IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 27, 2020, accepted February 16, 2020, date of publication February 27, 2020, date of current version April 7, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2976651

A Simple and Universal Measurement Method for the Efficiency of Pulsed RF Power Amplifiers

WEN-RAO FANG[1,2], WEN-HUA HUANG[2], WEN-HUI HUANG[1], CHAO FU[1,2], LU-LU WANG[2], TIAN-WEI HE[1], AND JIAN-GUO MA[3], (Fellow, IEEE)
[1]Department of Engineering Physics, Tsinghua University, Beijing 100084, China
[2]Science and Technology on High Power Microwave Laboratory, Northwest Institute of Nuclear Technology, Xi'an 710024, China
[3]School of Computers, Guangdong University of Technology, Guangzhou 510006, China

Corresponding author: Wen-Rao Fang (fangwenrao13@tsinghua.org.cn)

ABSTRACT This paper presents a simple and universal measurement method for the average efficiency and instantaneous efficiency of pulsed RF power amplifiers. The average efficiency of the traditional definition varies with different duties and thus lacks universality, because of the DC power consumption outside the RF pulse. In our proposed method, the DC power consumption within a pulse period is divided into different parts. The parameters of each part can be extracted-from simple measurements of the average voltage and current under different duties. The average efficiency and instantaneous efficiency of different duties can be calculated with the extracted parameters. Since current clamps or oscilloscopes are not necessary to measure the instantaneous voltage and current, this solution can be easily implemented in a simple and cost-effective way, to expand the application into compact and sealed circuits. Measurement uncertainties under different duties were analyzed of the method. Experimental results of the proposed method are consistent with theoretical efficiencies, which help validate the method.

INDEX TERMS Average efficiency, instantaneous efficiency, efficiency measurement, pulsed RF power amplifier, uncertainty analysis, various duties.

I. INTRODUCTION

RF power amplifiers (PAs) are essential components of most wireless systems. The application space includes wireless communication systems, radar, RF heating, jamming, imaging, and miniature DC-DC converters [1]. Much literature shows that PAs can be classified into two types: continuous wave (CW) PAs [2]–[4] and pulsed PAs [5]–[7]. Compared with CW PAs, pulsed PAs offer higher efficiency and are important for reducing size, weight and thermal stress [5]. Pulsed PAs are widely used in many kinds of radar systems, such as airport surveillance, ship surveillance, and weather observation systems [6].

The function of PAs is converting DC power to RF power. Many parameters are adopted to evaluate PAs, including output power, efficiency, gain and linearity. Efficiency is an important parameter when comparing and selecting PAs and plays a decisive role in power supply and thermal dissipation requirements [1], [8], [9]. Efficiency is defined as the ratio of RF-output power to DC-input power, i.e., $\eta = P_{out} / P_{dc}$. There are two commonly used definitions of efficiency for pulsed PAs: the instantaneous efficiency and the average efficiency. The instantaneous efficiency is the efficiency at one specific output level, which is the efficiency within the RF pulse. When amplifying signals with time-varying amplitudes, such as RF pulses, the average efficiency is more useful, which is defined as the ratio of the average output power to the average DC-input power: $\eta_{avg} = P_{out,avg} / P_{dc,avg}$ [9]–[12].

According to the definitions in [9]–[12], the average output power and the average DC-input power depend on the envelope probability-density function (PDF) of the amplified signal. Therefore, if the PDFs of the different signals are the same, the average efficiency should be the same. However, this conclusion is no longer valid in some pulsed PAs, which can be observed experimentally. Due to the power dissipation of a DC pulse modulator, the traditional definition of the measured average efficiency is only accurate for a fixed duty and cannot be adopted for other duties. If the pulse width or repetition frequency of the RF pulse changes, the average

The associate editor coordinating the review of this manuscript and approving it for publication was Yongle Wu.

efficiency will correspondingly change even if the PDF remained the same. Consequently, the universality of the traditionally defined average efficiency is limited in pulsed PAs.

Furthermore, the traditional measurement method of the instantaneous efficiency is based on the measurement of pulsed DC-input power, including the instantaneous voltage and current. Instantaneous current is usually measured by a current clamp or oscilloscope, which increases the complexity of the system. In high power PAs, the drain current is so large that a large current clamp cannot be mounted. It limits the application of traditional measurement methods in compact and sealed circuits.

To expand the applications of the measurement method, it is necessary to increase the universality and simplify of the measurement system. To achieve this goal, a novel measurement method for the efficiency of pulsed PAs is proposed in this paper. This new method overcomes the inherent drawbacks associated with traditional methods. In Section II, the disadvantages of the traditional measurement methods are summarized and analyzed. In Sections III and IV, the theory and uncertainty analysis of the new measurement method is discussed. Experimental data and analysis of the new measurement method are provided in Section V. Finally, a review and summary are provided in Section VI.

II. THE TRADITIONAL MEASUREMENT METHOD FOR PULSED PAS

A. TRADITIONAL MEASUREMENT METHOD FOR AVERAGE EFFICIENCY

The average efficiency of a device under test (DUT) is determined by the average RF-output power ($P_{out,avg}$) and the average DC-input power ($P_{dc,avg}$):

$$\eta_{avg} = P_{out,avg} / P_{dc,avg} \tag{1}$$

In pulsed RF PAs, $P_{out,avg}$ is detemined by the peak output power (P_{out}) and duty (D):

$$P_{out,avg} = P_{out} \cdot D = P_{out} \cdot \tau \cdot F \tag{2}$$

where τ is the width of the RF pulse and F is pulse repetition frequency. The value of P_{out} can be simply measured by a power meter.

The variable $P_{dc,avg}$ represents both the average DC-input power supplied to the PA and the average output power of the power source. It is the product of the voltage (V_{avg}) and the average current (I_{avg}) of the power source:

$$P_{dc,avg} = V_{avg} \cdot I_{avg}. \tag{3}$$

Both V_{avg} and I_{avg} can be easily obtained from a power source or multimeter. Therefore, traditional measurement methods to determine the average efficiency and its measurement system are simple.

Unfortunately, despite the simplicity of the traditional method, there are still some drawbacks that limit the application. Using the FET PA and drain modulation for an example,

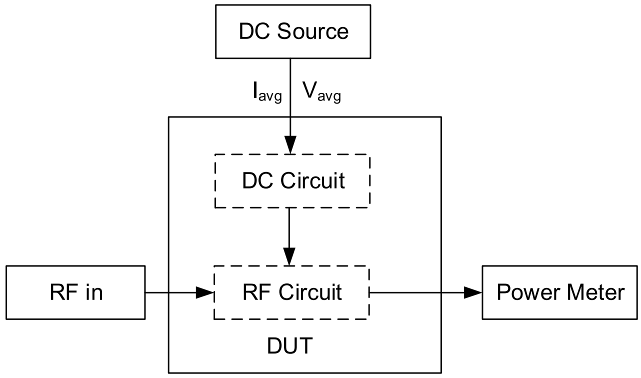

FIGURE 1. Traditional average efficiency measurement method block diagram.

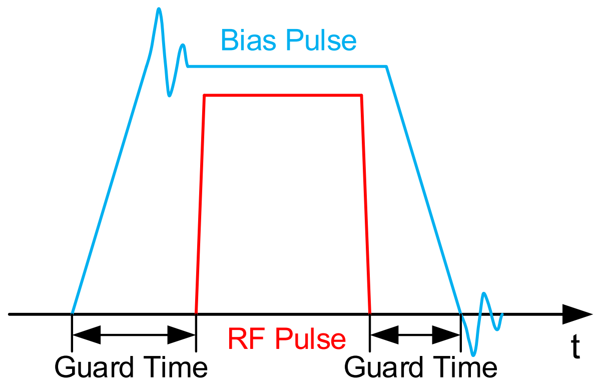

FIGURE 2. Timing diagram of the drain bias pulse and the RF pulse.

the power dissipation of the pulsed PA is not constant. Fig. 2 shows a common bias and RF waveform. To avoid the influence of the DC bias on output pulse shape, the RF pulse signal is amplified after the DC bias is stabilized [7], [13]. In addition to the bias stability period, the DC bias pulse contains a guard time, including risetime, falltime and ringing time. During the guard time, there is still power that is consumed and is not converted to RF energy.

In a short-pulse PA, the wasted power outside the RF pulse is comparable to the output power, leading to nonignorable unwanted efficiency declines. As the duty changes, the proportion of wasted power is different, hence the average efficiency varies with duty. It is scarcely possible to provide a certain average efficiency applicable to all duties even if the PDFs are the same. The average efficiency cannot reflect the ''global'' efficiency character of the measured circuit. As a consequence, declaration of duty is always required in describing the average efficiency of pulsed PAs [6], [14].

Meanwhile, the average efficiency is an overall efficiency of the DC and RF circuits. Distinguishing the efficiency of the DC and RF circuits provides designers more information to optimize them pertinently. Designers cannot evaluate these two types of efficiency separately using the traditionally defined average efficiency.

B. TRADITIONAL MEASUREMENT METHOD FOR INSTANTANEOUS EFFICIENCY

The instantaneous efficiency is the efficiency within the RF pulse and can be expressed as:

$$\eta = P_{out} / P_{dc,pls}, \tag{4}$$

where $P_{dc,pls}$ is the instantaneous DC-input power within the RF pulse. According to formula (4)), it can be seen that the instantaneous efficiency is independent of the power dissipation outside the RF pulse. As a result, the instantaneous efficiency is less sensitive to the duty, which improves its universality.

Although the instantaneous efficiency has more universality in evaluating the performance of pulsed PAs, there are still some problems. To obtain $P_{dc,pls}$, it is necessary to measure the instantaneous drain voltage (V_D) and drain current (I_D) of a pulsed PA. It is relatively easy to measure V_D with a voltmeter or oscilloscope, while measuring I_D remains a challenge in some occasions. The device under test (DUT) in Fig. 3(a) shows the typical structure of pulsed RF PA circuits. Pulsed RF PA circuits usually contain a DC and RF circuit. The DC circuit consists of a DC-DC converter and a pulse modulator. The RF circuit is composed of power transistors, RF chokes, DC blockers, isolators, etc. [7]. I_D is the internal drain current flowing from the DC circuit into the RF circuit.

A common method of measuring I_D is by means of a resistor. The resistor is welded between the DC circuit and the RF circuit, as shown in Fig. 3(a). The current delivered to the amplifier can be calculated based on the voltage drop across the resistor [15], [16]. The current measurement should maintain galvanic isolation, which ensures that no current flows directly between the load and the measuring circuit [17]. This direct measurement method of the current is undesirable as it does not guarantee good galvanic isolation.

Converting current to voltage with load after amplifying the current is another method to measure I_D. Fig. 3(b) shows the method from [18], where the current is first amplified by a current amplifier. Then the amplified current was converted to a voltage measured with a 50 Ohm-load. Similarly, galvanic isolation is still a problem, and the measurement system is complex.

The third method of measuring I_D is utilizing a current clamp, as seen in [13] and [19], and the block diagram is shown in Fig. 3(c). This is a noncontact way and could provide galvanic isolation. Nevertheless, the size of the current clamp is too large for some compact or sealed circuits. In lots of amplifier circuits, especially in T/R modules, the available space is insufficient for the current clamp. In addition, the conductor between the PA and drain bias switching circuit is always a planar circuit, such as a microstrip line. Current clamps cannot be easily mounted in such circuits, as shown in [7] and [14].

Traditional measurement methods for the efficiency of PAs are analysed above, with their drawbacks included.

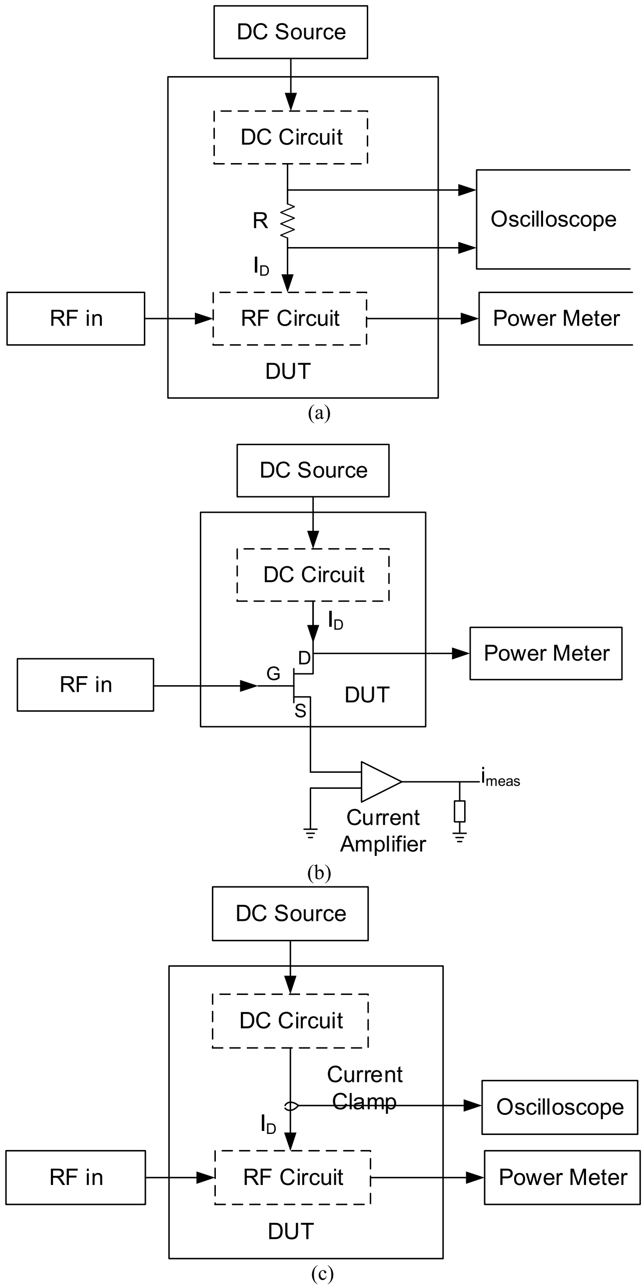

FIGURE 3. Traditional instantaneous efficiency measurement method block diagram: (a) with inserted resistance, (b) with current amplifier and current load, (c) with current clamp.

The universality of traditional measurement method for average efficiency is poor, especially for short-pulse PAs. Galvanic isolation is an unsolved problem in traditional measurement methods when measuring instantaneous efficiency, and the complexity of measurement systems limits the application of traditional measurement methods in some compact or sealed circuits. A novel measurement method for the efficiency of pulsed PAs is proposed in the following section. Better universality, better galvanic isolation and simpler measurement system can be realized with this new method.

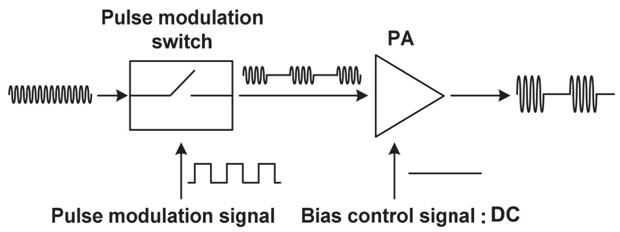

FIGURE 4. Input pulse modulation mode [7].

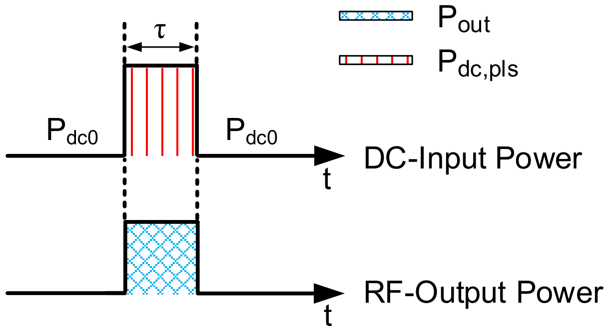

FIGURE 5. Instantaneous output power and DC-input power of the input pulse modulation mode.

III. A NEW MEASUREMENT METHOD OF PULSED PA EFFICIENCY

All the above considerations lead to defining a new measurement method that is different from traditional ones. For this purpose, the following fundamental requirements need to be considered.

1) The measured efficiency must reflect the "global" efficiency character of the measured circuit, and it should be applicable to various duties.

2) Isolation between the measurement system and DUT is necessary for reducing the influence on the DUT.

3) To expand the application to compact and sealed circuits, the simplicity of the measurement system should be considered.

Based on these points, a novel measurement method for efficiency will be proposed in this section. The measurement method generally consists of five steps.

1) Divide the DC-input power into several intervals in the time domain. Each part is defined by its unique property. Derive the formulas for the average efficiency and instantaneous efficiencies with the parameters of these parts.

2) Turn on the power source and DUT with the pulse modulator and RF source not triggered. Measure the quiescent power of the DUT.

3) Select 1∼3 duty sets. Measure the average efficiency of each DUT at a constant input RF power.

4) Extract the parameters of each interval through the measured average efficiency and derived formulas.

5) Calculate the average efficiency and instantaneous efficiency of the different duties with the extracted parameters.

As indicated in section II, the average efficiency varies with the duty. Actually, the average efficiency also differs with the nesting modes of the RF signal and DC bias pulse. The formulas for the average efficiency should be derived accordingly. In the following illustration, the measurement methods for three typical pulse switching modes are discussed.

A. INPUT PULSE MODULATION MODE

The input pulse modulation mode is shown in Fig. 4. Pulse modulation is performed using an external RF switch, and the PA subsequently amplifies the modulated signal [7]. The bias voltage of the PA remains the same.

In this mode, the instantaneous output power and DC-input power are shown in Fig. 5. The pulse width of the modulated signal is τ and the pulse repetition frequency is F. The power consumption of the power source is divided into two parts, namely, P_{dc0} and $P_{dc,pls}$. P_{dc0} is the quiescent power of the DUT, which can reflect the performance of the DC circuit, such as the DC-DC converter. $P_{dc,pls}$ is the instantaneous DC-input power within the RF pulse. P_{out} is the peak output power within the RF pulse, whereas the output power outside the RF pulse is 0.

In the traditional method, the average efficiency of this mode was expressed as:

$$\eta_{avg} = \frac{P_{out} \cdot \tau \cdot F}{V_{avg} \cdot I_{avg}}, \tag{5}$$

where V_{avg} is the output voltage and I_{avg} is the average output current of the power source, both of which can be easily read from a power source or voltmeter.

In the proposed method, the average efficiency is expressed as:

$$\eta_{avg} = \frac{P_{out} \cdot \tau \cdot F}{P_{dc,pls} \cdot \tau \cdot F + P_{dc0}\,(1 - \tau \cdot F)}. \tag{6}$$

The numerator is the output energy within a unit time, and the denominator is the DC-input energy during the same time. In this formula, P_{out}, τ and F are known. The unknown parameters are P_{dc0} and $P_{dc,pls}$. P_{dc0} repesents the quiescent power of the DUT. Here, we turn on the power source and DUT with the pulse modulator and keep RF source off. P_{dc0} is the product of V_{avg} and I_{avg} of the power source under this condition.

We next select one duty and measure the average efficiency using the traditional method and (5). Rearranging (6), we can obtain $P_{dc,pls}$ by:

$$P_{dc,pls} = \frac{P_{out}}{\eta_{avg}} + \frac{P_{dc0}\,(\tau \cdot F - 1)}{\tau \cdot F}. \tag{7}$$

With the extracted P_{dc0} and $P_{dc,pls}$, the average efficiency of any duties under the input RF power can be calculated by (6). The instantaneous efficiency can be calculated by (4).

B. CONSTANT GUARD TIME MODULATION MODE

The constant guard time modulation mode is shown in Fig. 6, and it is a hybrid pulse switching mode. There is a pulse

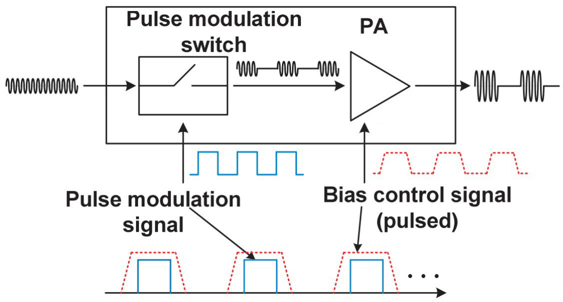

FIGURE 6. Hybrid pulse switching mode [7].

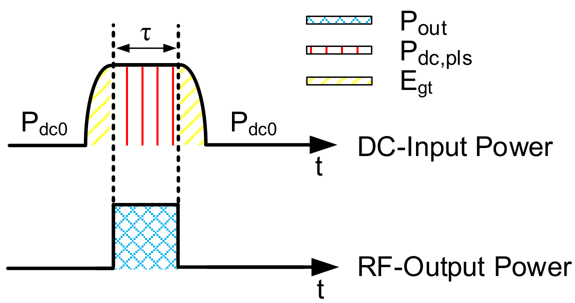

FIGURE 7. Constant guard time modulation mode.

modulation switch at the input of the PA, and the switch is operated synchronously with the bias control signal [7].

In this mode, the bias waveform and RF waveform are represented in Fig. 2. The instantaneous output power and DC-input power are shown in Fig. 7. The pulse width of the RF signal is τ and the pulse repetition frequency is F. The power consumption of the power source is divided into three parts: P_{dc0}, $P_{dc,pls}$ and E_{gt}. E_{gt} is the DC-input energy during the guard time of the single bias pulse, and it can reflect the performance of the DC circuit, including the DC-DC converter and pulse modulator. The definitions of P_{dc0}, $P_{dc,pls}$ and P_{out} are the same as the input pulse modulation mode. When the duty varies, the guard time remains unchanged, meaning that the pulse width of the bias control signal and the input RF pulse change synchronously.

In this proposed method, the average efficiency can be expressed as:

$$\eta_{avg}=\frac{P_{out}\cdot\tau\cdot F}{P_{dc,pls}\cdot\tau\cdot F+E_{gt}\cdot F+P_{dc0}\left(1-\tau\cdot F\right)}. \quad (8)$$

In this formula, P_{out}, τ and F are known. The measurement approach of P_{dc0} in this mode is the same as in the input pulse modulation mode.

There are two ways to measure the average efficiency and instantaneous efficiency of any duty. The first way is measuring the average efficiency under two pulse widths at a constant pulse repetition frequency. We assume that η_{avg1} and η_{avg2} are the measured average efficiency of the pulse widths τ_1 and τ_2, respectively, using the traditional method. From (8), the reciprocals of η_{avg} are:

$$\frac{1}{\eta_{avg1,2}}=\frac{P_{dc0}+E_{gt}\cdot F}{P_{out}\cdot F}\cdot\frac{1}{\tau_{1,2}}+\frac{P_{dc,pls}-P_{dc0}}{P_{out}}. \quad (9)$$

From (9), we can determine:

$$\frac{\tau_1}{\eta_{avg1}}-\frac{\tau_2}{\eta_{avg2}}=\frac{\left(P_{dc,pls}-P_{dc0}\right)\left(\tau_1-\tau_2\right)}{P_{out}}. \quad (10)$$

Then, $P_{dc,pls}$ can be obtained:

$$P_{dc,pls}=\frac{P_{out}(\eta_{avg2}\cdot\tau_1-\eta_{avg1}\cdot\tau_2)}{\eta_{avg1}\cdot\eta_{avg2}(\tau_1-\tau_2)}+P_{dc0}. \quad (11)$$

From (9), we can also determine that:

$$\frac{1}{\eta_{avg1}}-\frac{1}{\eta_{avg2}}=\frac{E_{gt}\cdot F+P_{dc0}}{P_{out}\cdot F}\left(\frac{1}{\tau_1}-\frac{1}{\tau_2}\right). \quad (12)$$

Then, E_{gt} can be obtained from:

$$E_{gt}=\frac{P_{out}\cdot\tau_1\cdot\tau_2\left(\eta_{avg2}-\eta_{avg1}\right)}{\eta_{avg1}\cdot\eta_{avg2}\left(\tau_2-\tau_1\right)}-\frac{P_{dc0}}{F}. \quad (13)$$

With the extracted values of P_{dc0}, $P_{dc,pls}$ and E_{gt}, the average efficiency of any duty can be calculated by (8). The instantaneous efficiency can be calculated by (4).

The second way is measuring the average efficiency under two pulse repetition frequencies at a constant pulse width). We assume that η'_{avg1} and η'_{avg2} are the measured average efficiency of the pulse repetition frequency F_1 and F_2 using the traditional method. From (8), reciprocals of η_{avg} are:

$$\frac{1}{\eta'_{avg1,2}}=\frac{P_{dc,pls}}{P_{out}}+\frac{E_{gt}}{P_{out}\cdot\tau}+\frac{P_{dc0}\left(1-\tau\cdot F_{1,2}\right)}{P_{out}\cdot\tau\cdot F_{1,2}}. \quad (14)$$

From (14), we arrive at:

$$\frac{1}{\eta'_{avg1}}-\frac{1}{\eta'_{avg2}}=\frac{P_{dc0}}{P_{out}\cdot\tau}\left(\frac{1}{F_1}-\frac{1}{F_2}\right). \quad (15)$$

Similarly, we can determine that:

$$\frac{\frac{1}{\eta'_{avg1}}-\frac{1}{\eta'_{avg2}}}{\frac{1}{\eta_{avg}}-\frac{1}{\eta'_{avg1}}}=\frac{\frac{1}{F_1}-\frac{1}{F_2}}{\frac{1}{F}-\frac{1}{F_1}}. \quad (16)$$

Rearranging (16), we finally obtain:

$$\eta_{avg}=\frac{\eta_{avg1}\cdot\eta_{avg2}\cdot F\left(F_2-F_1\right)}{\eta_{avg2}\cdot F_1\cdot F_2-\eta_{avg1}\cdot F_1\cdot F_2+\eta_{avg1}\cdot F\cdot F_2-\eta_{avg2}\cdot F\cdot F_1}. \quad (17)$$

The disadvantage of the second way is that the instantaneous efficiency cannot be calculated. Therefore, if the instantaneous efficiency is an indispensable parameter that must be measured, the first way is preferable.

Additionally, from (9), we can determine the linear relationship between $1/\eta_{avg}$ and $1/\tau$. If τ approaches 0, then the average efficiency also approaches 0. However, if τ is large enough, then $\eta_{avg}\approx P_{out}/P_{dc,pls}$, which is the same as the efficiency of CW mode. According to this linear relationship,

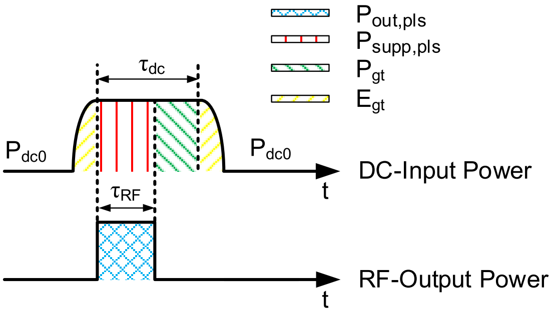

FIGURE 8. Varied guard time modulation mode.

the average efficiency under any pulse width τ can be easily calculated from:

$$\eta_{avg} = \frac{\eta_{avg1}\cdot\eta_{avg2}\cdot\tau\left(\tau_2-\tau_1\right)}{\tau\left(\eta_{avg1}\cdot\tau_2-\eta_{avg2}\cdot\tau_1\right)+\tau_1\cdot\tau_2\left(\eta_{avg2}-\eta_{avg1}\right)} \tag{18}$$

From (17) and (18), we see an interesting phenomenon. The variables η_{avg1} and η_{avg2} under τ_1 and τ_2 (or F_1 and F_2) are enough for the calculation of η_{avg}. The solution of $P_{dc,pls}$ and E_{gt}, as well as P_{out} and P_{dc0} are not necessary, making it easier to evaluate η_{avg}.

C. VARIED GUARD TIME MODULATION MODE

The varied guard time modulation mode is also a hybrid pulse switching mode, as shown in Fig. 6. The difference is that the guard time may vary due to the different demand.

In this mode, the instantaneous output power and DC-input power are shown in Fig. 8. The pulse width of the RF signal is τ_{rf}, whereas the pulse width of the bias pulse is τ_{dc}.-τ_{dc} is always larger than τ_{rf} so that the RF signal can be amplified completely. We assume the pulse repetition frequency is F as well. The power consumption of the power source is divided into four parts, i.e., P_{dc0}, $P_{dc,pls}$, P_{gt} and E_{gt}. E_{gt} is the DC-input energy during the rise and fall times of the single bias pulse. P_{gt} is the instantaneous DC-input power within the gap between the RF pulse and the rise/fall time of the bias pulse, which is a part of the guard time. The definitions of P_{dc0}, $P_{dc,pls}$ and P_{out} are the same as the input pulse modulation mode. When the duty varies, the guard time may change. It means that the pulse width of the bias pulse and the input RF pulse may not synchronously change.

In this proposed method, the average efficiency can be expressed as:

$$\eta_{avg} = \frac{P_{out}\cdot\tau_{rf}\cdot F}{P_{dc,pls}\cdot\tau_{rf}\cdot F+P_{gt}\cdot F\left(\tau_{dc}-\tau_{rf}\right)+E_{gt}\cdot F+P_{dc0}(1-\tau_{dc}\cdot F)}, \tag{19}$$

where P_{out}, τ and F are known. The measurement approach for P_{dc0} is the same as for the input pulse modulation mode. $P_{dc,pls}$ and E_{gt} can be obtained using the method in the constant guard time modulation mode by setting $\tau_{rf} = \tau_{dc}$ and measuring the average efficiency of the two pulse widths. Assuming that η_{avg1} and η_{avg2} are the measured average efficiencies under the pulse widths τ_1 and τ_2 using the traditional method. $P_{dc,pls}$ and E_{gt} are determined from (11) and (13), respectively.

Next, we select the pulse width of the third set and ensure that $\tau_{rf} < \tau_{dc}$. The measured average efficiency will be denoted as η_{avg3}. Rearranging (19), we arrive at:

$$P_{gt} = \frac{\tau_{rf3}}{\tau_{dc3}-\tau_{rf3}} \cdot\left[\frac{P_{out}}{\eta_{avg3}} - P_{dc,pls} - \frac{E_{gt}}{\tau_{rf3}} - \frac{P_{dc0}\left(1-\tau_{dc3}\cdot F\right)}{\tau_{rf3}\cdot F}\right]. \tag{20}$$

With the extracted parameters, the average efficiency of any duty under the same input RF power can be calculated by (19). The instantaneous efficiency can still be calculated by (4).

According to the derivation of the average efficiency and instantaneous efficiency, we only need to measure the average efficiency of 1∼3 duties. Throughout the entire process, the measurement of the instantaneous efficiency is not necessary. In section II, the difficulties in measuring the instantaneous efficiency and the complexity of the measurement system were presented. Therefore, the proposed method provides an opportunity to obtain a simple measurement system. The application of the novel method can be extended to compact and sealed circuits. Moreover, the average efficiency and instantaneous efficiency under varied duties can be calculated using a simple measurement. With the extracted parameters of the DC-input power, it is possible to evaluate the efficiency of the DC and RF circuits separately. All of these advantages indicate that this novel method fulfils all the fundamental requirements.

IV. UNCERTAINTY ANALYSIS OF NEW METHOD

The analysis of uncertainty plays an important part in this method. Uncertainty analysis can be used to assess the variability and prediction imprecision of the outcome variable due to the uncertainty of the input parameters. Understanding the uncertainty can also assist in choosing input parameters. In this paper, the uncertainty evaluation of the estimated average efficiency in the constant guard time modulation mode is performed. The conclusion is also applicable to the other two modes.

In the case of real measurement data, the main sources of uncertainty are related to the measurement instrumentation [20]. In (18), the input parameters are the pulse widths and measured average efficiency. The pulse widths are selected manually and set in the pulse generating device. The pulse widths can be set very accurately, meaning their uncertainties can be ignored. Therefore, the average efficiency is the main source of uncertainty influencing the outcome variable significantly. Optimizing the input parameters to minimize the uncertainty of the outcome variable is of great value.

Considering η_{avg} as a function, f, of the pulse widths and measured average efficiency, (18) can be rewritten as:

$$f\left(\tau;\tau_1,\tau_2,\eta_{avg1},\eta_{avg2}\right) = \frac{\eta_{avg1}\cdot\eta_{avg2}\cdot\tau\left(\tau_2-\tau_1\right)}{\tau\left(\eta_{avg1}\cdot\tau_2-\eta_{avg2}\cdot\tau_1\right)+\tau_1\cdot\tau_2\left(\eta_{avg2}-\eta_{avg1}\right)} \tag{21}$$

The Guide to the Expression of Uncertainty in Measurement (GUM) provides internationally agreed upon approaches to the evaluation of measurement uncertainty [21]. The law of propagation of uncertainty, given in the GUM as its main procedure for uncertainty evaluation, has been widely used in uncertainty analysis [22]–[25].

The uncertainties of η_{avg1} and η_{avg2} are denoted as $u(\eta_{avg1})$ and $u(\eta_{avg2})$, which are mostly affected by the accuracy of the output power and DC-input power measurements. According to the law of propagation of uncertainty and ignoring the uncertainties of the pulse width, the squared η_{avg} uncertainty is calculated from [21]:

$$u^2\left(\eta_{avg}\right) = \left(\frac{\partial f}{\partial\eta_{avg1}}\right)^2 u^2\left(\eta_{avg1}\right)+\left(\frac{\partial f}{\partial\eta_{avg2}}\right)^2 u^2\left(\eta_{avg2}\right). \tag{22}$$

Calculating the partial derivative of f, we arrive at:

$$\frac{\partial f}{\partial\eta_{avg1}} = \frac{\eta_{avg2}^2\cdot\tau\cdot\tau_1\left(\tau_2-\tau\right)\left(\tau_2-\tau_1\right)}{\left(\tau\left(\eta_{avg1}\cdot\tau_2-\eta_{avg2}\cdot\tau_1\right)+\tau_1\cdot\tau_2\left(\eta_{avg2}-\eta_{avg1}\right)\right)^2}. \tag{23}$$

Substituting(23) into(22), the squared η_{avg} uncertainty becomes (24), as shown at the bottom of this page.

For simplicity, we assume $u(\eta_{avg1})$ and $u(\eta_{avg2})$ are equal to u_0. Substituting (18) into (24), the squared η_{avg} uncertainty can be simplified to:

$$u^2\left(\eta_{avg}\right) = \frac{u_0^2\cdot\eta_{avg}^4}{\left(\tau_2-\tau_1\right)^2}\left[\frac{\tau_1^2\left(\tau_2-\tau\right)^2}{\eta_{avg1}^4\cdot\tau^2}+\frac{\tau_2^2\left(\tau-\tau_1\right)^2}{\eta_{avg2}^4\cdot\tau^2}\right]. \tag{25}$$

From the equations, we can find that the η_{avg} uncertainty is related to τ, τ_1 and τ_2. Before measuring η_{avg1} and η_{avg2}, elaborate selection of the pulse width becomes meaningful to achieve an accurately predicted value for η_{avg}. For a given τ_1 and τ_2, the optimum pulse width τ_{opt} with a minimum uncertainty can be calculated. To get a simple analytical solution, we ignore the change of the average efficiency with τ in (25), and solve the following partial derivative equation:

$$\frac{\partial u^2\left(\eta_{avg}\right)}{\partial\tau} = 0. \tag{26}$$

Then, we can determine τ_{opt} from:

$$\tau_{opt}\approx\frac{\tau_1\cdot\tau_2\left(\eta_{avg1}^4+\eta_{avg2}^4\right)}{\tau_1\cdot\eta_{avg2}^4+\tau_2\cdot\eta_{avg1}^4}. \tag{27}$$

It can be inferred that:

$$\min(\tau_1,\tau_2)\le\tau_{opt}\le\max(\tau_1,\tau_2). \tag{28}$$

Smaller uncertainty can be achieved by reducing the difference between the concerned τ and τ_{opt}. Therefore, the selected range $[\tau_1, \tau_2]$ should cover or be close to all of the concerned pulse widths.

V. EXPERIMENTS AND ANALYSIS

To verify the validity of the new measurement method, the efficiency of a pulsed RF PA was analyzed using the new measurement method. The measured circuit is presented in Fig. 9, which comprises the RF and DC circuits. The RF circuit was made up of four internally matched cascaded GaN HEMTs power amplifiers and five isolators which were specially developed. The cascaded power amplifiers, with drain voltage of 50 V, were capable of producing an output power of hundreds of Watts and a gain of more than 50dB under pulsed mode. The DC circuit mainly consists of DC-DC converters and a pulse modulator.

Both the RF and DC circuits were fabricated inside a shielding cavity where current clamps cannot be mounted. The instantaneous efficiency can hardly be measured using traditional methods. In addition, the average efficiency measured by traditional methods is only applicable to specific pulse parameters. Therefore, traditional measurement methods are not feasible for this circuit.

A. COMPARISON OF MEASURED AND THEORETICAL EFFICIENCY

Based on the novel proposed measurement, we only need to measure the average efficiency to obtain the ''global'' efficiency character. As shown in Fig. 9, V_{avg}, I_{avg} and the output RF power were indispensable parameters when calculating the average efficiency.

To assess the accuracy of the new method for the constant guard time modulation mode, the average efficiencies were measured when the pulse width varied from 400 ns to 2000 ns. The pulse repetition frequency was 500 Hz, and the PA was operated in a nonlinear state. Through a simple measurement,

$$u^2\left(\eta_{avg}\right) = \frac{\tau^2\cdot\left(\tau_2-\tau_1\right)^2\cdot\left[\eta_{avg2}^4\cdot\tau_1^2\left(\tau_2-\tau\right)^2\cdot u^2\left(\eta_{avg1}\right)+\eta_{avg1}^4\cdot\tau_2^2\left(\tau-\tau_1\right)^2\cdot u^2\left(\eta_{avg2}\right)\right]}{\left(\tau\left(\eta_{avg1}\cdot\tau_2-\eta_{avg2}\cdot\tau_1\right)+\tau_1\cdot\tau_2\left(\eta_{avg2}-\eta_{avg1}\right)\right)^4} \tag{24}$$

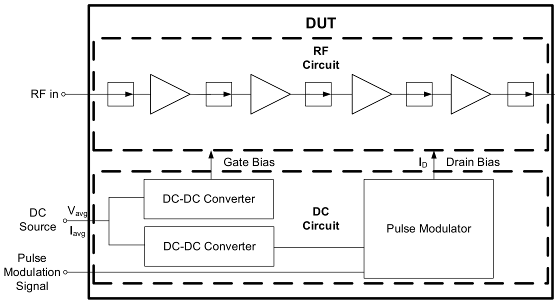

FIGURE 9. Block diagram of the measured PA.

TABLE 1. Measured average efficiency in constant guard time modulation mode.

Pulse Width/ns	Average Efficiency /%
400	11.42
600	14.33
800	16.42
1000	17.99
1200	19.15
1400	20.21
1600	21.02
1800	21.76
2000	22.58

the output value for P_{out} and P_{dc0} were obtained, which were normalized to 100 W and 37.6 mW. The measured average efficiency varied from 11.42% to 22.58%, as illustrated in Table 1.

The theoretical average efficiencies under pulse widths ranging from 400 ns to 2000 ns were calculated via formula (18), as shown in Fig. 10(a). 600 ns and 1800 ns were selected as τ_1 and τ_2, respectively. The maximum error between the theoretical results and the measured results was 0.25%, which occurred at 2000 ns. The maximum relative error was 1.09%. With the help of this new method, the instantaneous efficiency can be calculated without measuring the internal drain current. The theoretical instantaneous efficiency of this PA was 29.37%.

The validity of the new measurement method was also verified for linear PAs. The same PA was operated in linear state, while other parameters were kept unchanged. P_{out} and P_{dc0} were normalized to 53 W and 37.6 mW, respectively. The theoretical and measured average efficiencies are shown in Fig. 10(b). The selected input pulse widths, τ_1 and τ_2, were still 600 ns and 1800 ns. The maximum error and maximum relative error between the theoretical and the measured results were 0.21% and 2%, respectively, which occurred at 800 ns. The theoretical instantaneous efficiency was 20.73%.

From the result, we observe good consistency between the theoretical results and the measured results in the constant guard time modulation mode. This new method is applicable to both nonlinear and linear PAs.

To assess the accuracy of the method for varied guard time modulation modes, average efficiencies under pulse widths

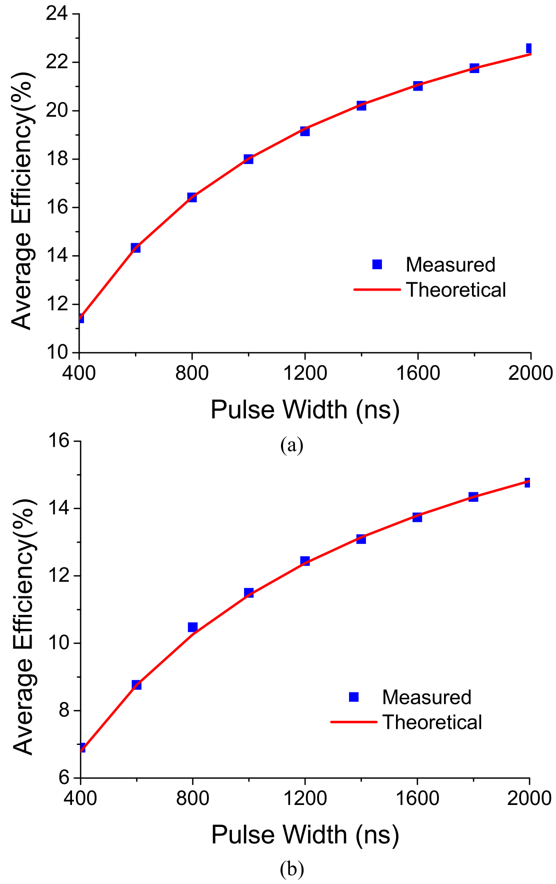

FIGURE 10. Measured average efficiency (symbol) and theoretical average efficiency (line) in constant guard time modulation mode when PA was: (a) saturated and (b) linear.

ranging from 400 ns to 2000 ns were measured. The pulse width of the bias pulse τ_{dc} was always larger than the pulse width of the RF signal τ_{rf}. The pulse repetition frequency was 500 Hz and the PA was operated in a nonlinear state. The measured power P_{out} and P_{dc0} were normalized to 100 W and 38.0 mW. The average efficiency varied from 11.34% to 21.95%, as illustrated in Table 2.

The theoretical average efficiencies under pulse widths ranging from 400ns to 2000 ns were calculated using formulas (18), (19) and (20), as shown in Fig. 11(a). The selected pulse widths, τ_1 and τ_2, were 400ns and 2000 ns. The selected pulse width τ_{rf3} was 400ns and τ_{dc3} was 1600 ns. The maximum error between the theoretical efficiency and the measured efficiency was 0.27%, which occurred at $(\tau_{rf}, \tau_{dc}) = (1200$ ns, 1200 ns). The maximum relative error was 1.45%. The theoretical instantaneous efficiency of this PA was 28.66%.

The theoretical efficiency and measured average efficiency of the linear PA are shown in Fig. 11(b). The PA was operated in a linear state and other parameters, including input pulse widths, were kept unchanged. The measured power P_{out} and P_{dc0} were normalized to 58 W and 38.0 mW. The maximum error between the theoretical and measured results was 0.11%, which occurred at $(\tau_{rf}, \tau_{dc}) = (1200$ ns, 2000 ns).

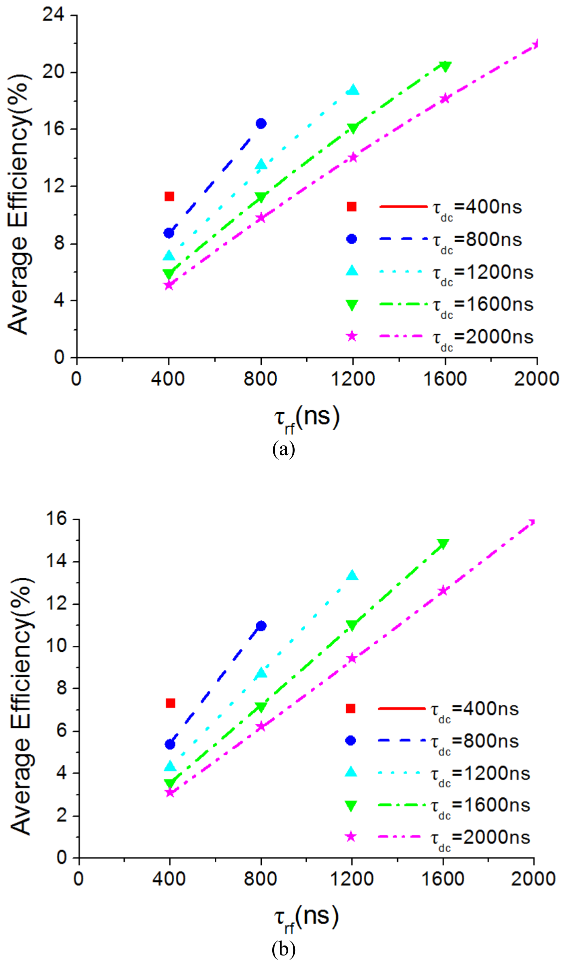

FIGURE 11. Measured average efficiency (symbol) and theoretical average efficiency (line) in varied guard time modulation mode when the PA was: (a) saturated and (b) linear.

TABLE 2. Measured average efficiency in varied guard time modulation mode.

UNIT: %

τ_{rf}/ns \ τ_{dc}/ns	400	800	1200	1600	2000
400	11.34				
800	8.76	16.42			
1200	7.12	13.51	18.72		
1600	5.95	11.33	16.18	20.48	
2000	5.13	9.83	14.05	18.18	21.95

The maximum relative error was 1.14%. The theoretical instantaneous efficiency of this PA was 22.46%.

Again, good consistency between the theoretical results and the measured results is observed.

B. COMPARISON OF THE MEASURED AND THEORETICAL UNCERTAINTIES

For illustrative purposes, the measurement uncertainty was determined for the constant guard time modulation mode. As discussed in Section IV, a smaller difference between the concerned τ and τ_{opt} means a smaller uncertainty of η_{avg}. Comparisons of the measured uncertainty and theoretical uncertainty of different τ_{opt} are given. Because the initial uncertainty, u_0, was not clear, the theoretical efficiencies and measured average efficiencies were normalized as follows:

$$u_{normalized}\left(\eta_{avg}\right) = u\left(\eta_{avg}\right)/\max\left(u\left(\eta_{avg}\right)\right). \tag{29}$$

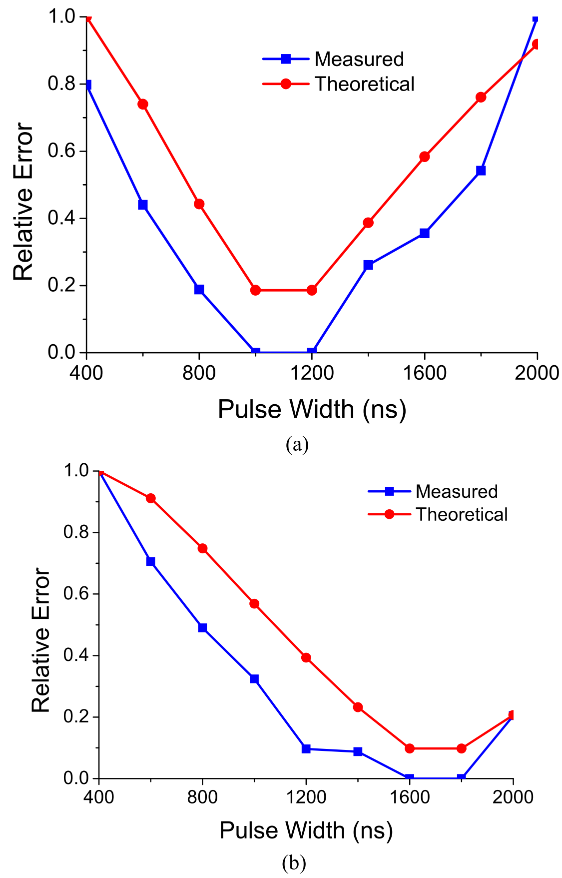

FIGURE 12. Normalized uncertainty of η_{avg} in constant guard time modulation mode: (a) (τ_1, τ_2) = (1000 ns, 1200 ns) and (b) (τ_1, τ_2) = (1600 ns, 1800 ns).

Fig. 12(a) shows the normalized theoretical uncertainties and measured uncertainties of η_{avg}. The selected pulse widths, $\tau 1$ and $\tau 2$, were 1000 ns and 1200 ns, respectively. The measured uncertainties were in good agreement with the theoretical results. Using the numerical calculation method, we find that the accurate optimum pulse width with a minimum uncertainty of η_{avg} was 1299 ns. Meanwhile, the approximate optimum pulse width, τ_{opt} in (27), was 1303 ns, which was fairly close to the actual value, verifying the validity of the approximation in (27).

Another example favors this uncertainty analysis as well. The selected pulse widths, τ_1 and τ_2, were changed to 1600 ns and 1800 ns, respectively, with the result illustrated in Fig. 12(b). The normalized theoretical uncertainties and measured uncertainties of η_{avg} had a similar tendency. The accurate τ_{opt} was 1699 ns, and the approximate τ_{opt} was 1701 ns. The experimental and theoretical results are in good agreement.

Experimental results demonstrate the importance of pulse width selection for accuracy. We should pay attention to the choice of measured pulse width based on the pulse width of interest. Another factor that affects the accuracy of the measurement is the reduction in power envelope during the pulse. In the discussion of Section III, the output power, P_{out}, is considered to be constant all the time. In our experiment, several tantalum capacitors and ceramic capacitors were used as capacitor bank in the pulse modulator to prevent the reduction in power envelope. Consequently, the reduction in power envelope was small enough and can be ignored. As a result, the accuracy of the measured efficiency was maintained.

VI. CONCLUSION

With a goal of reducing the complexity and expanding the application, a new measurement method for the average efficiency and instantaneous efficiency of Pulsed RF PAs has been established. The method reveals the formation mechanism of power consumption and efficiency. The performance of the method has been assessed through a number of experiments. Good agreement was achieved between the theoretical and measured results. The maximum error and maximum relative error between the theoretical efficiency and measured average efficiency was 0.21% and 2.00%, respectively, verifying the validity of the new method. In addition, the theoretical and measured uncertainties were in good agreement, which can assist in selecting measurement parameters to obtain good accuracy.

The proposed method shows better universality and better galvanic isolation over traditional methods. The simple measurement system enables the application in some compact or sealed circuits. With the development of GaN HEMTs, more and more pulsed PAs are used in active phase-array radars. This method can be implemented in large scale automatic T/R module test system, providing the ''global'' efficiency character and reducing the cost.

REFERENCES

[1] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popovic, N. Pothecary, J. F. Sevic, and N. O. Sokal, ''Power amplifiers and transmitters for RF and microwave,'' *IEEE Trans. Microw. Theory Techn.*, vol. 50, no. 3, pp. 814–826, Mar. 2002.

[2] M. R. Duffy, G. Lasser, M. Olavsbraten, E. Berry, and Z. Popovic, ''Efficient multisignal 2–4-GHz power amplifier with power tracking,'' *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 12, pp. 5652–5663, Dec. 2018.

[3] J. Deng, P. S. Gudem, L. E. Larson, and P. M. Asbeck, ''A high average-efficiency SiGe HBT power amplifier for WCDMA handset applications,'' *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 2, pp. 529–537, Feb. 2005.

[4] Q.-F. Cheng, H.-P. Fu, S.-K. Zhu, and J.-G. Ma, ''Two-stage high-efficiency concurrent dual-band harmonic-tuned power amplifier,'' *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 10, pp. 3232–3243, Oct. 2016.

[5] J. Dhar, R. K. Arora, S. K. Garg, M. K. Patel, and B. V. Bakori, ''Performance enhancement of pulsed solid state power amplifier using drain modulation over gate modulation,'' in *Proc. Int. Symp. Signals, Circuits Syst.*, Iasi, Romania, Jul. 2009, pp. 1–4.

[6] N. Miyazawa, M. Nishihara, K. Usami, M. Aojima, and T. Yamamoto, ''S-band 600 W and X-band 200 W high-power GaN HEMTs for radar transmitters,'' *SEI Tech. Rev.*, vol. 84, pp. 146–150, 2017.

[7] H.-J. Kim, W.-J. Cho, J.-H. Kwon, and J.-W. Lee, ''An X-band 100W GaN HEMT power amplifier using a hybrid switching method for fast pulse switching,'' *Progr. Electromagn. Res.*, vol. 78, pp. 1–14, Jan. 2017.

[8] R. Giofre, P. Colantonio, and F. Giannini, ''A design approach to maximize the efficiency vs. linearity trade-off in fixed and modulated load GaN power amplifiers,'' *IEEE Access*, vol. 6, pp. 9247–9255, 2018.

[9] F. Raab, ''Efficiency of outphasing RF power-amplifier systems,'' *IEEE Trans. Commun.*, vol. COM-33, no. 10, pp. 1094–1099, Oct. 1985.

[10] F. H. Raab, ''Average efficiency of power amplifiers,'' in *Proc. RF Technol. Expo.*, Anaheim, CA, USA, 1986, pp. 473–486.

[11] F. Raab, ''Average efficiency of class-G power amplifiers,'' *IEEE Trans. Consum. Electron.*, vols. CE-32, no. 2, pp. 145–150, May 1986.

[12] F. Raab, ''Efficiency of doherty RF power-amplifier systems,'' *IEEE Trans. Broadcast.*, vol. BC-33, no. 3, pp. 77–83, Sep. 1987.

[13] S.-W. Shin, ''Pulsed-bias pulsed-RF passive load-pull measurement of an X-band GaN HEMT bare-chip,'' *J. Korea Inst. Intell. Transp. Syst.*, vol. 10, no. 1, pp. 42–48, Jan. 2011.

[14] K. Kanto, A. Satomi, Y. Asahi, Y. Kashiwabara, K. Matsushita, and K. Takagi, ''An X-band 250W solid-state power amplifier using GaN power HEMTs,'' in *Proc. IEEE Radio Wireless Symp.*, Orlando, FL, USA, Jan. 2008, pp. 77–80.

[15] Keysight Technologies, ''PNA-X application-power-added efficiency (PAE),'' Keysight Technol., Santa Rosa, CA, USA, Appl. Note 1408-16, 2007, Accessed: Oct. 9, 2007. [Online]. Available: https://literature.cdn.keysight.com/litweb/pdf/5989-7293EN.pdf?id=1307265

[16] M. Begin, F. M. Ghannouchi, F. Beauregard, L. Selmi, and B. Ricco, ''Characterization of the transient behavior of a GaAs MESFET using dynamic I-V and S-parameter measurements,'' *IEEE Trans. Instrum. Meas.*, vol. 45, no. 1, pp. 231–237, Feb. 1996.

[17] C. R. Weggel, ''Circuit for measuring current in class-D amplifiers,'' U.S. Patent 5 629 616, May 13, 1997.

[18] Q. Smets, A. Verhulst, J.-H. Kim, J. P. Campbell, D. Nminibapiel, D. Veksler, P. Shrestha, R. Pandey, E. Simoen, D. Gundlach, C. Richter, K. P. Cheung, S. Datta, A. Mocuta, N. Collaert, A. V.-Y. Thean, and M. M. Heyns, ''Pulsed I-V on TFETs: Modeling and measurements,'' *IEEE Trans. Electron Devices*, vol. 64, no. 4, pp. 1489–1497, Apr. 2017.

[19] A. Nalli, A. Raffo, G. Avolio, V. Vadala, G. Bosi, D. M. M.-P. Schreurs, and G. Vannini, ''Extremely low-frequency measurements using an active bias tee,'' in *IEEE MTT-S Int. Microw. Symp. Dig.*, Seattle, WA, USA, Jun. 2013, pp. 1–4.

[20] A. Cataliotti, V. Cosentino, S. Guaiana, S. Nuccio, D. Di Cara, N. Panzavecchia, and G. Tine, ''Measurement uncertainty impact on simplified load flow analysis in MV smart grids,'' in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (IMTC)*, Houston, TX, USA, May 2018, pp. 1–6.

[21] *Uncertainty of Measurement—Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995)*, document ISO/IEC Guide 98-3:2008, International Standardization Organization, Geneva, Switzerland, 2008.

[22] M. Cox, P. Harris, and B. R.-L. Siebert, ''Evaluation of measurement uncertainty based on the propagation of distributions using Monte Carlo simulation,'' *Meas. Techn.*, vol. 46, no. 9, pp. 824–833, Sep. 2003.

[23] G. Wübbeler, M. Krystek, and C. Elster, ''Evaluation of measurement uncertainty and its numerical calculation by a Monte Carlo method,'' *Meas. Sci. Technol.*, vol. 19, no. 8, Jul. 2008, Art. no. 084009.

[24] G. D'Antona, L. Di Rienzo, R. Ottoboni, and A. Manara, ''Processing magnetic sensor array data for AC current measurement in multiconductor systems,'' *IEEE Trans. Instrum. Meas.*, vol. 50, no. 5, pp. 1289–1295, Oct. 2001.

[25] A. Baccigalupi, M. D'Arco, and A. Liccardo, ''Parameters and methods for ADCs testing compliant with the guide to the expression of uncertainty in measurements,'' *IEEE Trans. Instrum. Meas.*, vol. 66, no. 3, pp. 424–431, Mar. 2017.

WEN-RAO FANG received the B.S. degree from Tsinghua University, Beijing, China, in 2013, where he is currently pursuing the Ph.D. degree with the Department of Engineering Physics. His research interests include microwave circuit design, highly-efficient power amplifiers, high-power amplifiers, power amplifiers measurement, and modeling of GaN HEMT.

WEN-HUA HUANG, photograph and biography not available at the time of publication.

WEN-HUI HUANG received the B.S. degree in applied physics and the Ph.D. degree in accelerator physics from Tsinghua University, in 1999. He was a Guest Scientist with DESY, from 2000 to 2001. He is currently a Professor with the Department of Engineering Physics, Tsinghua University. His research interests include beam dynamics in linac, Thomson scattering x-ray source, beam diagnostics, and photocathode RF guns, and so on.

CHAO FU received the B.S. degree from Tsinghua University, Beijing, China, in 2015, where he is currently pursuing the Ph.D. degree with the Department of Engineering Physics. His research interests include microwave circuit design, highly-efficient power amplifiers, high-power amplifiers, and multistage power amplifiers.

LU-LU WANG, photograph and biography not available at the time of publication.

TIAN-WEI HE, photograph and biography not available at the time of publication.

JIAN-GUO MA (Fellow, IEEE) received B.Sc. and M.Sc. degrees from Lanzhou University, Lanzhou, China, in 1982 and 1988, respectively, and the Ph.D. degree in engineering from Duisburg University, Duisburg, Germany, in 1996.

From 1996 to 1997, he was a Postdoctoral Fellow with the Technical University of Nova Scotia, Halifax, NS, Canada. From 1997 to 2005, he was a Faculty Member with Nanyang Technological University, Singapore, where he was also the Founding Director with the Center for Integrated Circuits and Systems. From 2005 to 2009, he was with the University of Electronic Science and Technology of China, Chengdu, China. Since 2008, he has been the Technical Director with the Tianjin IC Design Center. From 2009 to 2016, he was the Dean of the School of Electronic Information Engineering, Tianjin University. He is currently with the School of Computers, Guangdong University of Technology, Guangzhou, China. He has authored or coauthored approximately 245 technical papers and four books. He holds seven U.S. patents granted and 30 filed/granted China patents. His current research interests include RFICs and RF integrated systems for wireless, RF device characterization modeling, monolithic microwave integrated circuit, RF/microwave circuits and systems and electromagnetic interference in wireless, RFID, and wireless sensing networks.

Dr. Ma was a recipient of the prestigious Changjiang (Yangtze) Scholar Award of the Ministry of Education of China, in 2007 and the Distinguished Young Investigator Award of the National Natural Science Foundation of China, in 2006. He has served the scientific community as a Reviewer and an Editor of several conferences and journals, namely, the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, where he is also the Editor-in-Chief.