28 GHz Monolithic Transmitter on GaN chip for 5G application

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***Abstract*—5G standard is targeting much higher data rates as compared to existing wireless technologies to accommodate the ever-increasing demand for faster wireless applications. A transmitter is required to implement a 5G system. In this paper, we are presenting a 28 GHz novel monolithic transmitter architecture on GaN substrate that offers Size, Weight, Area, Power and Cost (SWAP-C) advantages. The transmitter contains a Yagi antenna, which consists of three directors, two drivers, a strip line feed, a substrate and a ground plane. According to simulation results, the designed Yagi antenna has a compact size and low loss at the selected frequency of 28 GHz. At this frequency, its return loss, gain, and beam width are -38 dB, 8.69 dB, and 57.2 degrees, respectively. The second component in the monolithic chain is a bandpass filter (BPF), which offers enhanced selectivity and stopband suppression on GaN substrate. The Bandpass filter has a minimum insertion loss of 0.6dB at 28GHz. The rejection level is higher than 10 dB in the stop band. Further, a collaborative simulation of 28 GHz mixer for upconversion with CLASS-E power amplifier (PA) with integrated octature structure to achieve robust load insensitivity is presented. In this paper to design high-efficiency PA, we implemented harmonic load pull at both the input and output of the active device to obtain optimum impedances at fundamental and second-harmonic frequencies. After an iterative process, the optimum input and output impedances are obtained. In addition, we also implemented cascaded octature power cell structure. The proposed balanced PA achieves a saturated output power (Psat) of 13.5dBm and a maximum Power Added Efficiency (PAE_{max}) of 55%. It consumes 210mW power. The presented transmitter configuration is designed on a GaN substrate with a thickness of 0.8 mm, permittivity (Er) of 9.7, and loss tangent (TanD) of 0.025. Based on its performance at 28 GHz, the designed transmitter is being developed for the 5G application.**

Keywords- Yagi antenna;Filter; Mixer;Power amplifier; 5G.

I. INTRODUCTION

Fifth generation wireless network (5G) has become research focus since it could support the explosive growth of data traffic, massively interconnected devices, and new applications. It is expected that 5G will utilize spectrum at millimeter wave (MMW) frequencies to satisfy the demand for massive bandwidth since the spectrum resources in the lower frequency bands are running out. Resources have been invested to develop prototype millimeter wave 5G mobile communication systems, especially for frequency band such as 28GHz. Therefore 27.5 to the 29.5GHz band is a strong candidate for the new 5G radio interface and much of the research undertaken to date has considered this band. For example, Samsung Electronics has built a prototype system including beamforming antenna that works at 28GHz [1], However, to our knowledge single chip transmitter on GaN does not exist for the 5G application. An overview of the architecture and components for our transmitter module on a GaN chip are shown in Figure 1. The Integrated Chip consists of a chain of various individual components such as yagi antenna, power amplifier, bandpass filter, upconverter, mixer and matching circuitry.

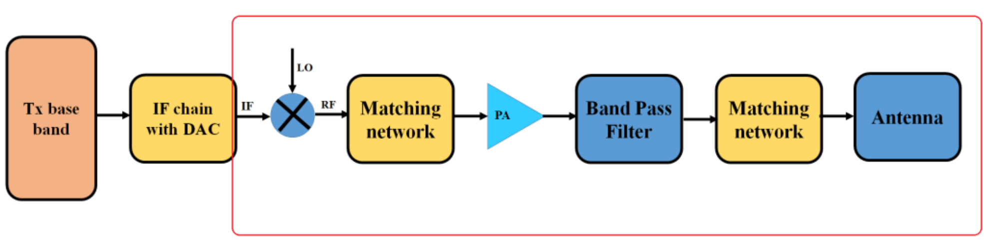


Figure 1. Transmitter architecture for 5G application

The presented transmitter configuration is designed on a GaN substrate with a thickness of 0.8 mm, permittivity (Er) of 9.7, and loss tangent (TanD) of 0.025. The goal is to ultimately fabricate the proposed transmitter module on GaN substrate.The Yagi antenna is designed using HFSS (High-Frequency Structure Simulator) simulation software. Rest of the blocks of the transmitter, bandpass filter, Mixer, Power amplifier, and matching network circuitry are designed using Advanced Design System (ADS) simulation software.

II. DESIGN AND RESULT & DISCUSSION OF TRANSMITTER MODULE ON GAN CHIP

A. *Yagi Antenna*

Yagi antenna was proposed by researchers from Japan usually for radio application [2]. Such antenna was

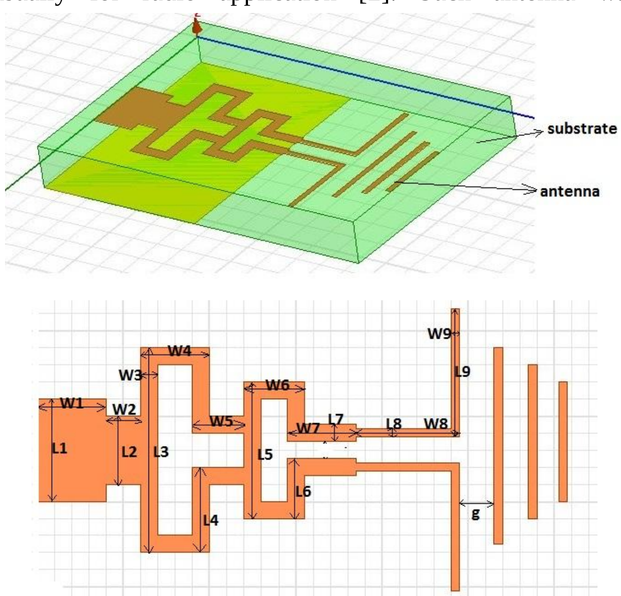


Figure 2. (a) 3D view of Antenna in HFSS (b) dimensions of yagi guda antenna

developed for X-band, Ku-band, and K-band, etc. Generally, a design of Yagi antenna places a driver and director's elements on one side of PCB and places a reflector on the reverse side. A driver is utilized for radiating electromagnetic wave whilst directors and a reflector is utilized to focus the electromagnetic wave radiation from its driver. But, the design of Yagi antenna is more challenging if it is being designed at 28 GHz on GaN substrate instead of PCB.

In this paper, we present the design of novel structure Yagi antenna, which shows good radiation efficiency and gain. The design of proposed Yagi antenna is shown in Figure. 2. It is composed of three directors, two drivers, a strip line for feed and a reflector. This antenna can be configured in MIMO format if needed. The antenna is made from gold with a thickness of 0.035 mm and electric conductivity of 4.1 x 107 Siemens/m considering GaN as substrate. In order to match antenna impedance with another device, the impedance was optimized for 50 Ohm. To fulfill such requirement, its feed- width was set to be 1.8 mm. Details of the Yagi antenna design parameters that allowed best performance is shown in Table I. Figure 3 shows simulated return loss of -38dB for 27.4 GHz to 28.4 GHz with a center frequency of 28 GHz. Antenna results are mentioned in Table 2.

TABLE I. DIMENSIONS OF PROPOSED ANTENNA

L1	L2	L3	L4	L5	L6	L7	L8	L9	g
1.8	0.9	2.5	1.2	2	0.8	0.5	0.3	2	0.1
W1	W2	W3	W4	W5	W6	W7	W8	W9	
1.5	0.7	0.5	1.5	0.5	1.5	1.8	2.5	0.3	

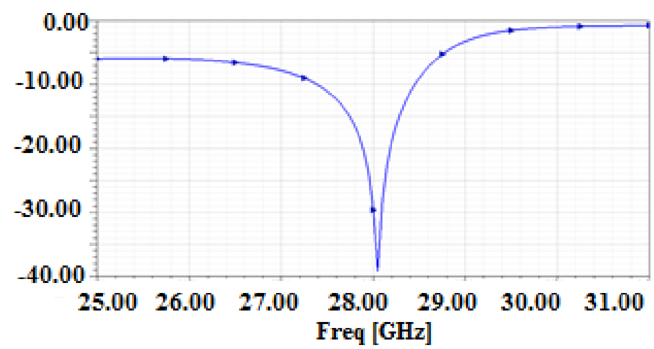


Figure 3. S11 response of return loss of antenna

TABLE II. ANTENNA RESULTS

Content		Units	
Antenna type			Yagi guda
Antenna size (L*W)		mm*mm	8*12
Peak Directivity		dB	8.9
Antenna bandwidth		GHz	27.4-28.4
Radiated power		W	0.8
Accepted power		W	0.9
Radiation Efficiency	At 28 GHz	%	96
VSWR	At 28	GHz	<1
GaN substrate details Assumed during simulation	Thickness	mm	0.8
	Er		9.7
	Tan D		0

B. *Band-Pass Filter Design*

Filters are an essential part of wireless communications systems as they are required to suppress undesired signals in the transceiver pass-band. The size, weight, cost, and loss of such filters must be kept as low as possible.

In this paper, the design of a core circuit using microstrip line has been conceived and designed as shown in Figure.4. Small size, low cost, and good performance multifunction

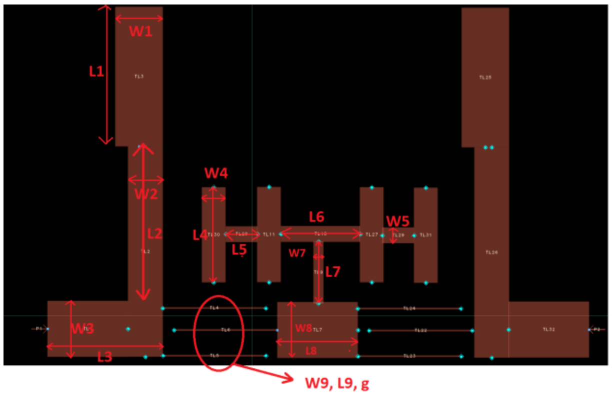


Figure 4. BPF structure with dimensions

filters are the main development trend in microwave/MMW domain. Filters with high selectivity and good stopband performances are extensively studied [3]. On the other hand, the GAN substrate has attractive characteristics, such as wide frequency range, static dielectric constant, low thermal expansion coefficient and very low water absorption [10]. In this paper, a Band-Pass Filter (BPF) based on broadside coupling H-shape resonators and half wavelength resonators are implemented on two-layer GAN substrate, which has relatively small sizes and good selectivity.

The dimensions of BPF filter are listed in Table 3.

TABLE III. DIMENSIONS OF PROPOSED FILTER

L1	L2	L3	L4	L5	L6	L7	L8	L9	g
8.8	13.5	5	6	2	5	4	5	6.5	0.5
W1	W2	W3	W4	W5	W6	W7	W8	W9	
3	2.2	3.5	1.5	1	1	0.6	3.5	0.1	

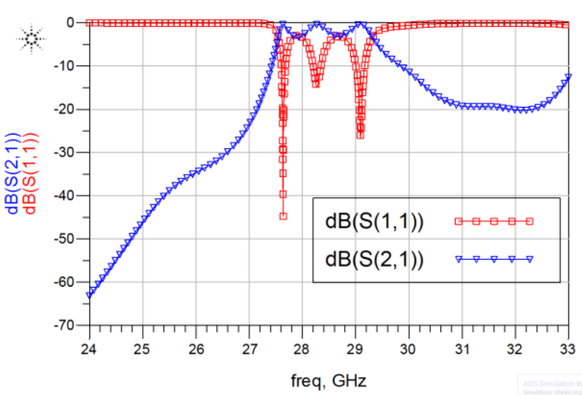
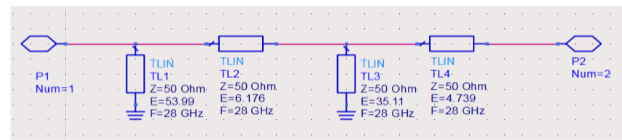


Figure 5. BPF structure with dimensions

Figure 5 shows the simulated results of the designed BPF. The 3dB bandwidth is from 27.6GHz to 29.2GHz. This filter has a minimum insertion loss of 0.6dB at 28GHz. The rejection level is higher than 10 dB in the stop band. The return loss of BPF is more than -40 dB at 28 GHz.

C. Impedance Matching Network

At 28GHz frequency, the reflected power occurs when the load impedance is not matched to the characteristic impedance of source (mixer) and load (PA). Impedance matching using the passive network is critical to achieving maximum power transfer, minimum reflection, and adequate harmonic rejection. In order to overcome such problems, we propose matching network approach is based



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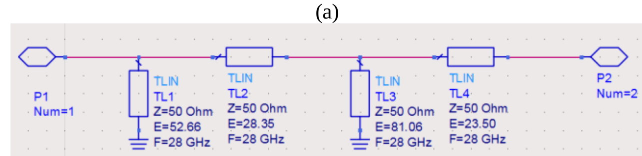
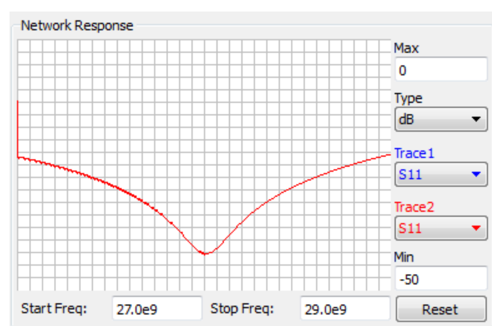


(b)

Figure 6. (a) the topology of the matching networks between the filter and antenna (c) the topology of the matching networks between the mixer and PA

on Smith chart. Through Smith Chart, we can get a matching network at a certain frequency easily. When utilizing the Smith Chart to design matching networks at the center frequency, the next steps should be followed:

- Find out the output impedance Z_{out} of previous stage transistor and the input impedance Zin of next stage transistor.



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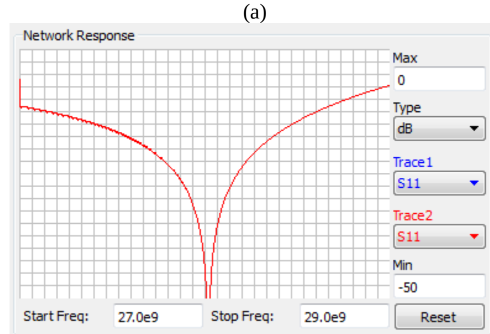


(b)

Figure 7. (a) Network Response of impedance Schematic of Figure. 6a (c) Network Response of impedance Schematic of Figure. 6c

- Find out the points of Z_{out}, Z_{in} in the Smith Chat.
- Describe the maximum equal Q curve Q_{max} from the points of Z_{ou}, Z_{in}.
- In the extension of the Smith Chart constructed by Q_{max}, add appropriate microstrips and capacitances to make Z_{out} and Zin conjugate match.

Then, consider the network composed of micro-strips as the initial matching network. We designed such matching network using ADS. This network is designed to operate at 28 GHz frequency with a normalized impedance of 50 Ω. Where ZS is source output impedance, ZL is load input impedance. We calculated stub values mentioned in Figure. 6 using ADS. Figure. 6 shows the objective function to optimize the whole matching networks. Figure.7 shows return loss plots of machining networks; the rejection level is higher than 10 dB in the stop band.

D. Mixer Design

The transmit Signal coming from baseband is almost at DC, hence it must be upconverted to high frequency at which antenna is working. In order to do that signal must be up-converted using MMW mixer. Doubly-balanced Mixers (DBM) are usually the desirable mixer because of their superior suppression of spurious mixing products and good port-to-port isolation [4]. An ultra-wideband balanced microstrip balun was reported [4], but this type of balun was difficult to fabricate. A 28 GHz mixer based on the Marchand balun was fabricated in 0.15ʒm GaAs PHEMT technology, similar to our proposed design in GaN technology.

In this paper, a 28 GHz doubly-balance mixer based on the [12] Marchand balun in the 27GHz to 30 GHz RF/LO range and DC to 5GHz IF is presented. The collaborative simulation of HFSS and ADS has been adopted in mixer design, the balun in LO port and RF port are simulated by the full-wave electromagnetic simulator in HFSS, then the S parameter data of the balun are exported to the mixer circuit in ADS. The mixer offers about 10dB typical conversion loss, high gain compression, higher than 20dB LO-to-RF isolations and about 10dB return loss across 27GHz to 30 GHz.

1) The Balun Design

The balun was simulated by using Ansoft HFSS and

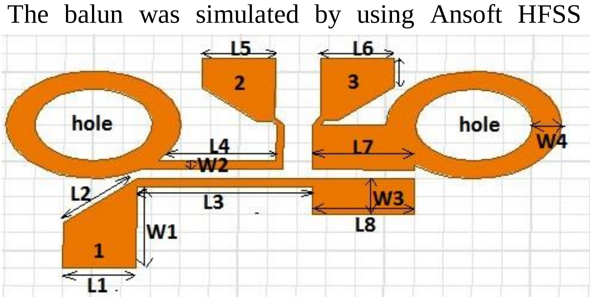


Figure 8. structure of mixer's balun

Agilent ADS. The Marchand balun was compensated by two open-circuited stubs at the output ports, the coupled line model in the circuit initially was used to predict the performance, and then simulated by using the full-wave electromagnetic simulator to improve the accuracy of the simulation finally. The 3D structure of the balun used in the mixer was drawn by HFSS and shown in Figure.8, which is designed for GaN substrate with thickness 0.8mm and dielectric constant 9.7. 1 is the input port and 2 3 are output ports. Impedances of three ports are all set to be 50 Ω and the microstrip line width is 0.25mm, and l. w2 and w3 stand for the length the width and the gap width of the microstrip lines, the hole is metallization and connected to ground. The Marchand balun is simulated by optimizing w2 and w3.

TABLE IV. TABLE TYPE STYLES

L1	L2	L3	L4	L5	L6	L7	L8
1.2	1.5	2.5	1.8	1.2	1.2	1.4	1.4
W1	W2	W3	W4				
1.2	0.2	0.5	0.3				

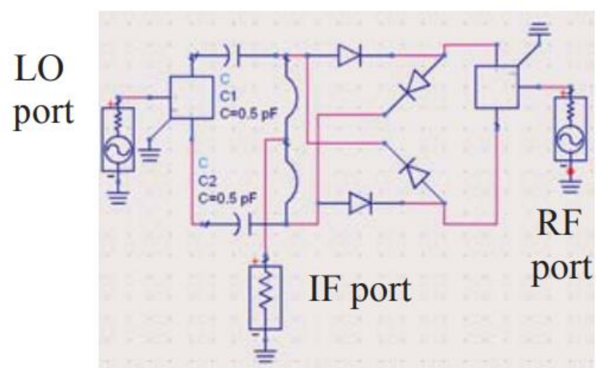


Figure 9. Double balanced mixer circuit in ADS

2) The Mixer Design

Then, the terminal S parameter data of the balun in HFSS are exported to the mixer circuit in ADS in Figure.9, the three ports network are set up to substitute the balun. RF

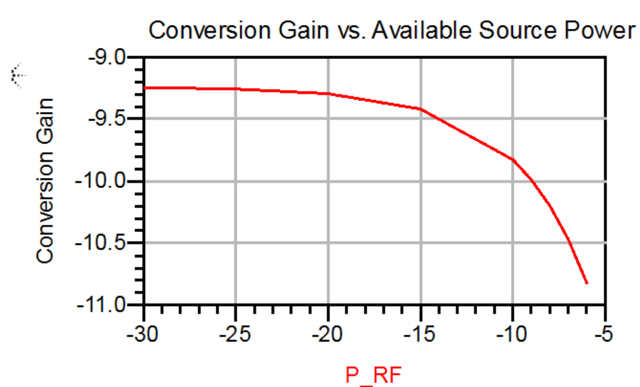


Figure 10. conversion Gain vs available source power

port and LO port is power source port, the IF port is load port, all the port is set to 50Ω. Two gold lines are set to near the real condition, the line is set to 5mm length and the diameter is 0. 1mm. The capacitances are used in LO port to make the minimal frequency of the IF port extend to DC. C1=C2=0.5Pf. The simulated result of the mixer circuit conversion gain was obtained using the harmonic balance method in Figure. 10. The type conversion gain is about 9. 3dB.

E. *Power Amplifier Design*

For wireless communication systems, power amplifiers (PAs) with high efficiency is critical as they consume the majority of the power of the systems and closely related to the thermal problem. As a result, many categories of high-efficiency PAs have been widely studied in recent years The Class-E amplifier is well known for its high efficiency and simple structure. Moreover, inherent output capacitor of a transistor deteriorates the performance of a Class-E amplifier at high frequency. To address above problems, the Class-E amplifier was designed by modifying the device output impedances at odd and even harmonics, so as to shape the output voltage and current that minimize the overlap to achieve high efficiency [7].

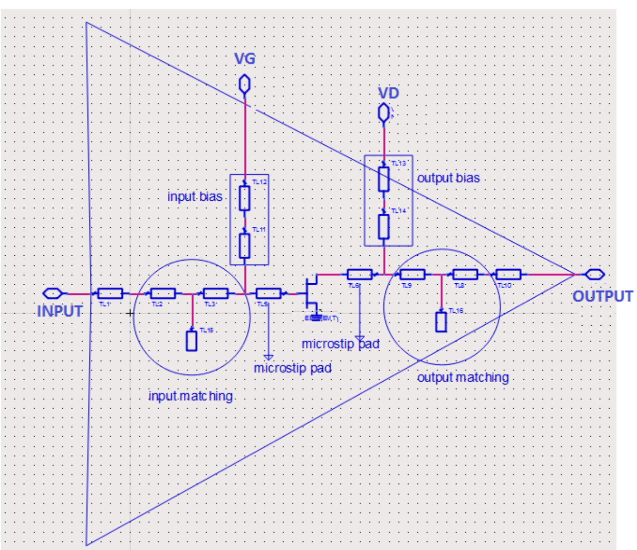
In this paper, a simple method of designing high-efficiency PA is presented. Compared with other works, this method is easier to design harmonic tuned PA and thus achieves relatively high efficiency with fewer harmonics to control. The simulated results indicate a high-efficiency Class-E PA is realized with 55% PAE and 13.5 dBm output power at 28 GHz.

However, the challenge of the MMW PA design is to deliver maximum output power with a maximum Power Added Efficiency (PAE) and high linearity [8]. For this purpose, to achieve high efficiency, we have implemented two techniques. Technique one is harmonic load pull conducted at both the input and output of the active device to obtain optimum impedances at fundamental and second-harmonic frequencies. After an iterative process, the optimum input and output impedances are obtained. Technique two is cascaded octature power cells structure is implemented. The presented circuit is implemented in GaN HEMT technology taking, the advantage of high-frequency performance and high power performance [9].

1) *Design process:*

To achieve the target output power, a total of eight stages were power-combined in the output stage. This output stage was driven by a pair of devices, and this, in turn, was driven by an input stage realized using a single transistor. The transistor sizes in each stage needed to be identical, and the basic power-combining topology needed to be similar.

The individual PA structure is shown in Figure. 11 is composed of three series transmission lines with one parallel open-circuit stub located between the first two lines are used as the impedance matching circuit, which is a simplified method of the distributed multi-frequency matching approach, as introduced previously [10]. The single transmission line before the open stub is used to tune the impedance of the second harmonic, while the two series



(a)

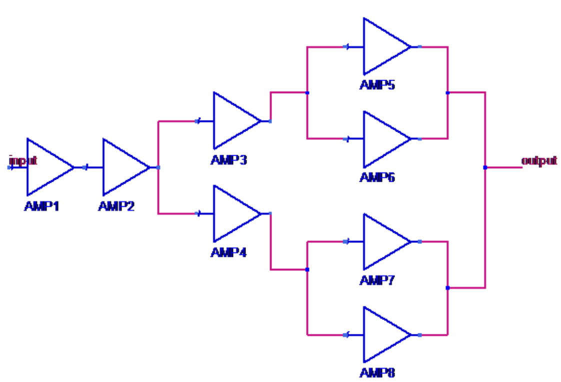


Figure 11. (a) single stage PA design (b) octature structure PA design

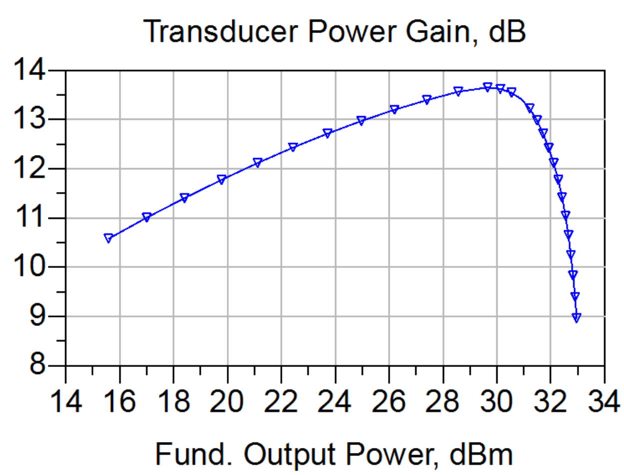


Figure 12. Transducer power gain of PA for single stage

transmission lines after the open stub are used to tune the impedance of the fundamental mode. Therefore, optimum impedance control at fundamental and second-harmonic frequencies can be realized simultaneously. The simulated large-signal performance is plotted in Figure. 12.

F. End to End Module performance

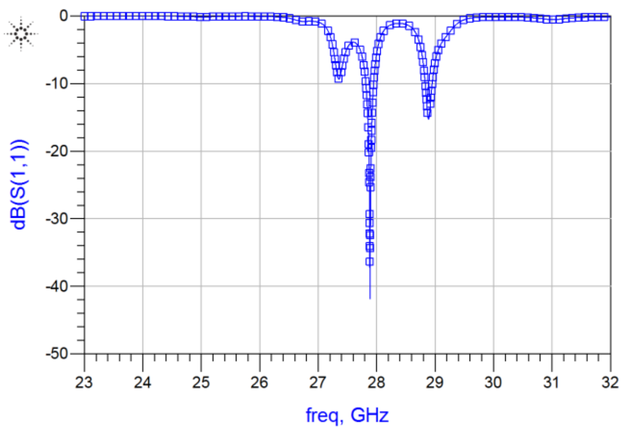


Figure 13. Simulated transmitter architecture end to end S11 response

To investigate the loss of proposed transmitter architecture, we have simulated S11 of transmitter module chain (with Yagi antenna, a BPF, mixer, matching network and power amplifier) in ADS. The results are shown in Figure.13. We plotted S11 to find the loss of the whole module and the S11 value at 28 GHz is lower than -30 dB, which is excellent.

III. CONCLUSION

The design of a novel transmitter module on a single chip using GaN/Si as the substrate is presented in this paper. The transmitter module consists of Yagi antenna, BPF, impedance matching network, up-conversion mixer and power amplifier. We investigated innovative designs for the transmitter components with potential for integration on a GaN substrate. To validate our designs, we selected 28 GHz but module design can be easily scaled to higher millimeter wave frequencies, such as 60 GHz for the 5G system. Designed transmitter module shows loss of less than -10 dB at 28 GHz, which can be further improved with design refinement. To our knowledge, this is first reported the design of monolithic transmitter module on GaN chip. Our proposed module will offer significant SWAP-C (size, weight, area, power and cost) advantages.

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