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HIGH EFFICIENCY CLASS E RF POWER AMPLIFIER BASED ON BINOMIAL MATCHING NETWORK

P. Aliparast [1] S. Aliparast [2, 3] S.H. Hashemi Mehneh [1]

1. Aerospace Research Institute, Ministry of Science, Research and Technology, Tehran, Iran
aliparast@ari.ac.ir, hmehne@ari.ac.ir
2. Department of Electrical Engineering, East Azerbaijan Science and Research Branch, Islamic Azad University, Tabriz, Iran, aliparast.s@gmail.com
3. Department of Electrical Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran

Abstract- In this paper we present design and implementation of a high efficiency Class E, Radio Frequency (RF), Power Amplifier (PA) with Gallium-Nitride (GaN), High Electron Mobility Transistor (HEMT). The proposed RF PA shows 17 W output power. We have used binomial matching network circuit for achieving required Band Width (BW). The proposed RF PA works with 28V power supply voltage and has more than 63% efficiency in working BW. In tradeoff between power efficiency and linearity and for achieving the required linearity of π/4-DQPSK modulation, we try to implement our structure near to EB-class instead of E-class. We can obtain two ton Intermodulation Distortion Third Harmonic (IMD3) in this condition better than -26 dBc in-band. Also we measure AM to AM conversion better than 0.3 dB/dB and AM to PM conversion less than 3.5 Deg/dB. We implemented our design with a Rogers printed circuit board (PCB) on a Cu hot plate for better thermal transferring.

Keywords: RF, PA, GaN, HEMT, Class E, Binomial.

I. INTRODUCTION

The Radio Frequency (RF) Power Amplifier (PA) is basically an electronic circuit which transfers the RF power to the load by amplifying the input power. The power amplifier design involves many challenging concerns at the same time such as output power, efficiency and linearity. Also the technology and type of transistor is important in the design of RF PAs.

Figure 1 shows typical RF frontend of a transmitter. The RF signal has been amplified by PA just before the antenna. As exhibited in Figure 1, the final block before the antenna is a High Power Amplifier (HPA). In this block the power of signal reaches the maximum value. Because of high power consumption, the efficiency of this stage is the most important block in determining the efficiency of the transmitter [13].

Most of the time a Gallium-Nitride (GaN), High Electron Mobility Transistor (HEMT) was chosen for the RF PAs. The parasitic capacitances of GaN HEMTs are low and their power density and voltage operation are high [10, 11, 12]. An AlGaN/GaN HEMT has excellent capabilities such as high power, high efficiency and high gain with high voltage operation due to its excellent material properties. There are many papers reporting AlGaN/GaN HEMTs with high output power characteristics for different bands [3, 4].

However there aren't many papers that report their band performance for practical usage. In this paper, we report design of a RF S-Band PA with AlGaN/GaN HEMT. The result indicates the implemented S-band AlGaN/GaN HEMT has high power capability covering practical frequency range for S-Band high power applications with proven device technology [2].

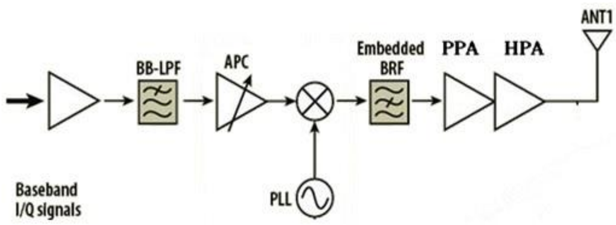

Figure 1. Typical RF frontend of a transmitter for a telemetry subsystem

II. TRANSISTOR SELECTION

Figure 2 shows the cross-section of the fabricated AlGaN/GaN HEMT structure [1]. The epitaxial layers were grown by MOCVD on the semi-insulating SiC substrates. Ti/Al and Ni/Au metallization process was used to form ohmic and Schottky contacts, respectively. SiN film was deposited using plasma CVD as a surface passivation layer [5].

Details of the device structure and fabrication process were reported in [6]. As described in [6], we could suppress the current collapse of the fabricated device by adopting this device structure. A 0.4 μm gate-length, 28 V process provides 4.5 W/mm for circuits between DC to 8 GHz [1, 9]. A review of GaN on SiC High Electron-Mobility (HEM) power transistors is presented in [1]. This review is very helpful for designers of HPAs.

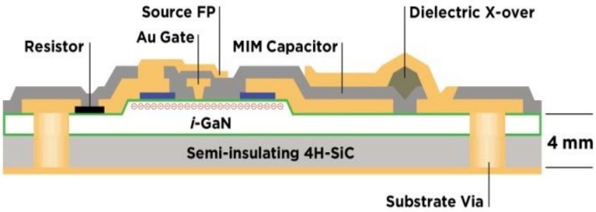

Figure 2. Cross section of a typical GaN HEMT MMIC process [1]

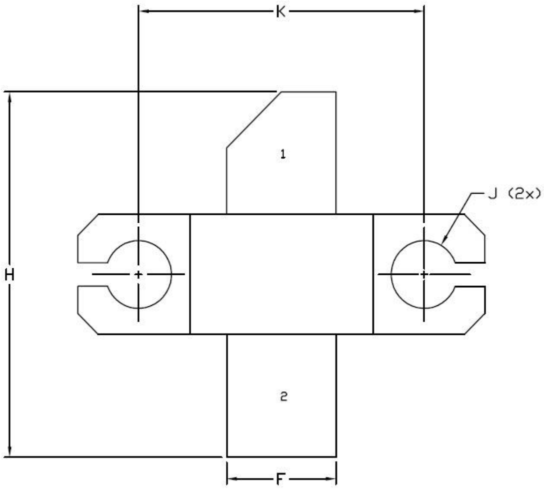

Figure 3. Layout of GaN HEMT Transistor
(Pin 1 is Gate and Pin 2 is Drain) [9]

Based on the given specifications by the manufacturers in the data sheet, a 35 W GaN HEMT Transistor (CGH40035F) from the CREE manufacturer has been selected for the design. Figure 3 shows layout of a GaN Transistor. This transistor was manufactured by CREE with part number of CGH40035F. The gate and drain width of this transistor is 5.45 mm.

III. DESIGN OF CLASS E RF HPA

As mentioned in section I the main part in the RF section of a transmitter is HPA. The efficiency of this part usually identifies the efficiency of the transmitter. The RF section of the proposed transmitter works in 2290 MHz frequency with 1 MHz BW. The power supply voltage is 28 V and it must send a signal power of about 20 W.

A. Binomial Multisection Matching Network

As shown in Figure 4, a Transmission Line (TL) with 17 mm width has been used for drain and gate of the transistor because of their pads. There are 4 capacitors in the output of the circuit. These capacitors decrease the output harmonics and lead to ohmic impedance in the output. We used a Binomial Multisection Matching Transformer (BMMT) after this stage. The parameters of the BMMT are [14]:

$$\Gamma(\theta) = A(1+\mathrm{e}^{-2j\theta})^N \quad (1)$$

where the Γ(gamma) is the voltage reflection coefficient, θ is length of the line and N is the number of TLs. Hence for binomial expansion we have:

$$\Gamma(\theta) = A\sum_{n=0}^{N} C_n^N \mathrm{e}^{-2jn\theta} \quad (2)$$

where C_n^N is:

$$C_n^N = \frac{N!}{(N-n)!n!} \quad (3)$$

Thus for input BMMT of the proposed HPA we have:

$$N = 2 \quad (4)$$

$$C_0^2 = 1\,,\ Z_1 = 12.96 \quad (5)$$

$$C_0^2 = 2\,,\ Z_2 = 31.9 \quad (6)$$

and for output BMMT of the proposed HPA we have:

$$N = 2 \quad (7)$$

$$C_0^2 = 1\,,\ Z_1 = 25 \quad (8)$$

$$C_0^2 = 2\,,\ Z_2 = 37.8 \quad (9)$$

B. PCB Implementation

We have used a RO4000 series Roger PCB to implement the designed HPA. In this board a 15µm gold plate has been used for top layer tracks. Also a thick Cu hot plate has been used for the bottom layer of the PCB. The transistor is directly mounted on the bottom layer thick Cu plate. This thick Cu plate helps to better the thermal dissipation for transistor.

IV. SIMULATION RESULTS

We used Keysight Advanced Design System (ADS) software for designing the proposed RF S-band Power Amplifier. A nonlinear model include all of the parasitic parameters have been used for post layout simulation of the proposed RF PA circuit.

A. Performance of the Proposed HPA

We have evaluated RF performance of the device.

Figure 5 shows the RF performance under continues wave condition. The pulsed gate bias is synchronized with input RF signal. The drain bias voltage and quiescent drain current was 28 V and 4.1 A (between class B and class E operation), respectively. So we obtained the results such as, high linear gain of 27 and PAE (Power-Added-Efficiency) of 63% in the frequency range of 2.29 GHz.

B. Input and Output Power Amplifier

Input Impedance, Z_{in} or Input Resistance as it is also called, is an important parameter in the design of a transistor amplifier and as such allows amplifiers to be characterized according to their effective input and output impedances as well as their power and current ratings. Matching for maximum Gain occurs when the amplifier is unconditional stable and load impedance is equal to the complex conjugate of the same source impedance (conjugate matching).

Complex conjugate simply refers to complex impedance having the same real part with an opposite reactance. Matching for maximum Output Power occurs when Optimum Load impedance (RL) is equal to Source impedance. In order to obtain maximum output power, typically the power amplifier is not conjugate matched.

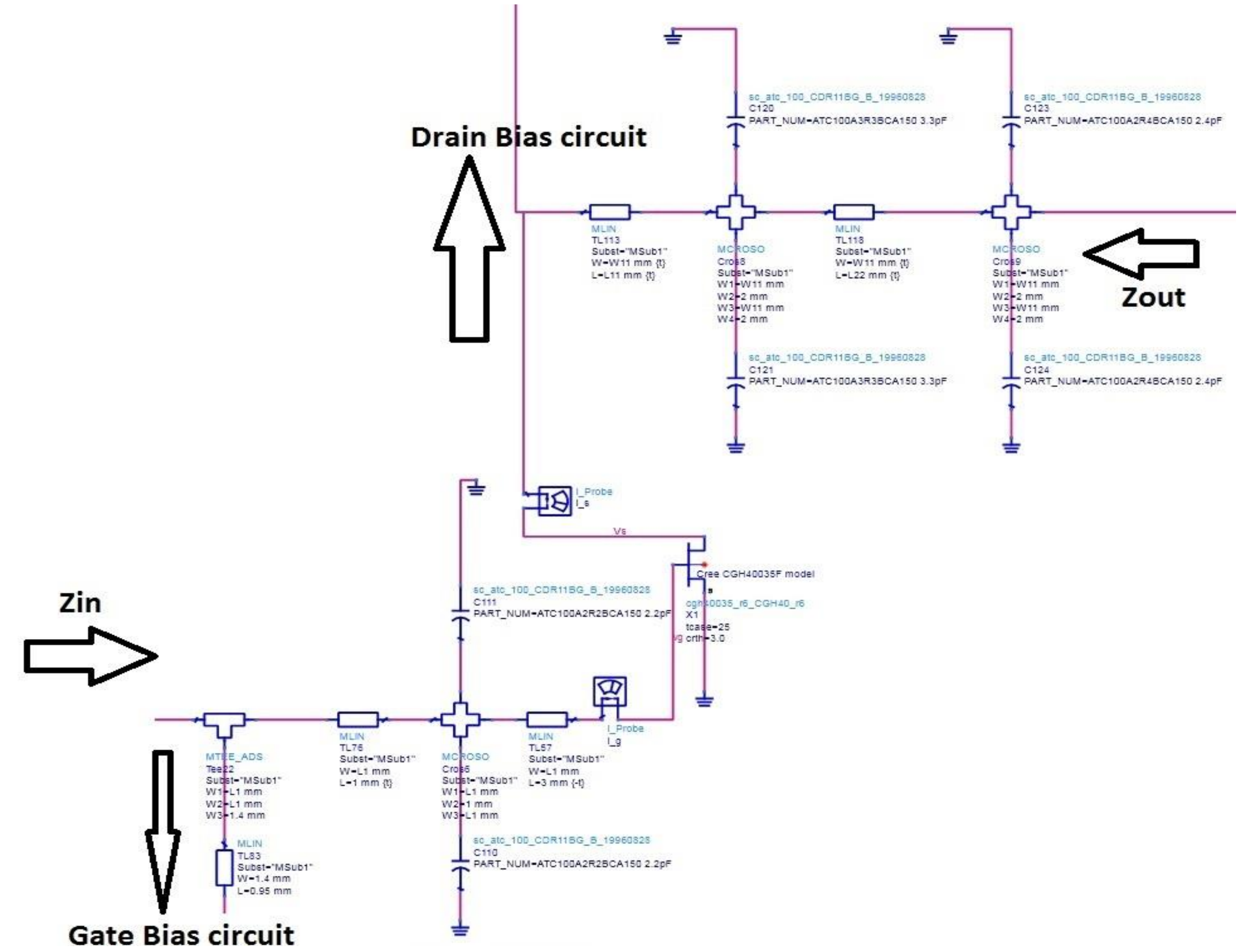

Figure 4. Schematic of the matching impedance of the proposed HPA

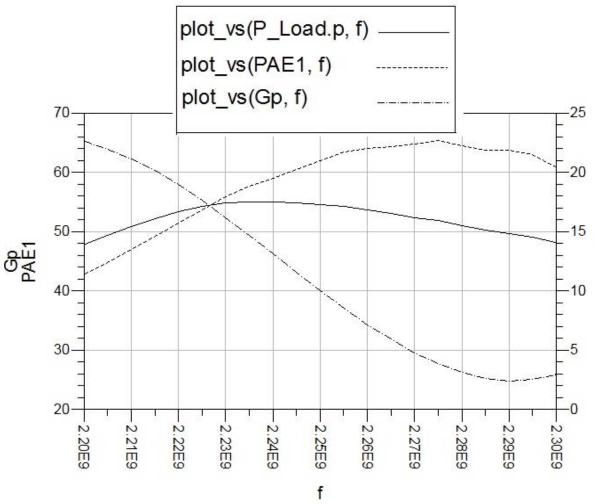

Figure 5. Simulated performance of continuous Class-E PA

Instead, the load is designed such that the amplifier has the correct voltage and current to deliver the required power [7]. If operation is at the optimal Power Added Efficiency point, optimal-power tuning produces about 1 dB to 3 dB of higher power. Gain is reduced (for small Pin) typically by a slightly smaller amount. Figure 6 shows input and output impedance of designed PA.

C. Voltage Standing Wave Ratio

VSWR (Voltage Standing Wave Ratio) is a measure of how efficiently radio-frequency power is transmitted from a power source, through a transmission line, into a load (for example, from a power amplifier through a transmission line, to an antenna).In an ideal system, 100% of the energy is transmitted. This requires an exact match between the source impedance, the characteristic impedance of the transmission line and all its connectors, and the load's impedance. The signal's AC voltage will be the same from end to end since it runs through without interference [7].

In real systems, mismatched impedances cause some of the power to be reflected back toward the source (like an echo). Reflections cause destructive interference, leading to peaks and valleys in the voltage at various times and distances along the line. VSWR measures these voltage variances. It is the ratio of the highest voltage anywhere along the transmission line to the lowest. Since the voltage doesn't vary in an ideal system, its VSWR is 1.0 (or, as commonly expressed, 1:1). When reflections occur the voltages vary and VSWR is higher 1.2 (or 1.2:1), for instance [8].

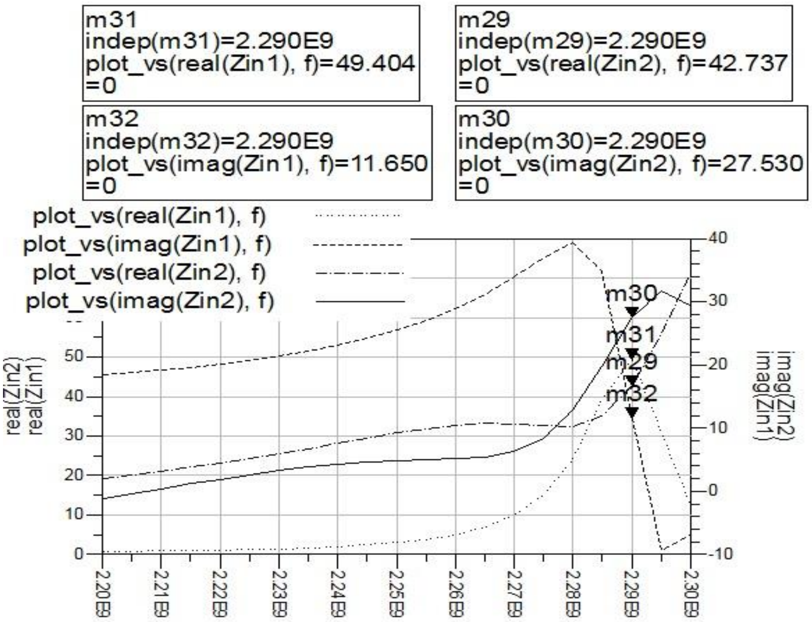

Figure 6. Simulated performance of input and output impedance for designed Class-E PA

Mathematically VSWR is the voltage ratio of the signal on the transmission line:

$$VSWR = \left|\frac{V_{\max}}{V_{\min}}\right| \quad (10)$$

where $V_{\max}$ is the maximum voltage of the signal along the line, and $V_{\min}$ is the minimum voltage along the line. It can also be derived from the impedances:

$$VSWR = \frac{(1+\Gamma)}{(1-\Gamma)} \quad (11)$$

where Γ (gamma) is the voltage reflection coefficient near the load, derived from the load impedance (Z_L) and the source impedance (Z_O):

$$\Gamma = \frac{(Z_L - Z_O)}{(Z_L + Z_O)} \quad (12)$$

If the load and transmission line are matched, $\Gamma = 0$, and $VSWR = 1.0$ (or 1:1). So Figure 7 shows the performance of input and output $VSWR$ for the proposed Class E HPA.

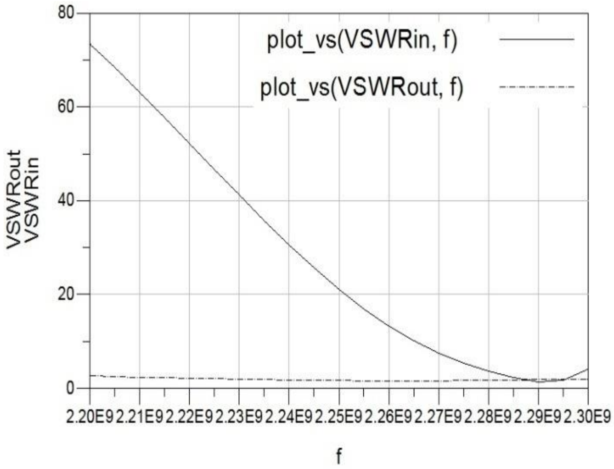

Figure 7. Performance of input and output VSWR for designed Class-E PA

D. P1 dB Compression Point

P1 dB compression point for PA defines the output level at which the amplifier's gain is 1 dB less than the small signal gain, or is compressed by 1 dB (P1 dB) [7]. Most amplifiers start to compress approximately 5 to 10 dB below P1 dB. Applying signal power levels above this point results in a decrease in Gain, therefore the change in output power will not be linear with respect to a corresponding change in input power to the point where the amplifier is at saturation (PSAT) and the gain equals zero. Operating at output levels above P1 dB is not a normal operation for a linear amplifier. Figure 8 shows 1 dB compression point for the proposed PA.

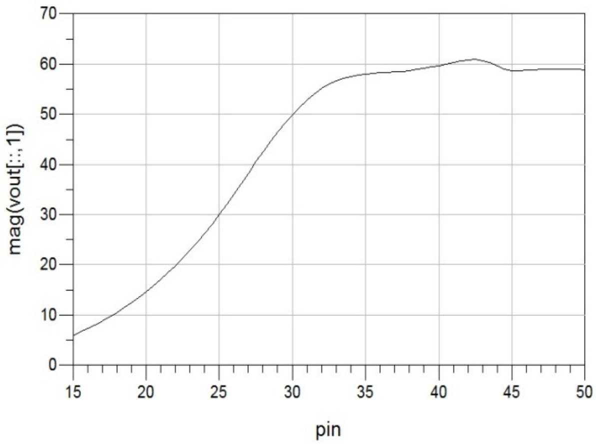

Figure 8. 1 dB compression point for the proposed PA

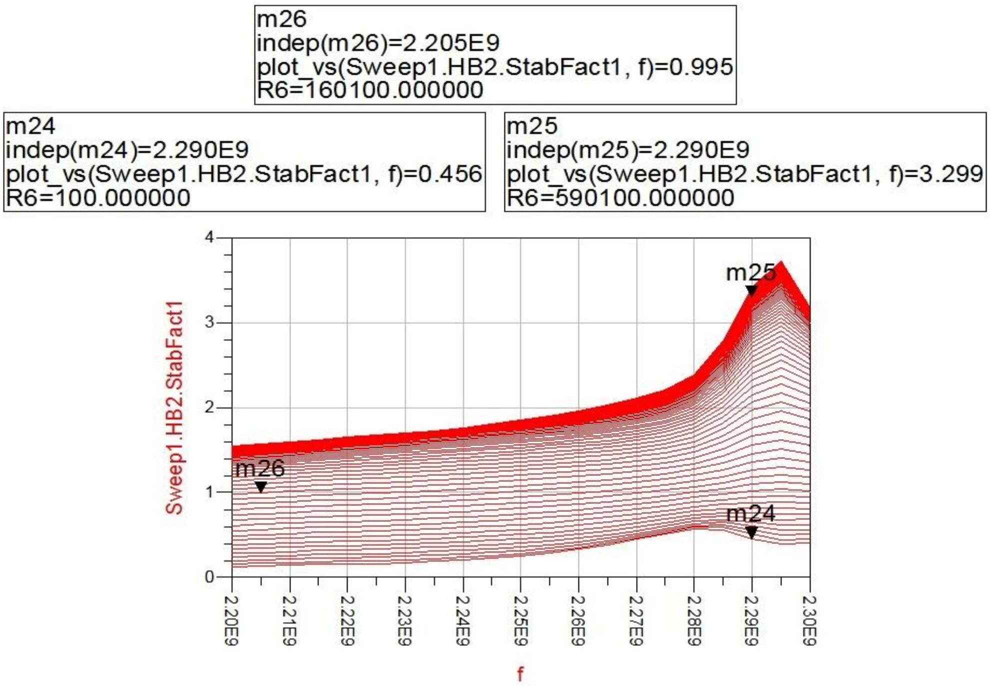

Figure 9. Stability of the proposed PA by analyzing *K*-factor

E. *K*-Factor for Power Amplifier

Stability of an amplifier is an indication of how immune it is to self-oscillation, so that it does not generate a signal at its output without an applied input. A commonly used indicator of stability is the *K*-factor. The *K*-factor of 1.0 is the boundary condition for unconditional stability. If it is greater than zero but less than 1.0 the amplifier is only conditionally stable [7].

$$K = \frac{1-|S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}\ S_{21}|} S_{11}.S_{22} - S_{12}.S_{21} \tag{13}$$

$$\Delta = S_{11}.S_{22} - S_{12}.S_{21} \tag{14}$$

where, S_{11}, S_{12}, S_{21} and S_{22} are the scattering parameters of designed RF PA. Figure 11 shows the stability of the proposed PA by analyzing *K*-factor in the range of operational temperature.

F. Performance Results

We pushed the proposed HPA to work in EB-Class to get suitable parameters such as PAE and linearity. We achieved P_{load} = 17 W, PAE = 63%, Z_{in} = 49.4+j11.6 Ohm, Z_{out} = 42.7+j27.5 Ohm, $VSWR_{in}$ = 1.1, $VSWR_{out}$ = 1.8, $K\text{-}Factor$ = 3.3 and GP = 27. Also we obtained IMD_3 = -26 dBc that let us to use this power amplifier with family of DQPSK modulations.

V. CONCLUSION

We have successfully designed and implemented the EB-Class RF power amplifier with 42.3 dBm output power and AlGaN/GaN HEMT for the operating frequency in S-band. We have used binomial multisection matching transformers structures for achieving suitable BW. The proposed structure shows a high linear power gain of 27 in frequency range of 2.29 GHz. It works with 28 V drain bias voltage in continues wave condition.

We know that both of the linearity and efficiency in RF PA are in a tradeoff but the simulation results show the developed AlGaN/GaN HEMT has a good PAE and linearity together. This goal has been achieved by pushed the proposed RF HPA to work in EB-Class instead E-Class.

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BIOGRAPHIES

Peiman Aliparast was born in Tabriz, Iran. He received the M.Sc. degree from Urmia University, Urmia, Iran, in 2007 and Ph.D. degree from University of Tabriz, Tabriz, Iran, in 2012 both in Electronics Engineering. From 2004 to 2008, he was with the Microelectronics Research Laboratory in Urmia University and from 2008 to 2012, he was a Research Assistant in Integrated Circuits Research Laboratory, University of Tabriz. He is currently an Assistant Professor in Aerospace Research Institute, Ministry of Science, Research and Technology, Tehran, Iran. His research interests are smart CMOS image sensors for biomedical applications, RFIC and MMIC for space telecommunication systems, analog and digital integrated circuit design for fuzzy and neural network applications, analog integrated filter design and high-speed high-resolution digital to analog converters. He is member of Iran Microelectronics Society (IMS) and IEEE.

Sevda Aliparast was born in Tabriz, Iran. She received the M.Sc. degree from East Azarbaijan Science and Research Branch, Islamic Azad University, Tabriz, Iran, in Electronics Engineering. Her research interests are smart home applications, MEMs, RFIC and MMIC for space telecommunication systems, analog and digital integrated circuit design.

Seyed Hamed Hashemi Mehne was born in Mashhad, Iran, 1978. He received the B.Sc., M.Sc. and Ph.D. degrees from Fredowsi University of Mashhad, Mashhad, Iran all in Applied Mathematics, in 1999, 2001, and 2005, respectively. Currently, he is an Assistant Professor at Aerospace Research Institute, Tehran, Iran. His research interests are optimal control, numerical mathematics, shape optimization and parallel computing.