Ku-band 360-W Pulsed Solid-State Power Amplifier with Excellent Comprehensive Performance

Shengqi Shen
The 13th Research Institute, China Electronics Technology Group Corporation, Shijiazhuang, Hebei, 050051, China
cetcnhy@hblwxh.onexmail.com
*Corresponding author’s e-mail: cetcnhy@163.com

Abstract. A design method of solid-state amplifier based on hybrid power-combining technique is presented in this paper. Also a 360-W pulsed solid-state power amplifier (PSSPA) constituted of 32 monolithic-microwave integrated-circuit power amplifiers (MMIC PA) operating in Ku band is designed successfully using this method. The PSSPA mainly consists of three stages of power-combining circuits and one stage of Wilkinson power-amplify module array. The power-combining circuits are respectively based on rectangular waveguide, coaxial line and microstrip line. The proposed combiner structures have the advantages of high power capacity, high power-combining efficiency and easy heat sink design. The measured results indicated that, in the frequency range of 15.5 GHz-16.5 GHz, the average output power is 362 W and the average active power-combining efficiency is 86.95%.

1. Introduction
As is well known, the solid-state power device has the advantages of small size, light weight, long service life, high operating frequency, low DC power consumption, high reliability, compact circuit and easy being integrated. However, the output power of solid state devices decreases with frequency and on-chip power combining becomes less efficient with increasingly larger devices\(^{[1,2]}\). In order to meet the requirements of high power in modern communication systems, the solid-state power-combining technique becomes an effective method to solve this technical bottleneck.

The typical power-combining technique currently mainly has the Wilkinson power-combining technique based on Microstrip line\(^{[1,2]}\), the spatially power-combining technique inside wave-guide cavity\(^{[3,4]}\), the radial waveguide spatially power-combining technique\(^{[5-7]}\). The comparison performances of the typically power-combining technique are shown in table 1.

| Type               | Combining efficiency | Isolation | Power capacity | Heat sink design |
|--------------------|----------------------|-----------|----------------|------------------|
| Wilkinson \(^{[1,2]}\) | poor                 | good      | poor           | easy             |
| Wave-guide cavity \(^{[3,4]}\) | good                 | poor      | good           | difficult (multitray) |
| Radial waveguide \(^{[5-7]}\) | good                 | good      | poor           |                  |

The Wilkinson power-combining technique has the advantages of easy heat sink design thanks to its planar structure, wide bandwidth and high isolation but disadvantages of larger loss and lower...
power capacity\textsuperscript{[8]}. The spatially power-combining technique inside a wave-guide cavity has the advantages of low loss, high power-combining efficiency and large power capacity, but disadvantages of low isolation, limited elements combined and difficult heat sink design\textsuperscript{[9]}. The radial waveguide spatially power-combining technique has the advantages of high power capacity, wide bandwidth, the perfect symmetry structure and high power-combining efficiency. But this power-combining technique faces the challenges of heat radiating performance and high isolation\textsuperscript{[10]}.

Aiming to disadvantages of the power-combining technique mentioned above and improve the comprehensive performance index, a hybrid power-combining design scheme is proposed. Using this method, a 360-W pulsed solid-state power-combining amplifier operating in Ku band is designed and fabricated, and its measured performance is good.

2. System design

The Schematic diagram of the proposed PSSPA is shown in figure 1. The first stage and the second stage circuits are composed of binary rectangular-waveguide power dividers with different sizes. The third stage circuit is composed of 4 four-way waveguide-coaxial power dividers with two coaxial probes coupled respectively in each wave-guide branch. The fourth stage circuit is a double-deck Wilkinson power-amplify module array. Each layer is composed of 8 modules. Each module is consisted of one Wilkinson divider, two MMIC PAs and one Wilkinson combiner.

![Figure 1. The Schematic diagram of the PSSPA based on hybrid power-combining circuits](image)

The proposed combiner structure has the advantages of high power capacity and high power-combining efficiency thanks to low less wave-guide structure and the symmetrical form. It is easy to design heat sink for its quasi planar structure. The end Wilkinson power divider is used to directly improve the isolation between the near ports.

3. Components design

The input signal is divided equally into four parts by the power divider in the first and the second stage. Their structures and sizes are shown in figure 2 and table 2 respectively. In this design, the rectangular waveguide adopt WR62, whose long side “a” equal 15.8 mm.

![Figure 2. The Configuration of the rectangular-waveguide power divider](image)
Table 2. The sizes of the first and second stage of the dividers (As shown in figure 2), unit: mm

| symbol | a   | b   | L   | Ca  | Ch  | bm | Lm | La | Lt | Lz |
|--------|-----|-----|-----|-----|-----|----|----|----|----|----|
| first size | 15.8 | 7.9 | 5   | 6   | 3.4 | 4  | 8  | 19 | 25 | 11 |
| second size | 15.8 | 7.9 | 3   | 6   | 3.4 | 4  | 5  | 11 | 12 | 11 |

Figure 3. The Configuration of the third stage divider

(a) E-field (b) H-field

Figure 4. The image of EM simulation of the third stage divider

Through the third stage of the divider, the input signal can be divided equally into sixteen parts. Its input port is waveguide port and its output port is coaxial port. The substrate material of coaxial port is PTFE with the relative dielectric constant 4.2. The structure and size of the divider in the third stage are shown in figure 3 and table 3 respectively. The figure 4 is the image of EM simulation at 15 GHz and phase 0°. It clearly shows the conversion from TE_{10} mode to the coaxial TEM mode.

Table 3. The sizes of the third stage divider, unit: mm

| Symbols | a   | b   | L   | Ch  | Lz  | Ls  | Lt  | D   | d   | Bj  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Sizes   | 15.8| 7.9 | 5   | 5.56| 22  | 5.62| 4.18| 4.1 | 1.27| 4.25|

4. Realization of the circuit

The former three stages can be connected together and fabricated at the same time. the photo of the fabricated circuit is shown in figure 5. The simulated and measured results are shown in figure 6. The
amplitude and phase curves of odd ports are respectively coincident to a curve and the amplitude and 
phase curves of even ports are respectively coincident to a curve in figure 6. From figure 6 can we get 
that the simulated results are agree well with the measured ones. The insertion loss are less than 0.3 dB 
in the frequency of 15 GHz to 17 GHz and the return loss are better than 15 dB. The insertion loss are 
less than 0.2 dB in the frequency of 15.6 GHz to 16.8 GHz and the return loss are better than 20 dB. 
From figure 6(b) can we also get that the phases of the two coaxial branches in the different 
waveguide arm are differed by 180°, but they are the same in the same waveguide arm. Therefore, the 
power amplifiers in the different waveguide arm are working in the push-pull type.

Figure 5. The product photograph of the former three stages power divider

The fourth stage circuit is a double-deck Wilkinson power-amplify module array. Each layer is 
composed of 8 Wilkinson power-amplify modules. Each module is consisted of one Wilkinson divider, 
two MMIC PAs and one Wilkinson combiner. The two layer arrays are arranged face to face. So it is 
very convenience for the radiator to be mounted on the backs of the arrays. The simulated model of 
the Wilkinson divider is shown in figure 7. The substrate is RT/duroid 5880 with h=0.254mm, εr = 2.2 .

The simulated and measured results are shown in figure 8. Transmission loss S21 and S31 are more 
than -3.3dB, return loss S11 and the isolation S23 is under -20dB from 13GHz to 18.6 GHz. It can be 
seen that the transmission loss caused by the single stage Wilkinson combiner is very small, but it can 
greatly improve the isolation.

The photo of the Wilkinson power-amplify module is shown in figure 9. The parameters of the 
MMIC PAs used are list below: 0.25 um HFET, two-stage amplify, DC power supply voltage is +28V, 
operating in 15.5 GHz-16.5 GHz, Psat is 41 dBm, the gain is 12 dB, the power added efficiency is 32%, 
the port impedance is 50 Ohm and the power dissipation is 30 w.

(a) The amplitude-frequency curve  (b) the phase-frequency curve

Figure 6. The simulated and measured results of the former three stages
5. Power measurement

The photo of the assembled 360-W PSSPA according to figure 1 is shown in figure 10. The measured results of The 360-W PSSPA at 16GHz is shown in figure 11. The measured results at other frequencies are shown in table 4 (The measured conditions: The width of the measured pulse is 100us and its duty cycle is 10%). At 15.5 GHz, the minimum output power is 355 w. The maximum output power is 374 w at 15.9 GHz. The average output power in the range of 15.5 GHz-16.5 GHz is 362 w. For the whole amplifier system, the minimum active power-combining efficiency is 85.3%, the maximum active power-combining efficiency is 89.9% and the average active power-combining efficiency is 86.95%.
Figure 10. The 360-W PSSPA

Figure 11. The measured results at 16GHz

Table 4. The power-measurement results of the PSSPA

| Frequency/GHz | 15.5 | 15.7 | 15.9 | 16.1 | 16.3 | 16.5 |
|---------------|------|------|------|------|------|------|
| Output power/W | 355  | 358  | 374  | 371  | 359  | 353  |

6. Conclusion

From the point of improving the combining efficiency and working reliability, this paper proposed a design method of power amplifier based on hybrid power-combining circuits. And a PSSPA constituted of 32 MMIC PAs operating in Ku band is designed, fabricated and measured. The measured results indicated that the average output power of this PSSPA is 362 W and the average active power-combining efficiency is 86.95%.

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