} \quad (5)$$

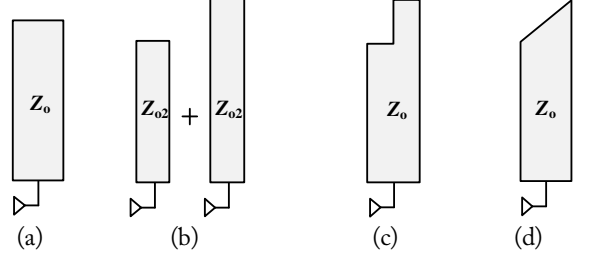


Fig. 1. Transmission lines for wider bandwidth: (a) conventional, (b) split, (c) stepped-end, and (d) slant-end.

where l_1 , l_2 are the lengths of two transmission lines, Z_{02} is the characteristic impedance of each transmission line, and “ \parallel ” represents the shunt connection of impedances.

Therefore, the transmission line in Fig. 1(c), combining the shapes of Fig. 1(b), would have near zero ohms at the frequencies at which the shortest and the longest parts of the line each becomes one quarter wavelength. This effectively results in a wider bandwidth as an impedance inverter.

Furthermore, a transmission line with a slant end, as shown in Fig. 1(d), could be regarded as having shunt connections of an infinite number of narrow stepped-end lines with incremental lengths, so it shows a better frequency response. Its impedance is expressed with (6), as follows:

$$\frac{1}{Z_{in,slant}} = \lim_{N \rightarrow \infty} \sum_{k=1}^N \left[\frac{1}{Z_{in,stepped}(Z_{0N}, l_k)} \right] \quad (6)$$

Table 1 compares the estimated bandwidth of transmission lines of Fig. 1(a), (c), and (d) at 3.4 GHz, at which the transmission lines are designed as second-harmonic shorts. In Table 1, the stepped- and the slant-end line shows wider bandwidth than the conventional one when an impedance under 5Ω is regarded as the target impedance.

In addition, in order to further improve the bandwidth over the characteristic impedance of the abovementioned open stubs, the sensitivity of the impedance Z_{in} to the frequency variation (hereafter referred to as *Sensitivity*) is defined as follows:

Table 1. Bandwidth comparison between conventional, stepped-end, and slant-end impedance inverters

Impedance inverter at 3.4 GHz	Bandwidth for $ Z_{stub} \leq 5 \Omega$
$TL_{conventional}$	1.68 MHz
$TL_{stepped-end}$	1.84 MHz
$TL_{slant-end}$	2.03 MHz

TL=transmission line.

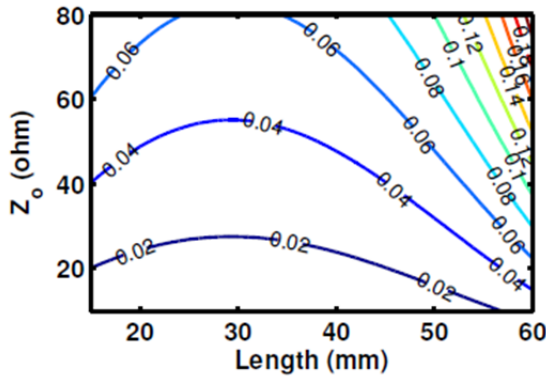


Fig. 2. Sensitivity (Ω/MHz) of an open-end stub over variations of the length and Z_0 of an open-end stub.

$$\begin{aligned} \text{Sensitivity} &= \frac{\partial Z_{in}}{\partial f} = \frac{\partial}{\partial f} \left(\frac{Z_0}{j \tan(2\pi f l \sqrt{\epsilon_{eff}} / c)} \right) \\ &= j Z_0 k l \sec^2(k f l) \frac{1}{\tan^2(k f l)}, \end{aligned} \quad (7)$$

where k is $2\pi\sqrt{\epsilon_{eff}}/c$.

This equation is used to find the optimal length and the characteristic impedance of the open-end stub to achieve the widest bandwidth in harmonic idlers (Fig. 2), at which 20–30 Ω show the lowest *Sensitivity*. This low Z_0 usually requires an impractically wide stub, and this justifies the splitting and shunt connecting of the open-end stubs.

III. DESIGN AND MEASUREMENT OF BROADBAND CLASS-F AMPLIFIER

To verify the proposed design, a class-F PA operating at 1.7 GHz was designed by employing a commercial 10 Watt, GaN HEMT transistor and was implemented on an FR4 substrate. The drain bias voltage was set to 28 V, and the bias current was set to 200 mA.

Using the aforementioned equations, a wideband matching network for a class-F PA was designed (Fig. 3). From the load-pull simulation based on the transistor model provided by the manufacturer, the fundamental impedance was set as $17+j14 \Omega$. As well, the split open-end transmission lines of Fig. 1(d) were designed to meet the class-F conditions over a wide bandwidth based on the in-house optimization algorithm [9]. Fig. 4 shows measured results of the designed matching networks, and the measured performance is shown in Fig. 5(a) and (b). Fig. 5 show that the PA has a peak drain efficiency of 82.1% and a bandwidth of 750 MHz (1.45–2.2 GHz) for efficiencies greater than 63.2%. The output power has a peak value of 14.45 W at 1.7 GHz and is

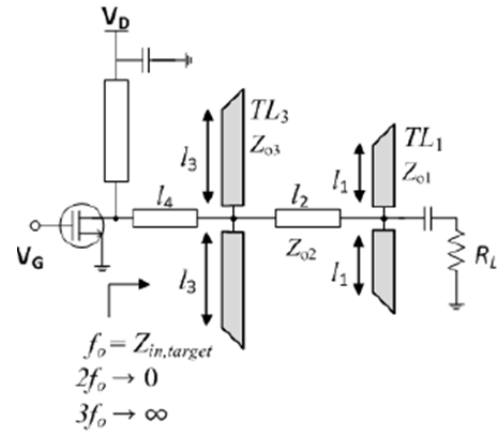


Fig. 3. Slant-end transmission lines (TL_1 and TL_3) in the broadband class-F output matching circuit.

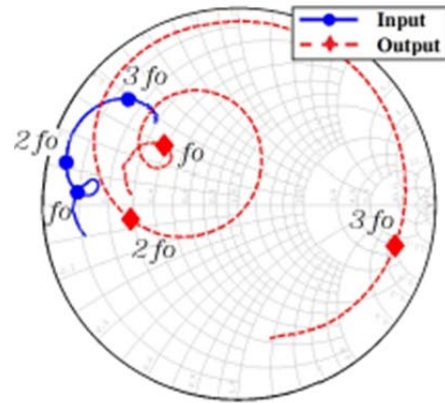


Fig. 4. Measured input and output matching networks with the slant-end transmission lines.

kept within ± 0.5 dB over the bandwidth. The implemented PA is shown in Fig. 6. Table 2 compares wideband class-F PA designs with various architectures. It is clear that the suggested design shows superb performance over conventional designs.

IV. CONCLUSION

This paper presents a design method to achieve wide bandwidth and high efficiency for power amplifiers. By splitting open-end transmission lines in the output matching network, the conditions for class-F operation could be maintained over a wider bandwidth. Furthermore, the circuit occupies less area than conventional wide-band class-F designs that require many harmonic controllers. To verify the suggested design, a broadband class-F PA operating at 1.7 GHz was designed on an FR4 substrate. The PA achieved a peak drain efficiency of 82.1% along with a bandwidth of 750 MHz for a higher than 63% efficiency. The maximum output power was 14.45 W at 1.7 GHz.

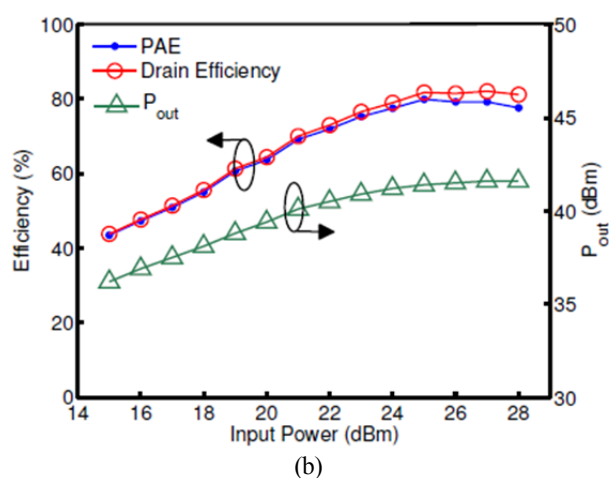
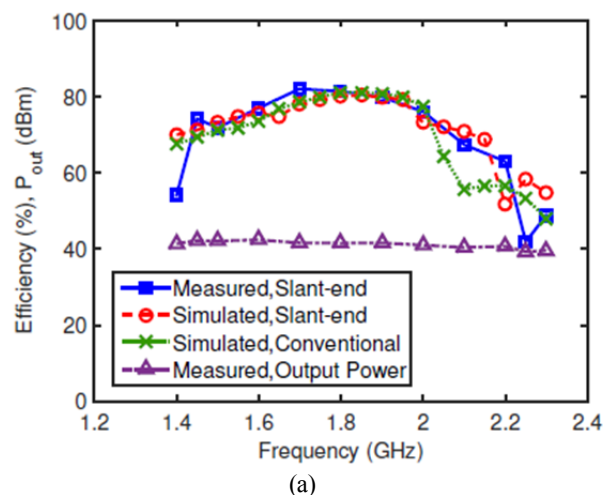


Fig. 5. Measured result of the class-F power amplifier (slant-end). (a) Efficiency and output power over frequency. (b) Efficiency over input power at 1.7 GHz.

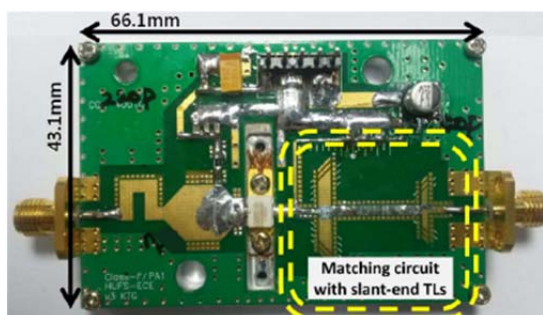


Fig. 6. Fabricated power amplifier with split open-end transmission lines.

Table 2. Performance comparison between wideband power amplifiers

	Bandwidth for > 60%	Freq. (GHz)	P_{out} (W)
This work	750 MHz	1.7	14.45
Ref. [4]	550 MHz	0.85	10.5
Ref. [7]	250 MHz	1.9	13

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Youngcheol Park



completed his B.S. in 1992 and his M.S. in 1994, both at Yonsei University. In 2004, he completed his Ph.D. in Electrical Engineering at Georgia Tech. In March 2007, he joined the faculty at Hankuk University of Foreign Studies, where he is a professor in the Department of Electronics Engineering. He has over 12 years of industrial experience with mobile phone design, RF circuits, and systems. His research interests include power amplifiers, digital signal processing for RF applications, measurement techniques for high precision signals, and applications of RADAR systems.

Taeggu Kang

completed his B.S. in 2012 and M.S. in 2014, both at Hankuk University of Foreign Studies. In 2014, he joined LIG NexOne.