CLASS BJF^{-1}: SIMPLIFYING THE DESIGN METHODOLOGY OF RF POWER AMPLIFIERS

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We present Class BJF^{-1}, our new class of amplifier, that achieves efficiencies higher than class B/J/J for a large range of possible load impedances that considerably simplifies the design space of broadband harmonically tuned amplifiers. The formulation for this class encompasses Class J (High linearity), CCF^{-1} (high efficiency), extended CCF^{-1}, and saturated PAs. We can choose better amongst this range to achieve the desired target performance. Three PA prototypes were designed by selecting impedances within the design space using a GaN HEMT CGH40010F. All achieved measured PAE in excess of 72%, and saturated output power Pout in excess of 41 dBm. The measured P1dB ranged from 30 dBm to 35 dBm, as chosen by design. Moreover, a 3dB bandwidth of 800 MHz was observed, despite using only narrowband techniques. This is because of the large design space coupled with a simple strategy of an impedance transformer in the matching network. The best performing amplifier achieved 79.7% drain efficiency and 42.2 dBm saturated output power at 2.6 GHz, giving a frequency weighted efficiency (FE= (average efficiency)*∜Center Freq) of 92.4% ∜GHz, representing one of the highest figures of merit achieved with this device reported to date.*

INTRODUCTION

Class J [1][2], relying on a continuum of voltage waveforms and continuous class F^{-1}(CCF^{-1}) [3], relying on a continuum of current waveforms, are capable of high efficiency under broadband frequencies. In [4], we presented a new class of amplifier, referred as Class BJF^{-1}, in which both current and voltage waveforms are manipulated. These proposed waveforms require a short at third and higher harmonic impedances which is easier to achieve at high frequency. This class achieves efficiencies higher than class B/J/J* for a large range of possible load impedances. Unlike the constant resistance and conductance required for the class B/J/J* and CCF^{-1} respectively, class BJF^{-1} has a range of real part of impedance values which considerably simplifies the design of broadband harmonically tuned amplifiers. This is demonstrated by the results presented in this paper.

Background

Class BJF^{-1} is defined by a well-defined set of waveforms as opposed to the generic second harmonic technique [5]. The magnitude of the second harmonic of the voltage waveform and the quadrature component of current waveform are proportional to parameters α and β respectively, just as in class B/J/J* and CCF^{-1}. In addition to these, the quadrature component of the current waveform in class J is partially removed by a factor k, to obtain class BJF^{-1} [4]. The impedances at the fundamental and second harmonic frequencies, denoted by $Z_{1,int}$ and $Z_{2,int}$ respectively, are calculated in terms of optimal loadline resistance (R_{opt}) as [4]

$$Z_{1,int} = \frac{R_{opt}\sqrt{1+\alpha^2}e^{-i\Psi_{pf}}}{\left(\left[1-\frac{16k}{9\pi^2}\right]\sqrt{1+\left(\frac{8\beta}{3\pi}\right)^2}\right)} \quad (1)$$

$$Z_{2,int} = \frac{i\alpha R_{opt}}{\sqrt{\left\{\frac{8(1-k)}{3\pi}\right\}^2+\{2\beta-(32\beta k)/(9\pi^2)\}^2}} \quad (2)$$

Where,

$$\Psi_{pf} = \tan^{-1}(\alpha) - \tan^{-1}\left(\frac{8\beta}{3\pi}\right) + \frac{1}{2}\tan^{-1}\left(\beta\left\{\frac{3\pi}{4} - \frac{4k}{3\pi}\right\}/(1-k)\right) \quad (3)$$

The Z_1 and Z_2 for k=0, 0.5, and 1 which achieve efficiency higher than class BJ are plotted in Fig. 1. Our loads at the second harmonic frequency span the entire |Γ|=1 circle, offering an even wider design space for choice of impedance in comparison to CCF^{-1} for a lower power factor. Interestingly, a combination of resistive load at the fundamental frequency with larger inductive or capacitive second harmonic load is also achieved in the process. This load setting is referred to as “saturated PA” which is shown to be an optimized version of class J achieving highest efficiency of 77 % PAE at 2.14GHz [6]. As the value of k increases, the optimal second harmonic load impedances move towards open condition whereas the fundamental load impedances move towards higher load resistances.

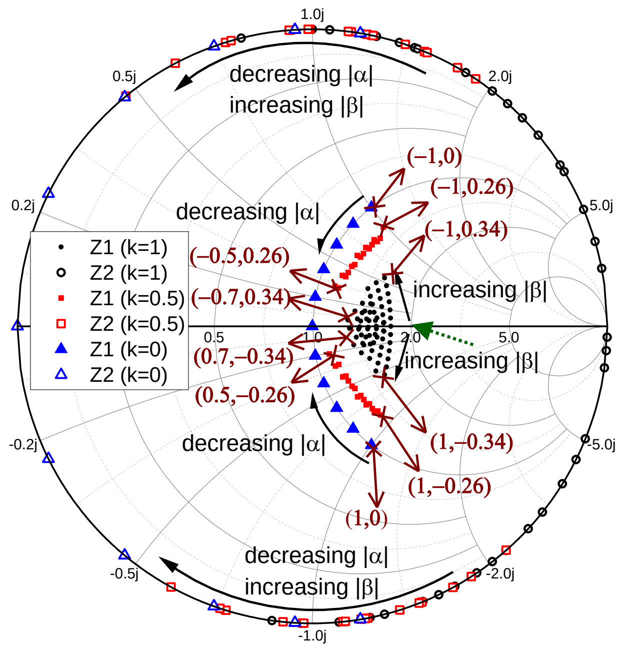

Fig. 1. Theoretical fundamental ($Z_{1,int}$) and second harmonic impedances ($Z_{2,int}$) for k=0, k=0.5, and k=1 and varying α and β. All these impedances achieve efficiencies between 91% and 78.5%.

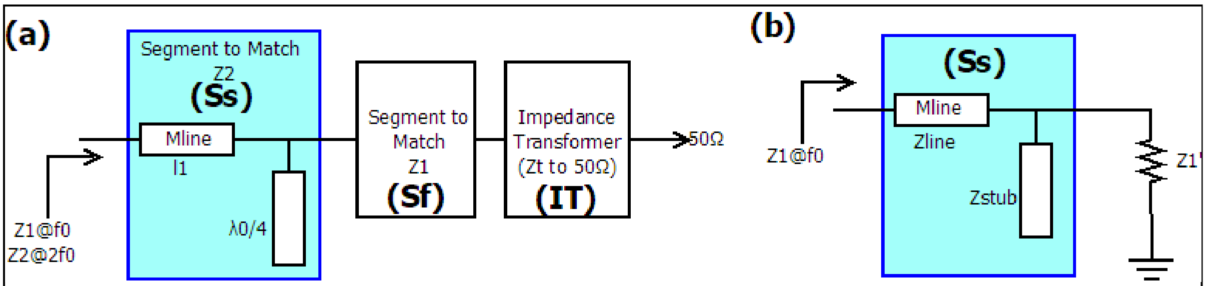

Fig. 2. (a) The block diagram of the matching network consisting of a segment to match the impedance at second harmonic frequency (Ss), a segment to match the impedance at fundamental frequency (Sf), and an impedance transformer (IT). (b) A setup to optimize the widths of Ss and Z1'

Methodology

A 10W GaN HEMT, CGH40010, is chosen for this study. The fundamental frequency is chosen as 2.6 GHz and the bias current as 150mA. The impedances at the intrinsic plane for varying(α,β,k) are calculated using (1), (2), and (3). The impedance at the intrinsic plane is embedded to the extrinsic plane using the negated version of the drain parasitic network of the power device [7]. The drain parasitic network consists of drain source capacitance and extrinsic parasitics at the drain viz, extrinsic drain inductance, capacitance and resistance and package parasitics [2].

The matching network is designed at a single fundamental frequency f0 and the corresponding second harmonic frequency 2f0. Even though the matching network is designed at a point frequency, the large range of available impedances shown in Fig. 1 results in high efficiency performance over a broader frequency range. The matching network is divided into three segments to match the impedances at (1) the second harmonic frequency (Ss), (2) fundamental frequency (Sf), and (3) an impedance transformer (IT), as shown in Fig. 2 (a). Each of these segments is designed separately and independently, simplifying the design procedure as described below:

1) The segment Ss has an open stub of quarter wavelength at the second harmonic, presenting a short at second harmonic. As a result, the succeeding segments of matching network Sf and IT do not affect the impedance at second harmonic frequency, allowing an independent control over the impedance at fundamental frequency. The length of the microstrip line (l1) in this segment is chosen to match Z_2 at 2f0.
2) The section Sf matches the impedance Z_1' to Zt. Z_1' is such that the overall matching network presents Z_1@f0 to the transistor as shown in Fig. 2 (b). Zt is chosen to be closer to $\sqrt{50 * real(Z1)}$. Matching to Zt results in a lower change in impedance with frequency than when matched to 50 ohms. Additionally, if required, Zt can be varied between $real(Z1)$ and 50 ohms, so that the width of the matching lines (Wline and Wstub) of this segment is within the specifications of the foundry.
3) An impedance transformer is required to match Zt to 50 ohms. The theory of the design of impedance transformer is readily available [8]. Alternatively, the automated module

available in commercial RF software such as keysight ADS [9] can be used to design the impedance transformer.

Results and Discussion

Three output matching networks were designed based on the method described in the previous section. To account for the non-linear nature of the intrinsic capacitances, the second harmonic impedance is obtained from the load-pull simulation at second harmonic frequency using the vendor model of the device, which includes the effect of non-linear capacitances, while placing the calculated fundamental impedance at the fundamental frequency. The output matching networks are fabricated on 0.762 mm R4350B Rogers substrate. The measured impedances at 2.6 GHz and the impedances at the intrinsic plane of the device for the fabricated output matching are plotted in Fig. 3.

The small signal gain of the designed amplifiers is measured using a VNA (ZVA-24) and the measured small signal gain is plotted in Fig. 4 (a). The 3 dB gain bandwidth of amplifiers 1, 2 and 3 are 400MHz (from 2.5 GHz to 2.8 GHz), 900 MHz (from 2.1 GHz to 3 GHz), and 500 MHz (from

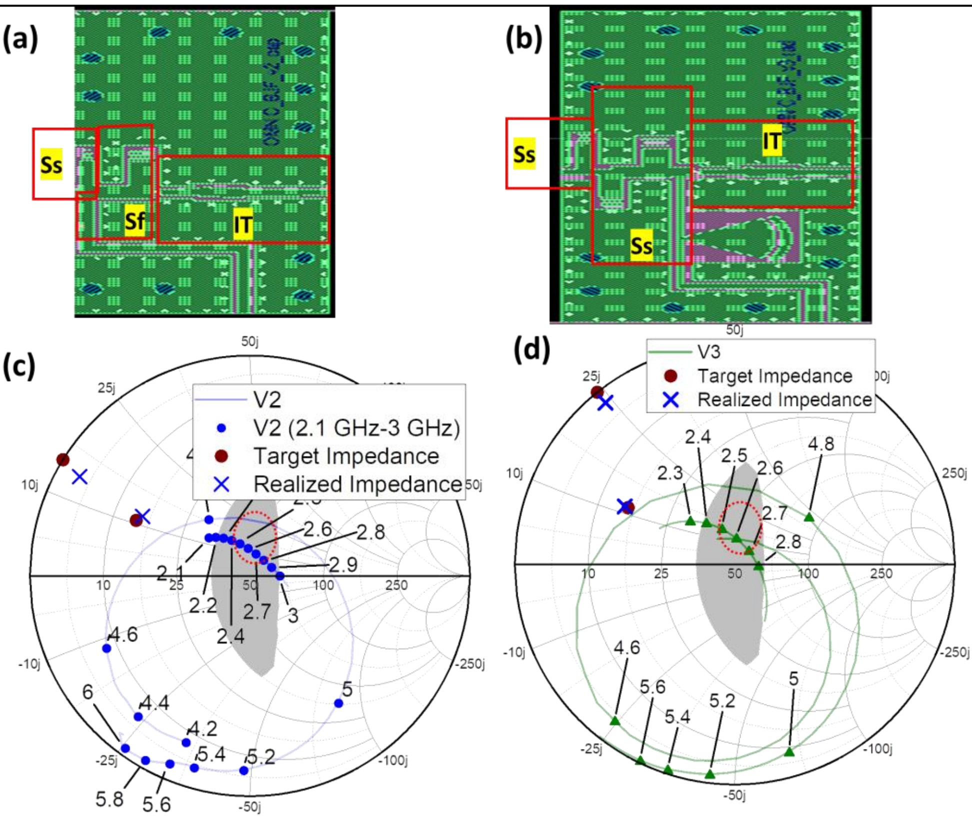

Fig. 3. Layout of the designed output matching network for (a) k=0.6, α=-0.5 and β=0.1 (Amplifier 2). (b) k=0.7, α=-0.6 and β=0.3 (Amplifier 3). (c) Theoretical and the realized fundamental (Z_1) and second harmonic impedances (Z_2) for Amplifier 2. (d) Theoretical and the realized fundamental (Z_1) and second harmonic impedances (Z_2) for Amplifier 3. In (c) and (d) the impedance is achieved by the matching network at the intrinsic plane. The impedances that overlap with the Class BJF^{-1} design space are highlighted.

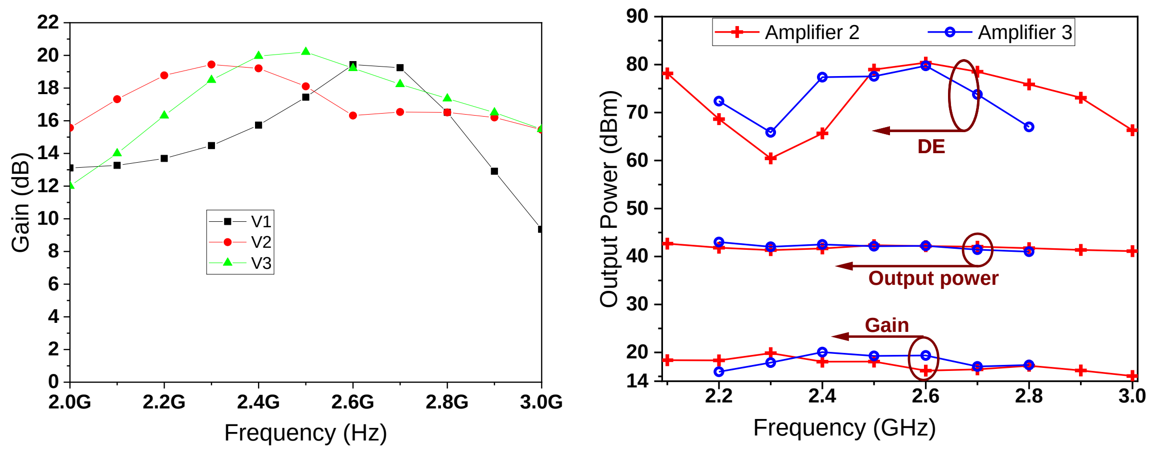

Fig. 4. (a)The measured small signal gain of the designed narrowband amplifiers with frequency. (b) The measured output power, gain, and drain efficiency (DE) of the amplifiers (Amplifier 2 and amplifier 3) with frequency.

2.3 GHz to 2.8 GHz) respectively. For these frequency ranges intrinsic impedances lie within the design space of class BJF^{-1} as shown in Fig. 3.

The measured Gain, output power, and DE of amplifiers 2 and 3 are plotted in Fig. 4 (b). The fabricated amplifier 2 demonstrates 79.5% DE and 42.2 dBm output power at 2.6GHz and the average DE over the bandwidth (from 2.1 GHz to 3 GHz) is 72.6 %. The fabricated amplifier 3 demonstrates 80.4% DE and 42.2dBm output power at 2.6GHz and the average DE over the bandwidth (from 2.2 GHz to 2.8 GHz) is 73.4 %. The frequency weighted efficiency (FE), defined as the average DE multiplied by fourth root of the centre frequency, of amplifier 2 and 3 is evaluated as 91.7 $\%\sqrt[4]{(\text{GHz})}$ and 92.4 $\%\sqrt[4]{(\text{GHz})}$. Both amplifiers have lower DE near 2.3 GHz because the intrinsic second harmonic impedance around this frequency has a large real part as opposed to the requirement of class BJF^{-1}. The designed amplifier is compared with other high efficiency amplifiers using the same device reported in the literature. The best performing amplifier (amplifier 3) demonstrates one of the highest FE achieved with this device reported to date.

TABLE I

COMPARISON OF THE DESIGNED AMPLIFIER WITH THE STATE-OF-THE-ART AMPLIFIERS USING CGH40010F REPORTED IN THE LITERATURE.

Ref.	Mode	Bandwidth (GHz)	Fractional Bandwidth (%)	Output power (dBm)	DE (%)	AE (%)	FE $\%\sqrt[4]{(\text{GHz})}$
[10]	CCF	0.55 - 1.1	66.7	39.3-41.2	65-80	74	70.5
[11]	CCF/F-1	0.4-2.3	140.7	39-42	62.3-80.5	71	76.5
[12]	CCF	1.45-2.45	51.3	40.4-42.3	70-81	75.9	89.7
[13]	SCIM	2.4-3.9	47.6	39.63-41.4	62-75	68.1	90.7
[14]	SCM	1.6-2.8	54.6	40-42.5	67.5-81.9	76.4	92.5
Amplifier 2	BJF-1	2.1-3	35.3	41-43	60-80	72.6	91.7
Amplifier 3 [4]	BJF-1	2.2-2.8	24.0	41-43	65.9-79.7	73.4	92.4

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, CCF/F^{-1} = Continuous class F/F^{-1},

CONCLUSION

We report the benefits of Class BJF^{-1} amplifiers i.e. high efficiency over an intrinsically large bandwidth and ease of design due to wider choice of impedances available in the design space of class BJF^{-1}. The matching is performed at a single frequency to target high power and efficiency. By dividing the matching network into segments, the matching at fundamental and second harmonic frequencies is performed independently simplifying the design process. Two amplifiers designed by this method demonstrated 600MHz and 900MHz bandwidth with the respective frequency weighted efficiency of 92.4 $\%\sqrt[4]{(GHz)}$ and 91.7 $\%\sqrt[4]{(GHz)}$ which represent two of the high-FE amplifiers reported using this device.

Acknowledgements

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