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Class BJF^{-1}: Pushing the boundaries of the performance of RF Power Amplifiers.

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Invited Paper.

Abstract

A new design space of contiguous mode amplifiers straddled in the centre of the Smith Chart, by Class J at one end and Class CCF^{-1} at the other, is presented. The waveforms require tuning of the second harmonic of the voltage and upto the third harmonic of the current, to derive the full benefit of harmonic tuning. This class is naturally realised by tuning the output capacitance C_{DS} of a GaN transistor, compared to the counterpart in class CCF. We have demonstrated several prototypes in this class with outstanding performance of efficiency, output power, bandwidth, and linearity.

Keywords: RF Power Amplifier, contiguous mode.

Introduction

5G mobile networks that offer download speeds of up to 10 Gbps require amplifiers with the highest efficiency and linearity, which presents a challenge both at the device as well as circuit levels. Contiguous mode amplifiers that evolved from continuum modes (i.e. B/J continuum [1], CCF[2], CCF^{-1}[3], ext. CCF^{-1}[4]) constrain the impedance along a 1D-arc on the Smith chart. More advanced modes (Fig 1) such as the Series of Continuous Modes (SCM) [5], Series of Inverse Continuous Modes (SICM) [7] called resistive-reactive series of modes, and other evolutions [9]–[12] define 2D design spaces via phase shifted waveforms of current and voltage that enable the second harmonic terminations to have both real and imaginary parts [13]. For example, waveforms in [9] contain a varying resistive part at the fundamental frequency and a reactive component at the second harmonic frequency. Our proposed Class BJF^{-1} waveforms, with load impedances shown in Fig 2 (a), are obtained by phase shifting the second harmonic voltage of Class J and manipulating the classical CCF^{-1} waveform to peak smoothly either to the right or to the left as shown in Fig 2 (b). The output power (P_{out}) and efficiency (η_{out}) are expressed with respect to that of Class B as ($P_{out|B}$) and efficiency ($\eta_{out|B}$):

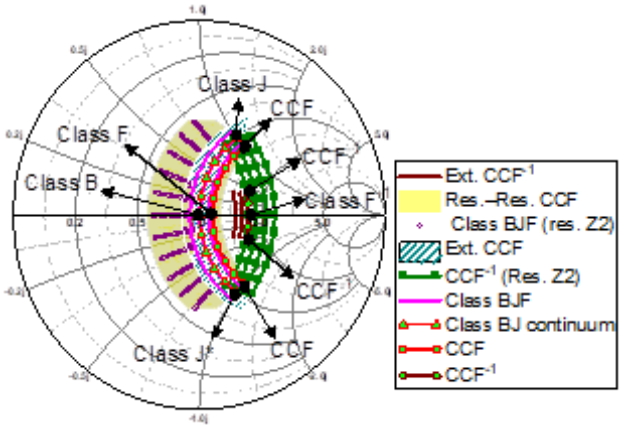

Fig. 1. Load impedances at fundamental frequencies of class B/J continuum [1], CCF[2], CCF^{-1}[3], ext. CCF^{-1}[4], Class BJF (SCM) [5], Resistive-resistive SCM [5]/CCF[6], and Resistive-resistive SCIM [7]/CCF^{-1} [8].

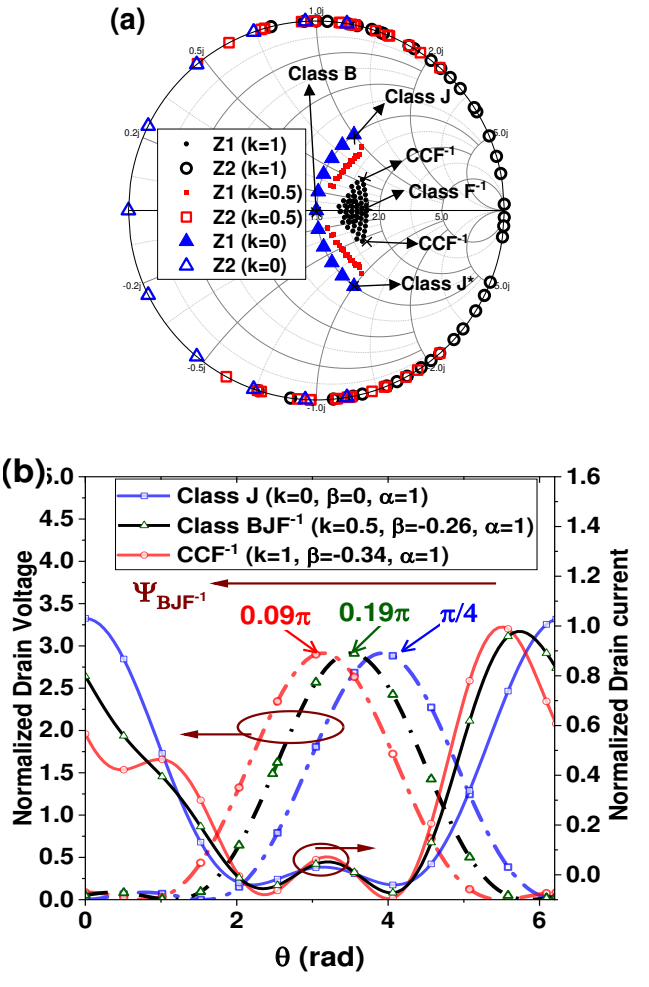

Fig. 2. (a) Load impedances at fundamental and the second harmonic frequencies of the proposed mode (class BJF^{-1}). (b) A comparison of the voltage and current waveforms of classes J, BJF^{-1} and CCF^{-1}, with phase angle.

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$$P_{out} \approx P_{out|B}\delta_v\delta_{Ii}\cos(\Psi_{pf}) \quad (1)$$

$$\eta_{out} \approx \eta_{out|B}\delta_v\delta_{Ii}\cos(\Psi_{pf}) \quad (2)$$

In (1) and (2), Ψ_{pf} is the phase difference between the current and voltage waveforms in Class J.

The contour plots for the theoretical maximum efficiency at a given fundamental impedance in Fig. 2 (a) are plotted in Fig. 3. The extended 91% contour (marked by A) reveals that the efficiency of class F^{-1} can also be achieved through the proposed waveforms which are not defined previously in class CCF^{-1}, further providing an additional aspect of flexibility of design.

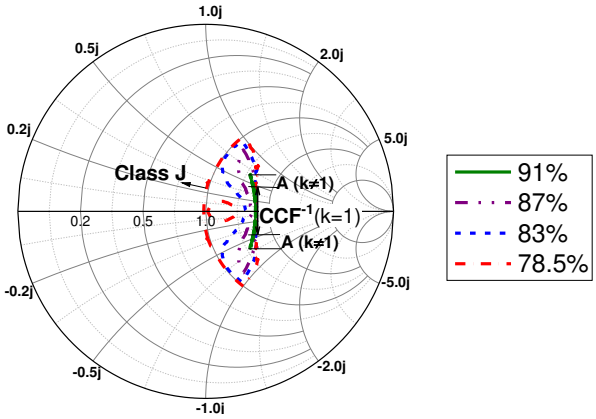

Fig. 3: Contour plot of the theoretical efficiency for impedances in Fig. 2 (a).

Methodology

We have reported Class BJF^{-1} amplifiers biased in deep class AB with the CGH40010 and CGH40025 using narrowband as well as broadband techniques from 2.6-4.6 GHz. The drain parasitic network of the power device consisting of the intrinsic drain-source capacitance (C_{DS}) and a T-network of inductance, resistance, and capacitance were used to access the current generator plain of the transistor [14].

Three narrowband amplifiers (V1, V2, and V3) were biased

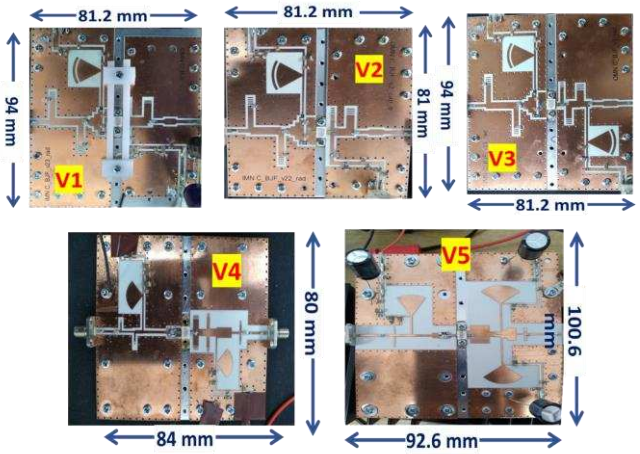

Fig. 4: Photographs of fabricated amplifiers operating in class BJF^{-1}. Narrow band amplifiers matched at 2.6 GHz are denoted by V1, V2, and V3. Broadband amplifiers are V4 and V5. V4 is a 10 W Power amplifier with Frequency range 2.2 GHz – 4.6 GHz. V5 is a 25 W Power amplifier with Frequency range 2.2 GHz – 3.3 GHz

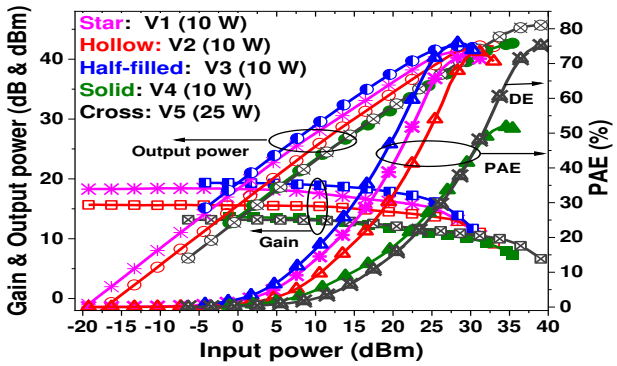

Fig. 5: Measured gain, output power, and PAE of the amplifiers at 2.6 GHz.

at Vdsq=28 V, Idsq=150 mA and fabricated on 0.762 mm R4350B Rogers substrate shown in Fig. 4. We have developed a methodology that identifies the optimal impedances from the class BJF^{-1} design space and their corresponding broadband matching networks simultaneously using a particle swarm optimization approach [15] Two amplifiers (V4 and V5) (Fig 4) were designed using this approach. Amplifier V4 is biased at Vdsq=28 V, Idsq=150 mA and V5 uses the CGH40025 at Vdsq=28 V, Idsq=300 mA. The matching networks for the broadband were fabricated using 0.508 mm RO4003C shown in Fig 4.

C. Measurement Result

The measured transducer gain, output power and efficiency at 2.6 GHz for all prototypes are plotted in Fig. 5. Prototypes V1-V3 achieved efficiency > 70% and the output power of all the amplifiers designed using the 10W part (V1 to V4) is greater than 42 dBm. Even though, V2 and V3 are matched only at 2.6 GHz, they still result in 600 MHz and 900 MHz bandwidth respectively due to the large design space of class BJF^{-1}, signifying high tolerance to mismatch, high yield and flexibility available to the designer. V4 has lower efficiency at 2.6 GHz because it is designed for broadband performance by sacrificing the efficiency at 2.6 GHz. The broadband performance of these amplifiers is plotted in Fig. 6. On the other hand, amplifier V4 demonstrates a ±1 dB gain flatness, output power greater than 40 dBm, and efficiency between 51% and 70% over a target frequency range of 2.4–4.6 GHz. When benchmarked against reported amplifiers of similar

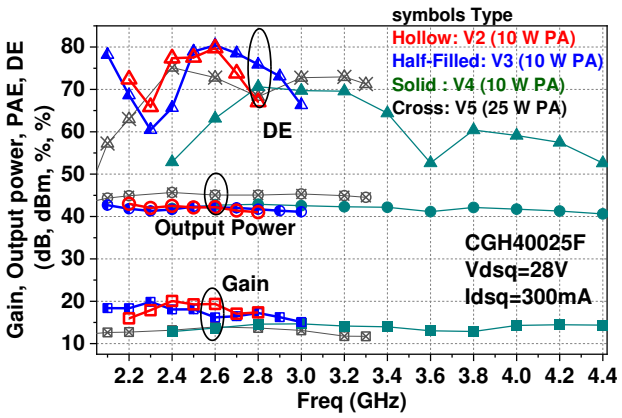

Fig. 6: The broadband performance of amplifiers V2, V3, V4, and V5.

bandwidth, these indicate a high frequency weighted efficiency. Amplifier V4 demonstrates high output power over the entire range with respectable FE, even though, it operates at 4.6 GHz, the highest operating frequency reported for this device and an exceptional performance in comparison to other amplifiers using the 25W part [16].

Conclusions

We demonstrate a new class of contiguous mode amplifiers with record performances achievable due to their considerable tolerance to mismatch and high yield. The high efficiency is necessary to address the increasing energy consumption of upcoming mobile communications networks.

TABLE I

Comparison of the designed amplifier with state-of-the-art amplifiers of comparable bandwidth using the CGH40010F reported in the literature.

Ref.	Mode	Bandwidth (GHz, %)	Output power (dBm)	DE (AE) %,(%)	FE
[17]	J	2.3-2.7, 16	40-40.8	60-69(63)	78.3
[5]	SCM	1.6-2.8, 54.6	40-42.5	67.5-81.9 (76.4)	92.5
[7]	SCIM	2.4-3.9, 47.6	39.63-41.4	62-75 (68.1)	90.7
[2]	CCF	1.45-2.45, 51.3	40.4-42.3	70-81 (75.9)	89.7
[18]	HT	1.8-2.7, 37.6	40.6-41.7	68-77 (73.3)	90
[19]	E	1.7-2.4, 34.1	38.9-41	71-87 (76.4)	91.3
Amp. V2 [20]	BJF-1	2.2-2.8, 24.0	41-43	65.9-79.7 (73.4)	92.4
Amp. V3	BJF-1	2.1-3, 35.3	41-43	60-80 (72.6)	91.7
Amp. V4	BJF-1	2.4-4.6, 62.8	40-42.8	51-70(60.3)	82.4

AE = Average Efficiency, FE=AE*$\sqrt[4]{Center\ Freq.(in\ GHz)}$, HT = harmonic tuned, SCM = series of continuous modes, SCIM=Series of inverse continuous modes

Acknowledgments

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