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Solid-state power amplifiers for space: going to extremely high frequency

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Abstract: Concentrating on the high frequency demands of solid-state power amplifier (SSPA) for space usage, the methodology and key techniques of the Q band 20 watts, V band 10 watts and W band 2 watts SSPAs are proposed in the present study. The GaN HEMT monolithic microwave integrated circuits (MMICs) are utilized as basic power amplifier units for power and efficiency enhancement. The high efficiency multi-ways low loss power combination techniques including magic T and radial-line were developed to achieve high output power. Copper diamond and heat pipes were applied to overcome heat dissipation and thermal flux challenges. By considering the strictly space qualification and components derating requirements, all products show state-of-art performances, which are used and verified in application for satellites payloads or terminal transmitters. To the authors knowledge, this is the first time the EHF band SSPA are developed and qualified for space usage in China. The designs proposed in the paper meet the demands and requirements for future satellite projects, to strongly support high frequency and high throughput space communication tendency and targets realization.

Key words: Q band, V band, W band, GaN, solid-state power amplifier (SSPA), space based

PACS: 85

星载固态功率放大器:迈向极高频

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摘要:聚焦于星载固态功率放大器的高频化,设计并实现了Q频段20W、V频段10W以及W频段2W的固态功率放大器。基于氮化镓功率单片技术,提升了单元的功率和效率;基于魔T和径向线的高效率、低插损多路功率合成技术,实现了整机高功率输出;铜金刚石和热管的应用和工艺攻关,克服了多热源、高热流的工程瓶颈。Q频段和W频段固放首次在轨应用,以及V频段固放在地面发射机中的应用。考虑到严苛的空间考核条件以及器件为满足在轨长寿命的降额要求,产品均性能优良稳定。文中的Q频段和W频段固放是我国首次开发并在轨搭载验证的星载连续波固态功率放大器,为我国后续极高频段高通量卫星的载荷实现提供了有力技术支撑。

关 键 词:Q频段;V频段;W频段;氮化镓;固态功率放大器;星载

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Introduction

In the perspective of reaching global and ubiquitous wireless connectivity, the satellite segment will play a key role. The claimed objective is to reach so-called high throughput connectivity in order to make the satellite segment a potential "backbone in the air" for next-generation digital communication services, characterized by high-speed and stringent quality-of-service (QoS) requirements[1]. Such an ambitious objective is not realistically achievable by only exploiting currently saturated bandwidth portions (Ku and Ka bands)[1]. For this reason, extremely high frequency (EHF) bands (30~300 GHz) for broadband transmission over satellite links is currently a hot research topic. In particular, the Q to V band (30~50 GHz) and W-band (75~110 GHz) offer very promising perspectives, to realize the hundreds of Gigabits or even Terabits communication capability per single satellite.

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Solid state power amplifier (SSPA) is one of the typical and key active products of satellite payloads, which mainly complete the microwave signal amplification, gain controlling, phase controlling and etc. SSPA is widely used in the millimeter and commercial communication satellite, navigation satellite, sensor satellite high data transmitter system, phase shift array antenna, which determines the mainly performances of the downlinks and is the main power consumption carrier.

Constrained by the high frequency output power and efficiency capability, typical aerospace used SSPA is mainly works beyond K band. The solid power amplifier in EHF and Terra Hertz (THz) tuned out to be a huge challenge for the next generation of satellite payloads. Based on the Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) monolithic microwave integrated circuits (MMICs), this paper presented the three typical SSPAs working in Q band, V band and W band respectively, with low loss multi-way combiners and integrated structures which are qualified for space usage.

Section 1 will mainly focus on the Q band 20 watts SSPA. V band 10 watts SSPA and W band 2 watts SSPA will be introduced in Section 2 and Section 3 respectively. Then the comparison with the latest reports or literatures will be included in the conclusion section.

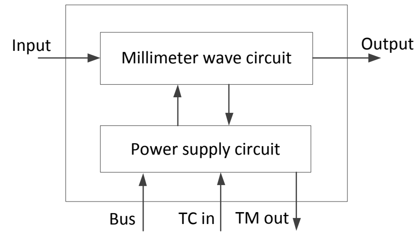
1 Q Band SSPA

Q band SSPA is mainly used in the high throughput satellite (HTS) Q/V bands transponder, to amplify the broad bandwidth signal to required output power range with good linearity performance. As the complete product, the SSPA is constructed by two parts: millimeter wave circuit and power supply circuit. Millimeter wave circuit is mainly used to realize the millimeter wave signal amplifying, controlling, temperature compensation and power/temperature telemetry (TM). Power supply circuit including DC/DC converter is mainly used for bus voltage transfer, response to the tele-command (TC) data and TM data return, as shown in Fig. 1(a).

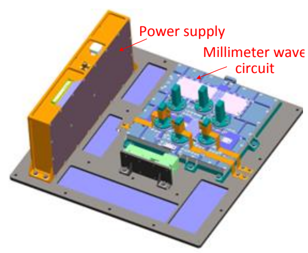
As separated into two parts in function, the structure of the SSPA has also two corresponding parts: millimeter wave circuit which is horizontal assembled, and power supply circuit which is vertical installed, with cable connected between them for voltage supply and TM data back. And in this paper, we will mainly focus on the millimeter wave part, and the power supply part will be briefly introduced.

The prototype of millimeter wave circuit is shown in Fig. 2(a), including two gain amplifiers, one temperature compensation circuits, one drive power amplifier, 1 to 4 power divider, 4 ways power amplifiers, 4 to 1 power combiner, and coupling power detector circuit, to realize the function of gain amplification, high power output, power detection and temperature compensation and TM, etc. Figure 2(b) depicts the gain and output power distribution of every stage, with the input power of -6 dBm.

In Q band SSPA, Multi-way power divider and combiner need to be carefully designed and fabricated to meet the stringent requirements of power combination efficiency at the high frequency, broad bandwidth, and large power condition. The waveguide 1 to 4 power divid-



(a)

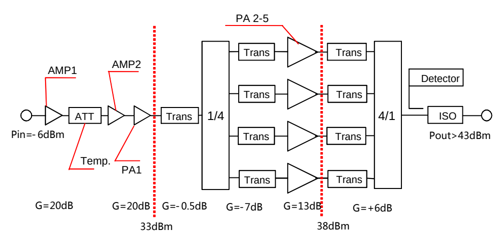


(b)

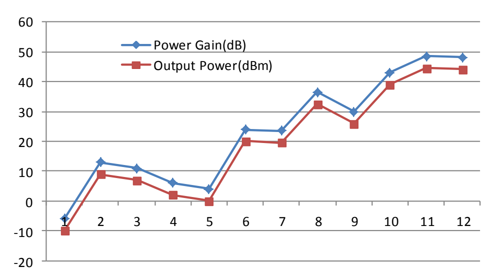
(c)

Fig. 1 Q band SSPA: (a) function diagram, (b) 3-D model of Q band SSPA, (c) photograph of material object

图 1 Q频段固态功率放大器:(a)工作框图,(b)产品三维模型,(c)实物图



(a)



(b)

Fig. 2 The prototype and corresponding gain and power distribution of Q band SSPA millimeter wave circuit: (a) prototype, (b) the gain and power distributions of every stage

图 2 Q频段固态功率放大器毫米波链路原理图和增益、功率分布图:(a)原理图,(b)增益和功率分布图

er and 4 to 1 power combiner are integrated in the millimeter wave circuit structure with the MMICs, bias/filter circuits and controlling printed circuit board (PCB), which realizes the active and passive integration to save dimension and weight, and enhance the efficiency and power at the same time as compact arrangement. The broadband high-power splitter/combiner are designed in two stages of magic T architecture, as shown in Fig. 3. The insertion loss simulated in the 5 GHz bandwidth is smaller than 0.1 dB, with return loss at the input and output ports of better than -17 dB. The isolation between the divided ports is higher than 22 dB, which offers an excellent performance for lowering adjacent ports influences. By utilizing this specific topology, the reliability of the SSPA can be satisfied as one way's invalid will not transferred to the other ways.

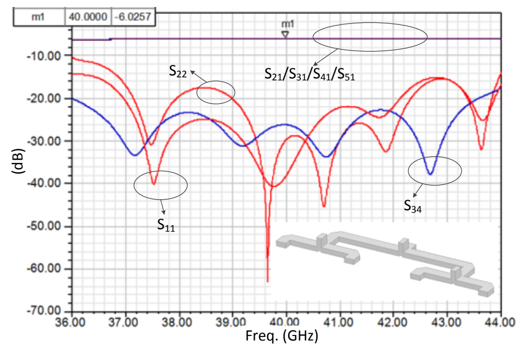
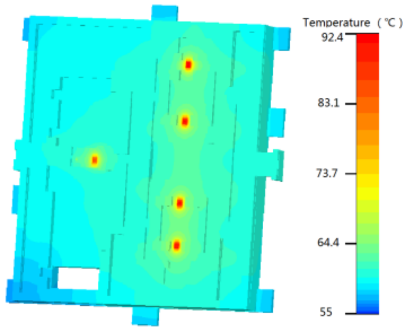


Fig. 3　Q band broadband power divider/combiner (4 ways)

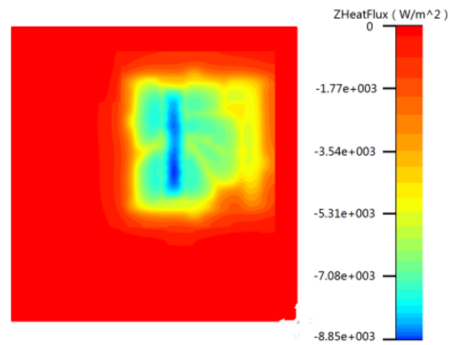
图3　Q频段4路功率分配和合成器

Because of low efficiency and high output power, the huge heat consumption and high thermal flux turned out to be a technical bottleneck for space usage. Especially for this product, the 4 ways power amplifier is integrated in a compact architecture, which further exacerbates the challenge of heat handling. The copper diamond heat sink is used under the GaN MMICs as heat sink for the first stage heat dissipation, which offers nearly 2.8 times thermal conductivity (550 W/C·K) compared to the CuW material (192 W/C·K), with similar coefficient of thermal expansion of GaAs or GaN MMICs. Heat pipes are embedded in the SSPA structure as well to decrease thermal resistance and flux from the heat sink to the housing board. The thermal simulation and infrared thermography measurement show that the GaN MMIC's shell temperature (from heat sink surface) can be hold under 92.4 ℃, which will ensure that the GaN MMICs' gate temperature controlled lower than 150 ℃, to satisfy the space long-life usage requirement, as depicted in Fig. 4. The maximum heat flux is 8.85×10^3 W/m^2, within the safety specification of heat flux and gross for the satellite housing heat pipes.

Q band SSPA millimeter wave circuit is shown in Fig. 5. Multi-layers compact structure is utilized to realize the millimeter wave channels, waveguide transitions, magic T units, loads, heat pipes and direct current (DC) feedings circuits. The loads are used for magic T isolation ports matching. The waveguide separated into upper and lower parts. MMICs, PCBs, substrates and heat sinks are located in the cavities of waveguide lower part, and connected with waveguide by E-plan transitions. Orthogonal arranged heat pipes are embedded at the bottom of waveguide, with DC feedings vertical through to connect the back PCBs to the waveguide plan ones. Back cover and front covers are used for protection and electromagnetic shielding.



(a)



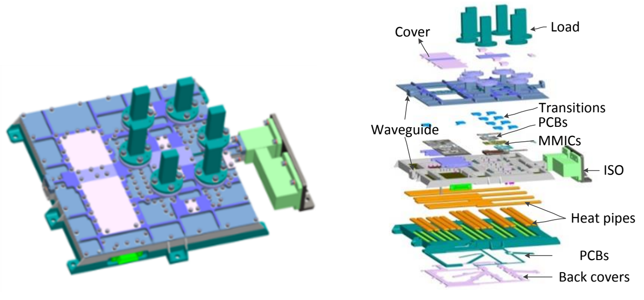
(b)

Fig. 4　Q band SSPA thermal simulation and infrared thermography: (a) shell temperature of the GaN MMICs, (b) heat flux at bottom

图4　Q频段固态功率放大器热仿真分析图:(a)氮化镓功率芯片壳温,(b)背面热流密度图

The power supply mainly provides the DC feeding for solid state power amplifier. The +100 V Bus voltage is converted to +20 V by Phase-Shift-Full-Bridge (PS-FB) topology, which improves efficiency by using synchronous rectifier technology. Then +20 V output voltage is converted to +5 V and -5 V out voltages by Half-Bridge (HB) topology. +20 V provide drain current to the GaN power amplifier chips, +5 V provide drain current to the gain amplifying and pre-drive stage amplifier chips, -5 V is utilized for the gate bias voltage of all MMICs and temperature compensation circuits.

As Fig. 6(a) shown, when the power on signal is received by tele-command circuit, auxiliary power supply circuit works first to generate +12 V for Pulse-Width-Module (PWM) and -5 V as bias voltage. The PWM gen-



(a) (b)

Fig. 5 Q band SSPA millimeter wave circuit structure: (a) integrated structure, (b) explosion figure

图5 Q频段固态功率放大器毫米波链路模型图:(a)集成后的结构,(b)爆炸图(单元分布图)

erate pulse when -5 V voltage is set up, and then the PSFB and HB start to work for +20 V, +5 V, -5 V continuously output. Auxiliary power supply stops when the all output voltage enters the steady state. Also, the power supply circuit includes the over-current (OC) protection, under-voltage (UV) protection and no negative voltage protection.

Figure 6(b) depicts the simulation results of power supply. The +100 V input voltage will be converted to 20 V, -5 V, and +5 V output with specified currents and time sequence. As shown in the Figure, -5 V is first output and then +20 V and +5 V are outflow with over 10 milliseconds delay. Fig. 6 (c) presents the conversion efficiency of the main power consumption part (+20 V) according to the current quantity. The efficiency at the rated output power is nearly 94%, which shows very good results.

The photograph of the proposed SSPA is shown in Fig. 1 (b) and Fig. 1 (c). The measurement results are summarized in Fig. 7. The output power is at the range of 42. 9dBm to 44. 8dBm with the efficiency of 7% to 10. 5%, at the frequency range of 37 GHz to 42. 5 GHz. Within 2 GHz bandwidth from 38. 5 GHz to 40. 5 GHz, the output power is higher than 44 dBm with the efficiency higher than 10%. The peak output power is nearly 44. 3 dBm, with efficiency of 10. 5%. All the measured results calculate power supply efficiency and the loss of output isolator.

2 V Band SSPA

V band SSPA is developed for Q/V uplink or inter-sat link. Limited by lower output power of MMICs compared to Q band, 8 ways radial-line power combiner/divider is designed for highly integration and compact dimensions, as depicted in Fig. 8. The simulation results of V band 1 to 8 divider and 8 to 1 combiner show that the insertion loss is lower than 0. 1 dB, with the port reflection coefficient better than -16 dB. However, the isolation between the divide ports is only -7 dB, which means the adjacent MMICs will be influenced if one is in-

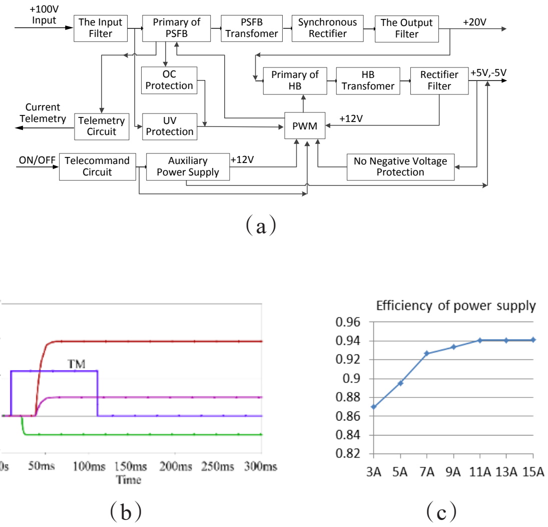


Fig. 6 DC/DC power supply for Q band SSPA (a) topology diagram, (b) output voltage serious simulation results, (c) efficiency vs. 20 V's current (main power consumption part)

图6 Q频段固态功率放大器电源电路(a)原理框图,(b)输出电压时序图,(c)20 V输出电压支路(主功率支路)电流和效率关系图

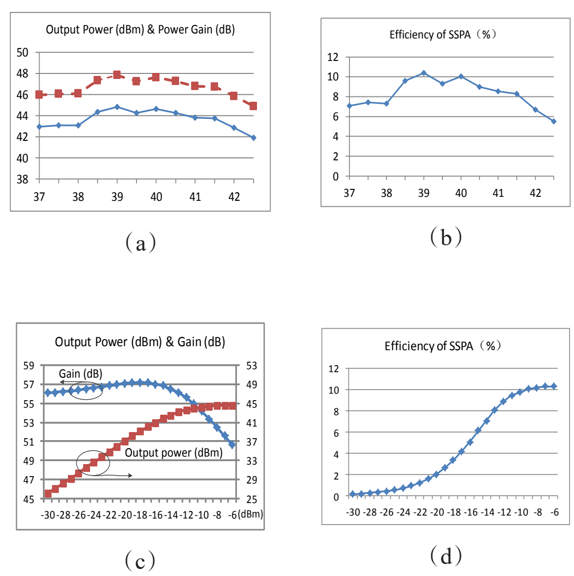


Fig. 7 Q band SSPA measurement results (a) output power and gain vs. frequency, (b) efficiency at rated input power vs. frequency, (c) gain and output power vs. input power, (d) efficiency vs. input power

图7 Q频段固态功率放大器测试结果 (a)输出功率、增益随频率变化图,(b) 整机效率随频率变化图,(c)输出功率、增益随输入功率变化图,(d)整机效率随输入功率变化图

valid. This influence may not totally accept in the space usage as high reliability is as important as specification performances, and one core chip's loss should not transfer to the others. However, in some cases, especially as terminal transmitter, the multi-way radial-line power combiner shows significant advantages for more compact integration, smaller size, lower cost etc., which can be an acceptable and sometimes preferred method.

The end stage of V band SSPA is shown in Fig. 9. Input power divider and output power combiner are assembled together, with waveguide to coaxial transition embedded in the structure as well. The single unit of power amplifier is predicted to exhibits more than 1.7 W output power by utilizing 2 W GaN MMIC, as the insertion loss of transition and microstrip line cannot be neglected in high frequency band. 8 units of power amplifiers are located around the side of the divider/combiner. Microstrip line to waveguide H plan transitions are used for connection of MMICs with divided branches. Back covers are used for heat dissipation and waveguide short end in the microstrip line to waveguide transitions.

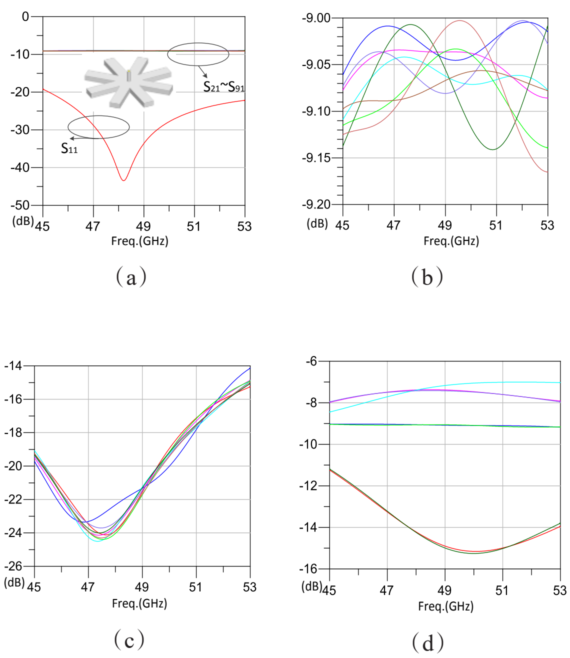


Fig. 8 V band 1 to 8/8 to 1 divider/combiner simulation model and results (a) simulation model, transition and reflections simulation results, (b) transition coefficient, (c) reflection of divide ports, (d) isolation between divide ports

图 8 V 频段 1 分 8 功分器和 8 合 1 合路器仿真模型及结果 (a)仿真模型、传输系数和反射系数(公共端口),(b) 传输系数(8 路),(c)功分端口的反射系数,(d)功分端口的隔离度

The fabricated end stage of V band SSPA is shown in Fig. 9(b). The photograph of the V band SSPA with drive stage and the measurement results are summarized in Fig. 10. With the drive stage of amplifier, the gain is higher than 26 dB. The proposed power amplifier exhibits more than 10 watts output power, and more than 10% efficiency in the frequency range of 47~52 GHz. The peaking output power and efficiency can achieve 11.3% and 40.7 dBm, respectively. The corresponding combination efficiency can achieve as high as 85% at the frequency between 48 GHz and 50GHz.

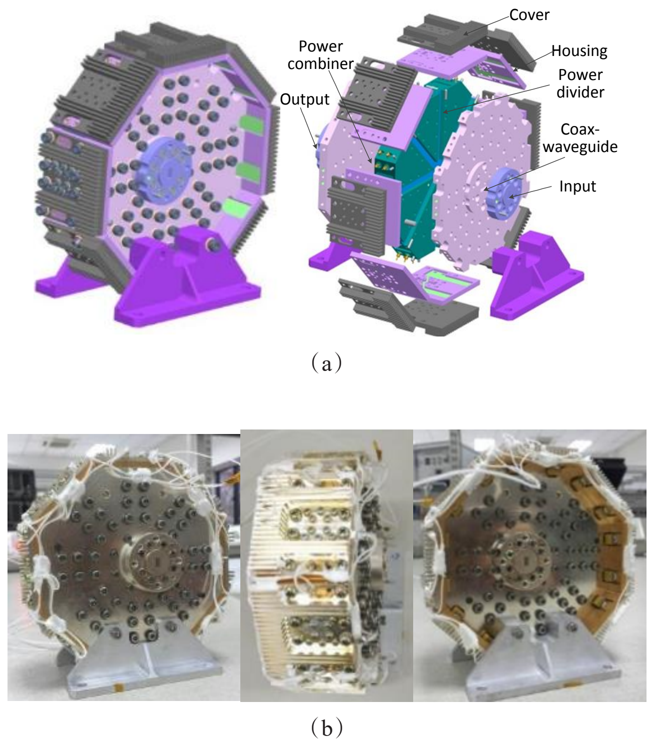


Fig. 9 End stage of V band SSPA (a) design structure (model and explosive), (b) fabricated V band end stage SSPA (Input side; GaN MMICs units and output side)

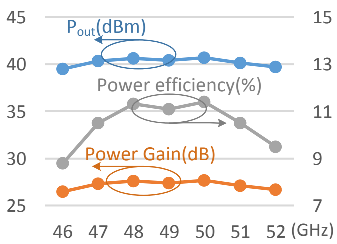
图 9 V 频段固态功率放大器末级模块 (a)设计结构(模型和爆炸图),(b) V 频段功率放大器末级实物图(输入面、氮化镓功率芯片单元和输出面)

3 W Band SSPA

W band SSPA is the key unit of W band high throughput communication and microwave remote sensing system. To achieve more than 2 watts output power in the 4 GHz bandwidth, the SSPA used 2 ways combination of high power GaN MMICs. The W band product is also constructed by two parts as Q band SSPA: millimeter wave circuit and power supply circuit, which are connected with cable as well, and placed on one plate.

Figure 11(a) depicts the millimeter wave circuit's topology, composed by multi-stage MMICs, waveguides, microstrip lines, magic T power divider/combiner, waveguide loads, isolator etc., which complete the functions of gain amplify, power enlarge, circuit filter, temperature telemetry and inter-stages matching. As Fig. 11 shown, the signal is gain amplified by two stages of small signal amplifier MMICs, and then power amplified by the

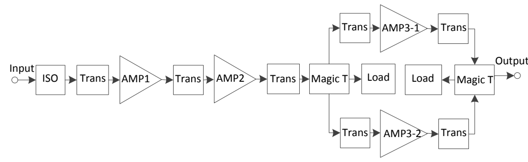
(a)



(b)

Fig. 10 V band SSPA product and measured results (a) photograph, (b) measurement results

图10 V频段功率放大器产品和测试结果 (a)产品测试照片, (b) 测试结果



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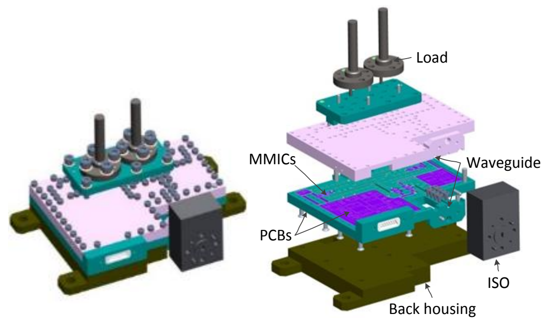

(b)

Fig. 11 W band SSPA millimeter wave circuit (a) millimeter wave circuit schematic, (b) integration structure and explosion figure

图11 W频段功率放大器毫米波链路 (a)原理框图,(b) 集成结构和爆炸图

two parallel ways of GaN MMICs, which are combined by the magic T, embedded in one structure for highly integration, to achieve the output power specification.

PCBs are utilized for DC filter, DC supply, negative voltage transfer, and temperature telemetry. Transition from waveguide and microstrip line are also used. With 0.127 mm thickness quartz substrate, transition loss is extremely reduced to small than 0.15 dB during in the operation frequency range.

Figure 12 shows the magic T simulation model and results. Within 4 GHz bandwidth, from 92 GHz to 96 GHz, the insertion loss is lower than 0.1 dB, with the reflection coefficient of better than -24 dB, and isolation of better than 30 dB. The transition of MMICs to magic T or waveguide is realized by micro-strip line coupling to the H-plan of waveguides, which can distribute good transition performance and easy for micro-assembly controlling. The quartz substrates are also utilized for lower loss tangent and better manufactory accuracy.

All the units are design and assembled in three-layer structure, for DC supply, microwave channel and magic T load separately, as shown in Fig. 11(b). This highly integrated architecture ensures the small footprint and light weight, which are also the key specifications for satellite SSPA. Isolator is assembled at the input port of SSPA for the connect protection of the previous stage (frequency convertor). As the output port is matched by the magic T, the VSWR is good enough for connection with the antenna, the isolator is cut down.

The power supply is designed based on two-transistor forward topology. Because the topology can achieve magnetic reset by itself, it is widely utilized for medium and small power range of aerospace power supply. The block diagram is shown in Fig. 13 (a), after receiving the turn on instruction, the auxiliary power supply works first to generate +12 V and -5V voltage. +12 V is supplied to PWM and -5 V is supplied to millimeter wave circuit. After the PWM circuit is powered on, power supply starts to work and enter into the start-up phase. Auxiliary power will stop working for higher efficiency when the power output +15 V and -5 V are stable.

The power supply circuit also includes under voltage protection, over current protection and no negative voltage protection functions. The output voltage telemetry and current telemetry are also provided by the power supply.

Figure 13(b) depicts the simulation results of power supply. The 100V input voltage will be converted to +15 V and -5 V output with specified currents and time sequence. As shown in the Fig. 13(b), -5 V is first output and then +15 V are outflow with 10 ms' delay. Fig. 13 (c) offers the measurement result of conversion efficiency of +15 V according to the current quantity, which shows that the efficiency can achieve more than 85% at rated output power.

The proposed W band SSPA is fabricated and tested for verification. The photograph of the integrated SSPA is shown in Fig. 14(a). The measurement result including power supply is depicts in Fig. 14(b) as well. Within the frequencies of 92 GHz to 96 GHz, the output power is among the range of 33 dBm to 34.1 dBm. The corresponding power gain achieves 29.5 dB to 31 dB, with

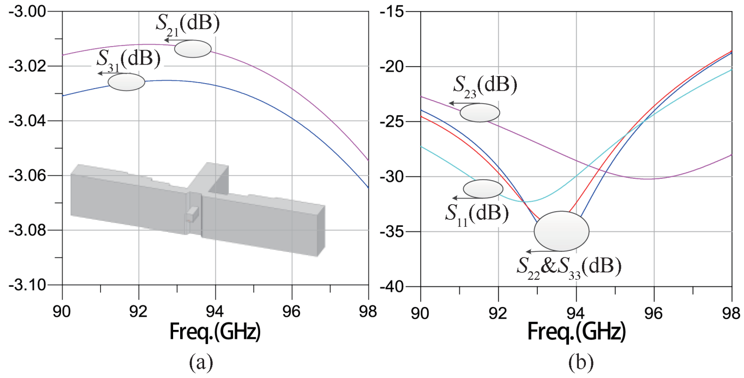

Fig. 12 W band magic T model and simulation result (a) model and transmission coefficient, (b) reflection and isolation coefficient

图 12 W 频段魔 T 模型和仿真结果 (a)模型和传输系数,(b) 反射系数和端口隔离度

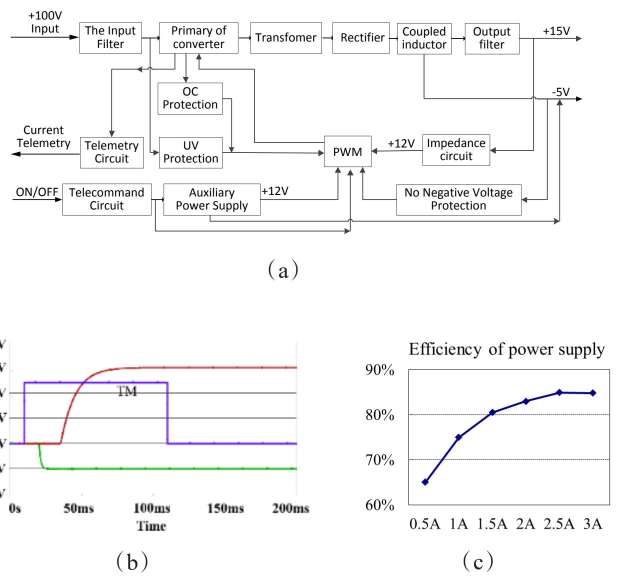

Fig. 13 Power supplier circuit schematic and efficiency curve (a) schematic, (b) output voltage serious, (c) efficiency vs. 15 V's current (main power consumption part)

图 13 W 频段功率放大器电源电路 (a)原理框图,(b) 输出电压时序,(c) 15 V 输出电压电流和效率关系图(主功率部分)

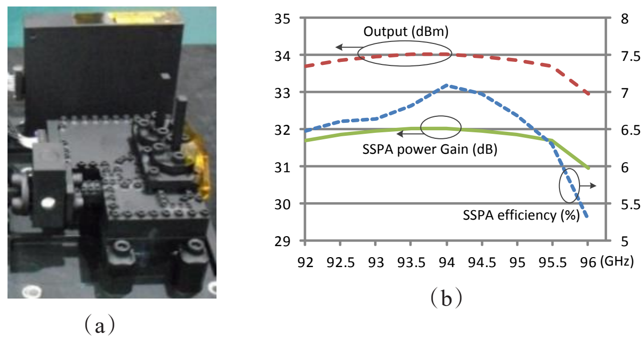

Fig. 14 W band SSPA photograph and measurement results (a) photograph, (b) measurement results

图 14 W 频段功率放大器整机图片和测试结果 (a)整机图片,(b)测试结果

the efficiency of 4.5% to 7.1%. The peak output power is 34.3 dBm in 94 GHz and the efficiency is more than 7%. Considering the 80% efficiency of DC/DC convertor, the millimeter wave chain efficiency is as high as 8.7%. As far as author's knowledge, this shows state of art performance, especially under the restriction of strict aerospace qualification requirements.

4 Conclusion

Three SSPAs of EHF bands for space payload usage or terminal transmitter are discussed in the paper, including Q band 20 watts, V band 10 watts and W band 2 watts. All the products utilize appropriate waveguide power divider / combiner and GaN HEMT MMICs for high output power achievement. All the millimeter wave parts are highly integrated for demission miniaturization. The contrasts of the proposed SSPAs to the latest reports or literatures of EHF SSPA are summarized in Table 1. By considering the huge effort and design balance to satisfy the space standard and components derating for long life reliability, the proposed products show very good performances.

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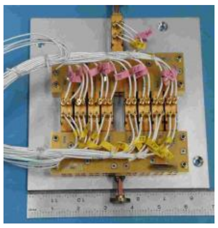
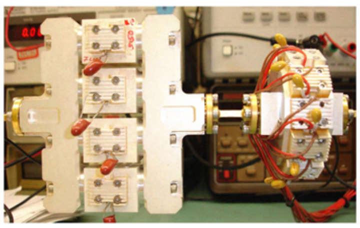
Table 1 Compare with latest literatures

表1 与相关文献比对结果

Ref.	Frequency	Output power	Gain	Efficiency	State
[3]	33. 5~38 GHz	8~21 W	14~16 dB	8%~21% (Millimeter wave part)	Model piece
[6]	59~63 GHz	12. 8 W (peak)	34 dB	16% (Millimeter wave part)	Model piece
[9]	80~100 GHz	29~33 dBm	8~12 dBm	/	MMIC
[19]	94~98 GHz	2. 5~5 W	18 dB	7% (Millimeter wave part)	Model piece
This work	37~42 GHz	20~30 W	50 dB	7%~10% (with power supply)	Space qualified
This work	47~52 GHz	>10 W	>26 dB	9. 5%~11. 5% (Millimeter wave part)	Ground transmitter
This work	92~96 GHz	2~3. 5 W	>31 dB	4. 5%~7. 1% (with power supply)	Space qualified



(a)



(b)

Fig. 15 V band SSPA and W band SSPA of references (a) V band SSPA of Ref. [6], (b) W band SSPA of Ref. [19]

图15 典型V频段和W频段功率放大器 (a)V频段功率放大器[6],(b) W频段功率放大器[19]

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