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Abstract

We report an ultra-wideband and high efficiency sub-6GHz power amplifier, which is based on periodically varied load modulation with frequency. Key novelties are frequency-periodic load modulation over multiple contiguous frequency bands combined with digitally assisted dual-input configuration, which provides optimum signal combination, magnitude and phase of dual-input signals. The amplifier using 0.15-um GaN HEMT FETs achieved drain efficiency of 45-62% over 1.4-4.8GHz that is 110% fractional bandwidth at 6dB power back-off. This, to the best of the authors' knowledge, is the widest fractional bandwidth reported so far for a load modulated amplifier at these frequency range. It is a very promising PA technology for 5G base station, enabling reduction of the total cost of ownership (TCO) for operators.

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A Novel 1.4-4.8 GHz Ultra-Wideband, over 45% High Efficiency Digitally Assisted Frequency-Periodic Load Modulated Amplifier

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***Abstract*— We report an ultra-wideband and high efficiency sub-6GHz power amplifier, which is based on periodically varied load modulation with frequency. Key novelties are frequency-periodic load modulation over multiple contiguous frequency bands combined with digitally assisted dual-input configuration, which provides optimum signal combination, magnitude and phase of dual-input signals. The amplifier using 0.15-µm GaN HEMT FETs achieved drain efficiency of 45-62% over 1.4-4.8GHz that is 110% fractional bandwidth at 6dB power back-off. This, to the best of the authors' knowledge, is the widest fractional bandwidth reported so far for a load modulated amplifier at these frequency range. It is a very promising PA technology for 5G base station, enabling reduction of the total cost of ownership (TCO) for operators.**

***Keywords*— GaN, power amplifier, PAE, dual-input power amplifier, load modulation.**

I. INTRODUCTION

Recently, advanced wireless communication systems apply high peak-to-average power ratio (PAPR) signals to cope with crowded spectrum and higher speed data demands. RF power amplifiers (PA) for base stations require high efficiency at a large back-off power level. In particular, an amplifier over 1-5 GHz becomes increasingly important for next generation mobile communication systems such as sub-6GHz 5G to achieve high capacity communication with forward compatibility, while maintaining backward compatibility for the 3G-4G system. At present, the Doherty Power Amplifier (DPA) is widely used in base station, to achieve high efficiency at large back-off level. However, the DPA is fundamentally limited to narrow frequency range due to the frequency dependent λ/4 inverter for load modulation. Hence, to expand bandwidth with high efficiency of PA, circuit technologies to widen the bandwidth of DPA [1] and various non-Doherty configuration have been studied [2]-[3].

In this work, we report an ultra-wideband and high efficiency sub-6GHz power amplifier, which is based on periodically varied load modulation with frequency. A novel frequency-periodic load modulated output combiner is fabricated and demonstrated. Our design offers several types of load modulation, such as a virtual open stub Doherty [4], an outphasing, a general Doherty, an anti-phase outphasing and so on with periodicity in multiple contiguous frequency bands, as shown in Fig. 1. 0.15-µm GaN HEMT is used in the demonstrator. Input circuit is dual-input configuration with digitally assist which finds optimum signal combination, magnitude and phase of dual-input signals. The amplifier achieved drain efficiency of 45-62% over 1.4-4.8GHz which is 110% fractional bandwidth at power back-off of 6dB. This, to the best of the authors' knowledge, is the widest fractional bandwidth reported for a load modulated amplifier at these carrier frequency.

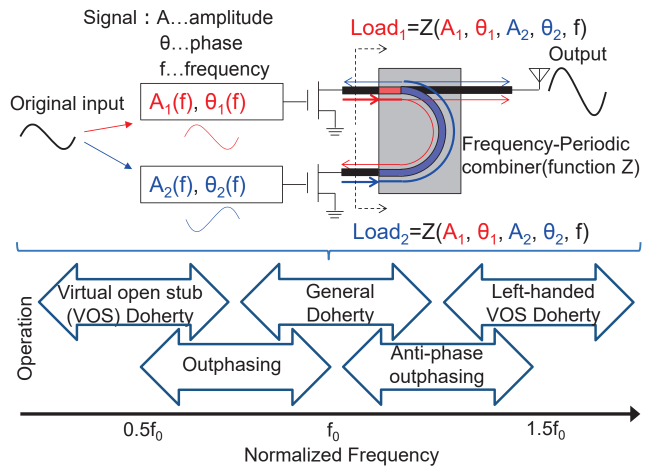

Fig. 1. Concept of the frequency-periodic load modulated amplifier.

II. FREQUENCY-PERIODIC LOAD MODULATED AMPLIFIER CIRCUIT

A. Circuit Configuration

The schematic of circuit diagram of frequency-periodic load modulated amplifier is shown in Fig. 2. The circuit employs two GaN FETs. The equivalent transmission line is connected to each FET at the equivalent current source plane of the device. A device capacitance C_{ds} is absorbed into the equivalent transmission line. An additional transmission line with electrical length of 90 degrees at the center frequency is further connected to one side of the FETs. Characteristic impedance of combiner based on above transmission lines is chosen to be the optimum load resistance of FET, R_{opt}. Output matching network (OMN) is connected at the output of the combiner. In the input side, input matching network (IMN) including stabilization circuit is connected.

The concept of absorbing device capacitance into a part of the equivalent transmission line is shown in Fig. 3. The goal is to mimic the frequency response of the ideal transmission line by using transistor's C_{ds} and additional component at the

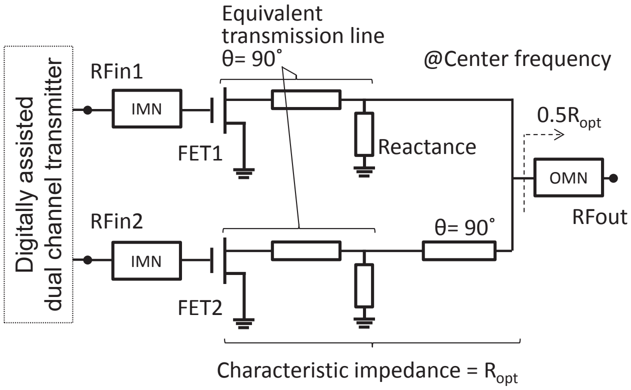

Fig. 2. Schematic of the circuit diagram of frequency-periodic load modulated amplifier.

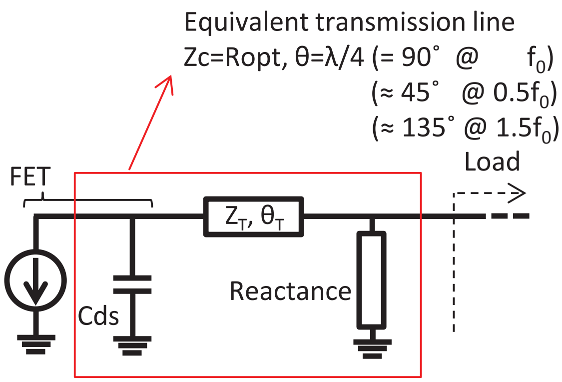

Fig. 3. Schematic of the equivalent transmission line with absorbed output capacitance of FET.

outside of transistor over a wide frequency range. Electrical length of equivalent transmission line is λ/4 (90 degrees) at the center frequency, and ideally, it is proportional to frequency. If the equivalent transmission line includes large lumped component or resonant component, it is challenging to mimic the frequency response of the ideal transmission line.

B. *Circuit Operation According to Frequency*

The frequency-periodic load modulated amplifier is able to realize a variety of load modulation, such as virtual open stub Doherty, outphasing, general Doherty, and anti-phase outphasing on the basis of frequency periodicity. In this section, the difference of resistive load modulation for each frequency is explained, especially focusing on back-off power level operation. In the description, the center frequency is denoted as f_0. The gate voltages of FETs are biased at the threshold point of FETs. In this case, EFTs turn-on and -off are controlled by input signal magnitude.

Around f_0, the amplifier operates as a general Doherty amplifier as shown in Fig. 4. In this case, FET1 operates as a main amplifier, and FET2 operates as an auxiliary amplifier with proper input signal control. At the back-off power level, no signal is generated to FET2. In that case, FET2 is turned off because of its biasing at the threshold voltage. FET2 brunch becomes open circuit, and T1 line functions as an impedance transformer. Load impedance of FET1 is thus twice of R_{opt}, which is the same as general Doherty load modulation condition.

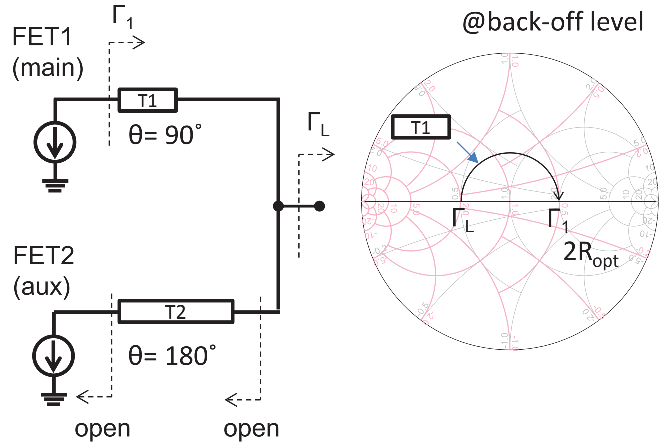

Fig. 4. Circuit configuration and load modulation around f_0 (General Doherty amplifier).

Around $0.5f_0$, the amplifier operates as a virtual open stub Doherty amplifier which is one of the extended back-off configurations. Resistive load modulation point at $0.58f_0$ is shown in Fig. 5. At this frequency, FET1 operates as an auxiliary amplifier, and FET2 operates as a main amplifier with certain input signal control. Compared with relationship between the main and the auxiliary of f_0-Doherty, the relationship between FET1 and FET2 is exchanged. At the back-off power level, no signal is applied for FET1. In that case, FET1 is turned off, thus FET1 brunch works as open stub. Then, T2 works as impedance transformer. Due to the effects of the virtual open stub and long transmission line, load impedance of FET2 is more than the twice of R_{opt}, while keeping resistive load modulation.

Around $1.5f_0$, the amplifier operates as the left-handed virtual open stub Doherty amplifier. Around $0.5f_0$ case, T1 works as capacitive component. On the other hand, around $1.5f_0$ case, T1 behaves as inductive component.

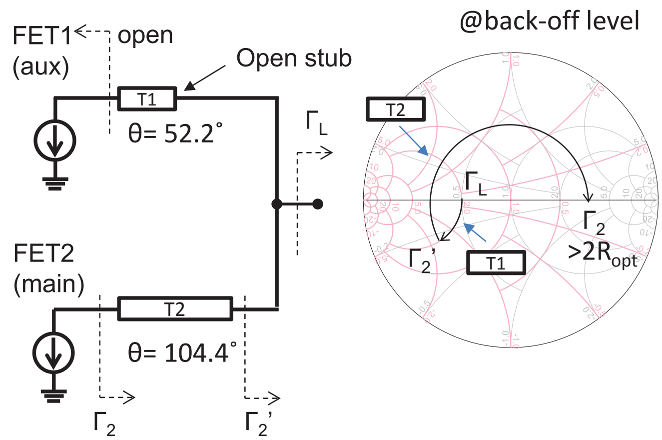

Fig. 5. Circuit configuration and load modulation at $0.58f_0$ (Virtual open stub Doherty amplifier).

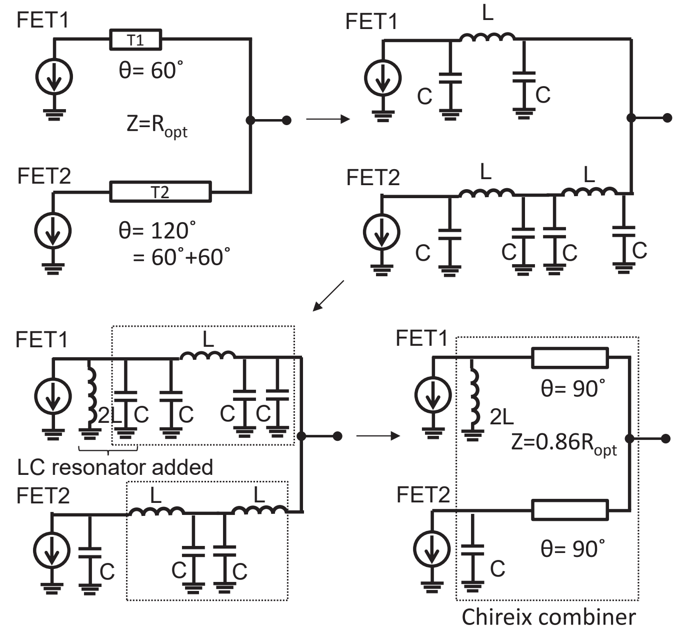

Fig. 6. Circuit configuration and load modulation at $0.67f_0$ (Outphasing amplifier).

Between $0.5f_0$-f_0, the amplifier operates as an outphasing amplifier. Resistive load modulation point at $0.67f_0$ is shown in Fig. 6. As shown in Fig. 6, the combiner that includes the 60 degrees and 120 degrees equivalent transmission lines is converted to Chireix combiner. It can be converted from distributed circuit to lumped circuit. Circuit components are recombined, and then it is converted from lumped circuit to distributed circuit again. Outphasing amplifier operation occurs by changing the input signal phase difference.

Between f_0-$1.5f_0$, the amplifier operates as an outphasing amplifier, however which is anti-phase relationship with $0.5f_0$-f_0 outphasing. Resistive load modulation point at $1.33f_0$ is shown in Fig. 7. As shown in Fig. 7, relationship between the capacitance and the inductance for FET1 and FET2 of f_0-$1.5f_0$ outphasing is exchanged with respect to $0.5f_0$-f_0 outphasing. It means that, for f_0-$1.5f_0$ outphasing, input signal phase difference is opposite to $0.5f_0$-f_0 outphasing.

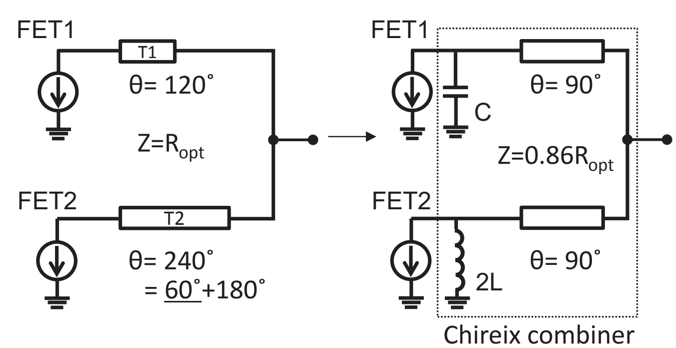

Fig. 7. Circuit configuration and load modulation at $1.33f_0$ (Outphasing amplifier, anti-phase of $0.5f_0$-f_0).

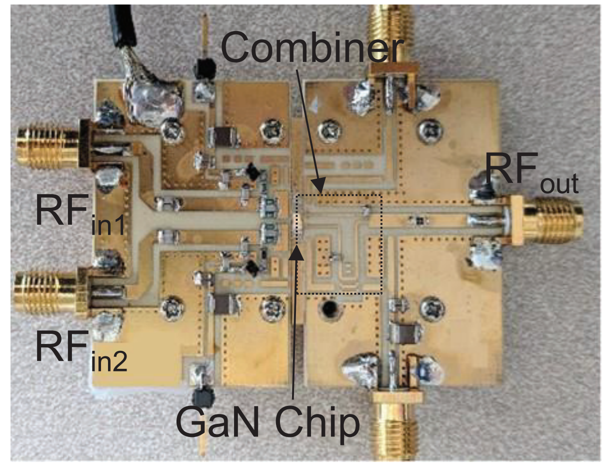

Fig. 8. Photo of the assembled 0.15μm-GaN HEMT frequency-periodic load modulated amplifier.

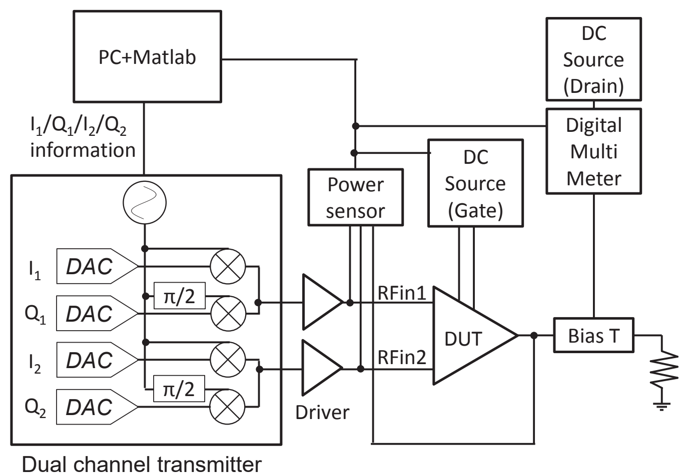

Fig. 9. Schematic of digitally assisted dual channel transmitter measurement system.

III. Measurement Result

Fig. 8 shows the photo of the assembled GaN frequency-periodic load modulated amplifier. Upper one is FET1, and lower one is FET2. In this work, OMN to 50Ω load in Fig. 2 is not needed, due to transistor R_{opt} is synthesized to be 100Ω.

The measurement setup is illustrated in Fig.9. Dual channel transmitter is used for input signal generation. Digitally assist optimization algorism in Matlab in PC generates I_1 and Q_1 signal for FET1, and I_2 and Q_2 signal for FET2. In our case, phase difference and amplitude of input signals are controlled in baseband I/Q domain. Apparently, these phase and amplitude of dual-input signals lead to a high dimensional space for wideband and power sweep, in dual-input measurement. The digitally assist algorism finds the optimum status according to the evaluation function based on amplifier characteristics, e.g. output power, efficiency and gain.

Fig. 10 shows drain efficiency versus output power for several exemplary RF frequency centered at 3.1GHz. At all tested frequency, drain efficiency at 6dB back-off power is above 45%. Fig. 11 describes input signal condition of drain efficiency measurement of Fig. 10. Left axis shows input power ratio between FET1 and FET2. Right axis shows phase difference between input signals of FET1 and FET2.

$$Power\ ratio = \frac{P_{in\_FET1}}{P_{in\_FET1}+P_{in\_FET2}} \quad (1)$$

$$Phase\ difference = Phase_{in\_FET2} - Phase_{in\_FET1} \quad (2)$$

As one can see, Fig. 11 measured conditions clearly demonstrate operation mode alternating. At 1.6GHz and back-off power level, majority input power is delivered to FET2. It means that FET2 operate as main amplifier and the amplifier operates as Doherty-like. Next, at 2.8GHz and back-off power level, most of input power is delivered to FET1, it means role of FET2 is switched from main to auxiliary. Again, at 4.6GHz, back-off power level, majority input power is delivered to FET2, it means FET2 operate as main amplifier. On the other hand, at 4.2GHz, since the variation of phase difference is dominant, the amplifier behaves as outphasing-like. Note, when power ratio is 0 or 1, phase difference is indefinite.

Fig. 12 shows measured ultra-wide bandwidth of designed amplifier. 45-62% of drain efficiency is achieved across the measured frequency range 1.4-4.8GHz at 6dB power back-off level. Output power at 6dB back-off is approximately 31.5dBm. Fractional bandwidth of 110% is achieved. This, to the best of the authors' knowledge, is the widest fractional bandwidth reported so far for a load modulated amplifier at these carrier frequency range.

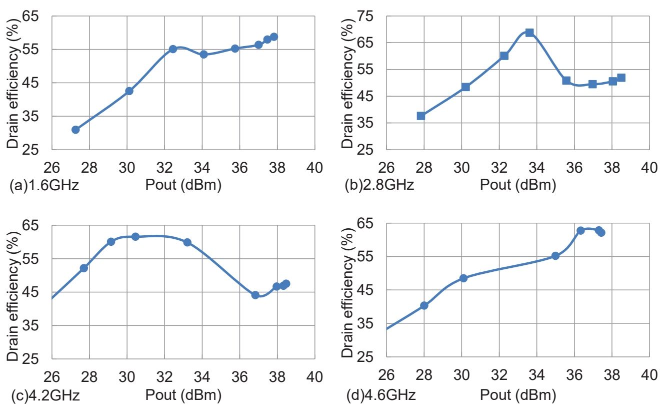

Fig. 10. Measured drain efficiency with power sweep at different frequency.

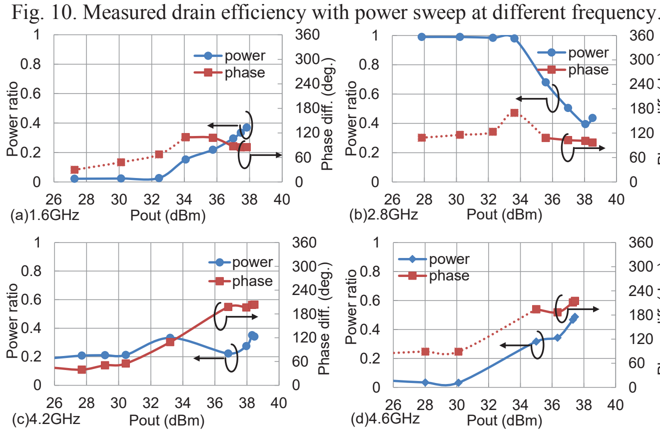

Fig. 11. Measured input signal condition with power sweep at different frequency.

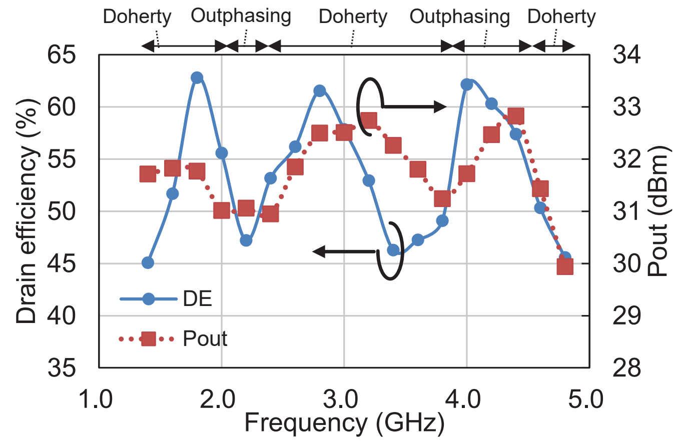

Fig. 12. Measured frequency dependences of drain efficiency and output power at 6dB power back-off level.

Table 1. Comparison of sub-6GHz high efficiency wideband amplifiers.

Ref.	Year	Freq. (GHz)	Fractional BW(%)	Efficiency (%)	Pout (dBm)	Configutration	backoff
[1]	2012	3.0-3.6	18	38-56	37-38	Doherty	6dB(CW)
[2]	2013	1.0-3.0	100	48-68	37.1-38.9	Doherty-Outphasing	6dB(CW)
[3]	2017	0.9-2.15	82	32-36	30.0-30.7	Envelope tracking	6.5dB(Mod.)
Here	2018	1.4-4.8	110	45-62	29.9-32.8	FPLMA	6dB(CW)

Table 1 shows the state-of-the-art performance of sub-6GHz wideband amplifiers with high efficiency. Compared with other amplifiers, this new frequency-periodic load modulated amplifier (FPLMA) reported by us has the widest bandwidth with drain efficiency over 45%.

IV. Conclusion

By exploring a novel output combiner circuit topology and leveraging its frequency periodicity, the demonstrated GaN PA maintains high average efficiency over the widest fractional bandwidth, relying on the various load modulation mechanism within multiple contiguous frequency bands, respectively. This contribution further expands next generation base station PA design space, assisted by digital optimization and cutting-edge GaN HEMT technology.

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