A Developing Approach of 600 W SHF TWTA for Communications Using Cathode Ripple Reduction Technique

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Abstract

In this paper, we propose a developing approach of 600 W super high frequency(SHF) traveling wave tube amplifier (TWTA) for communications. Also, we make a TWTA called the experimental-TWTA(ETWTA), which uses a cathode ripple reduction technique to improve RF performance. After implementation, we discuss, and compare it with some other TWTAs. Its RF performance is better than that of other TWTAs. Therefore, this methodology can be used to develop the high power SHF TWTA for communications.

Key words : Cathode Ripple Reduction Technique, SHF TWTA, Developing Sequence, R-L-C Low Pass Filter, Ripple.

Ⅰ. Introduction

Traveling wave tube(TWT) remains the best source for efficient generation of microwave power over broad frequency bandwidths. TWTAs are the hardware of choice for the vast majority of these space based communications systems. TWTAs provide the optimum solution because of their inherent ability to efficiently process high power at high frequencies with significantly better linearity and efficiency than other technologies[1]. For a 100 W amplifier the larger size(10 %) and mass(65 %) of the TWTA compared to an solid state power amplifier(SSPA) can be more than compensated by the higher power, efficiency, and bandwidth (more than 200 MHz) of the TWTA, which allows using a minimum number of TWTAs to support redundancy requirements, and thus helps to effectively optimize the satellite power budget[2].

Power supply specifications should be required to meet RF performance characteristics and to prevent defocusing of the TWT electron beam. Ripple from the power supply and the TWT pushing factors will determine the amount of signal distortion contributed by the TWTA in the areas of amplitude, phase, and frequency modulation. Ripple and AC components on the voltage of the anode and collector of TWT normally introduce a little spurious modulation. However, the cathode voltage produces much spurious components and so should be well filtered. Ripple and AC components can cause both amplitude modulation(AM) and phase modulation(PM) on the RF signal being amplified by the TWTA.

Following is a description of some of the more important TWTA features, design, implementation, and test attributes. In this paper we develop a prototypic TWTA called the ETWTA, which uses a cathode ripple reduction technique to improve RF characteristics. The technique is to use a passive R-L-C filter. After its implementation, we test its RF performance, discuss its characteristics, and then compare its main performance with that of some other TWTAs.

Ⅱ. Developing Approach

To develop the TWTA, we follow the developing sequence as Fig. 1. This paper particularly concentrates on several steps shown at dotted line in Fig. 1: detailed design, implementation, test and evaluation.

2-1 Design

In order to design TWTA, the following contents should be considered:

- ♦ TWTA should be designed for high power TWT.
- ♦ Power supply unit(PSU) should supply the constant voltage to the helix, collector, heater, cathode, etc. It should also have monitoring functions for the state of TWT, over-voltage and current, etc.
- ♦ To test and repair easily, TWTA should be designed by modules.
- ♦ Interfaces such as mounting, cooling, thermal protection, and fail-safe power supply circuitry must be considered to prevent damage to PSU and TWT in the event of a failure of one of these elements. RF input and output interfaces must not place unnecessary stress on the TWT RF connection and vacuum windows.

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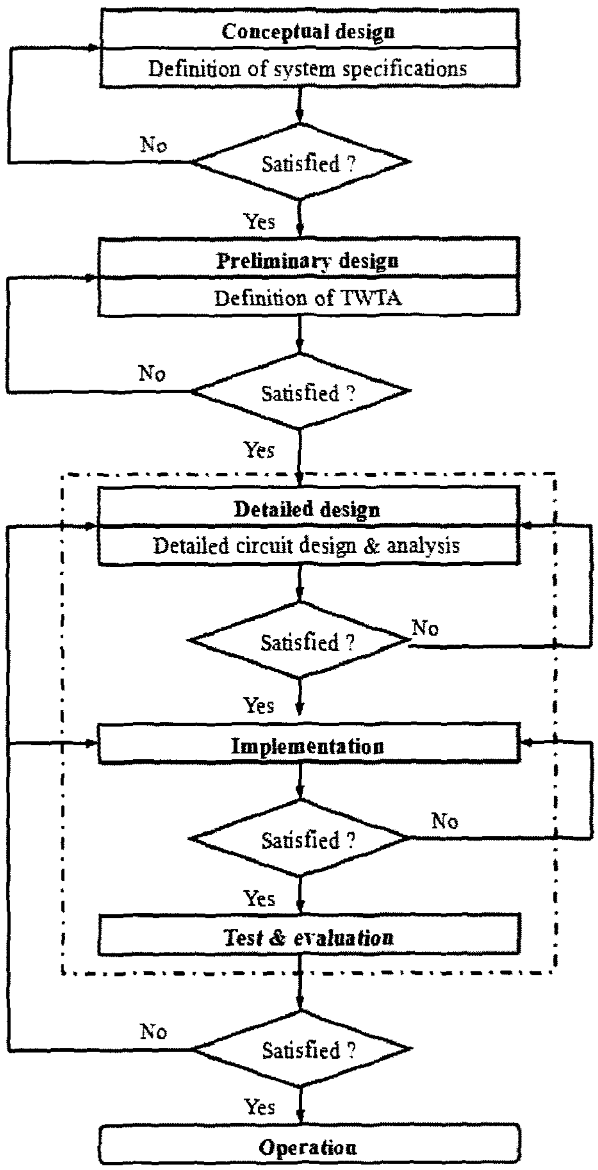


Fig. 1. Developing sequence of TWTA.

TWTA consists of RF module and TWT amplifying RF signal, PSU supplying the power, monitoring, and controlling for the every module, and cooling module. Fig. 2 below depicts its configuration. PSU is consisted of main power stabilization module, power conversion module, high voltage module, TWTA control module, and heater power & transmission control module. The function of each module is illustrated as follows. The main power stabilization module is to provide stable voltage, to protect TWTA from output over-voltage, and to detect over-temperature error by using feedback control. Power conversion module is to invert power and to send the converted power to high voltage module. High voltage module is to supply the stable high voltages to the cathode, collector, and helix of TWT[3]. Also, it has a protection circuit. Heater power/transmission control module is to control focus electrode(FE) and heater power and has detection function for errors. TWTA control module is to interface a TWTA with system control equipment. It interchanges the TWT control and state data with system control equipment through RS-485 port. TWT is to amplify the RF signal. PSU supplies voltages for TWT to amplify it appropriately. RF module is composed of isolator, dual directional coupler, linearizer, etc. To satisfy performance requirements, there is an increasing trend of designers incorporating pre or post-linearization modules with the power amplifiers(SSA or TWTA) to improve overall system efficiency and linearity[4],[5]. Normally we use the commercial RF parts that meet the design specifications and parameter values.

Shown in Fig. 3 is a functional diagram of the TWTA. Its operational principle is as follows. RF module takes charge of the role that amplifies an input signal at constant level. The variable attenuator controls the output level of the RF signal incoming to TWT. The amplified signal using TWT goes to the antenna through isolator and W/G coupler. PSU produces high voltages and supplies them to the TWT. The function of cooling module is to maintain the inner temperature of TWTA under the required temperature.

RF module composes of isolator, drive amplifier, variable attenuator, harmonic filter, dual directional coupler, linearizer, etc. We normally choose the RF part products that meet the design specifications and parameter values. To select optimal components, we calculate TWT flange output and TWTA rated power values through power budget for RF module and TWT.

2-2 Cathode Ripple Reduction Technique

If the factor that changes electron beam velocity varies with time, the result is phase modulation of the RF output signal. The main factor affecting the velocity of the beam is the cathode voltage. Other affects have a few effects. The use of AC voltage on the heater can introduce a small amount of spurious modulation on the RF signal being amplified by the TWTA.

In order to reduce the ripple voltage in PSU, we can increase the capacitor bank. However it may increase the charging energy, provide the excess energy at arcing and cause damage to TWT. The reduction of low frequency ripple current requires a large DC capacitor or a passive L-C resonant circuit to be connected to the DC line. However, these components tend to increase both the product volume and the cost[6]. Therefore, in order to improve the problem for cathode ripple voltage of TWT, this paper uses the cathode ripple reduction filter at the output of high voltage module, as shown in Fig. 4. It is an R-L-C low pass filter.

The cathode ripple reduction filter is configured as Fig. 5.

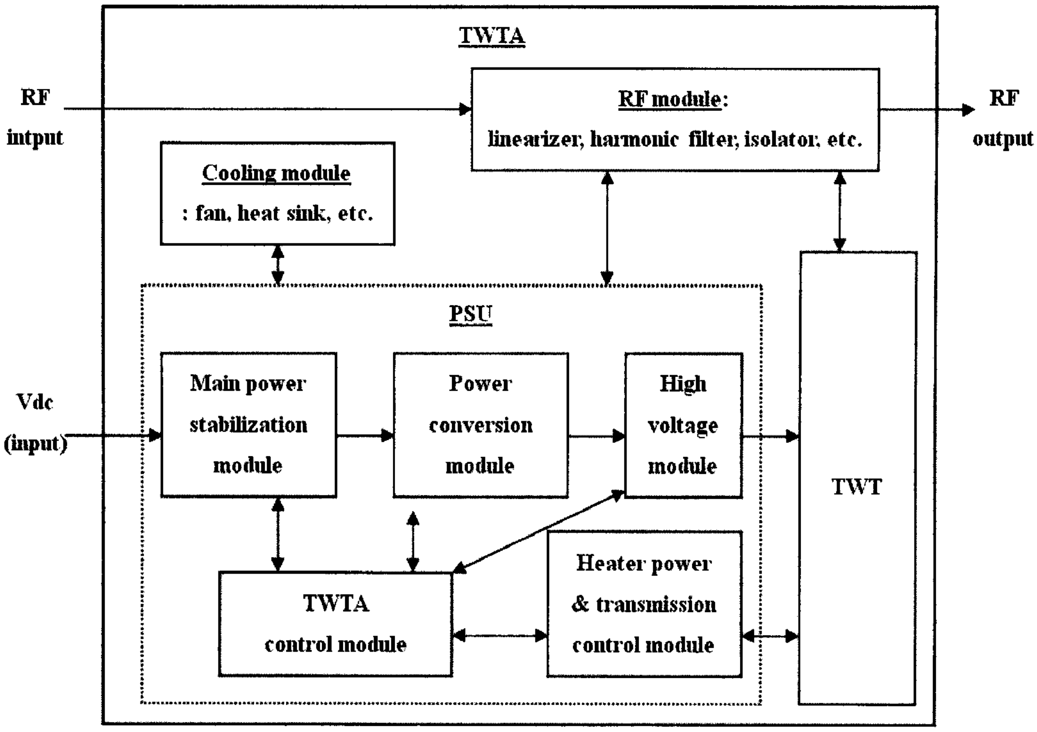


Fig. 2. Block diagram of TWTA.

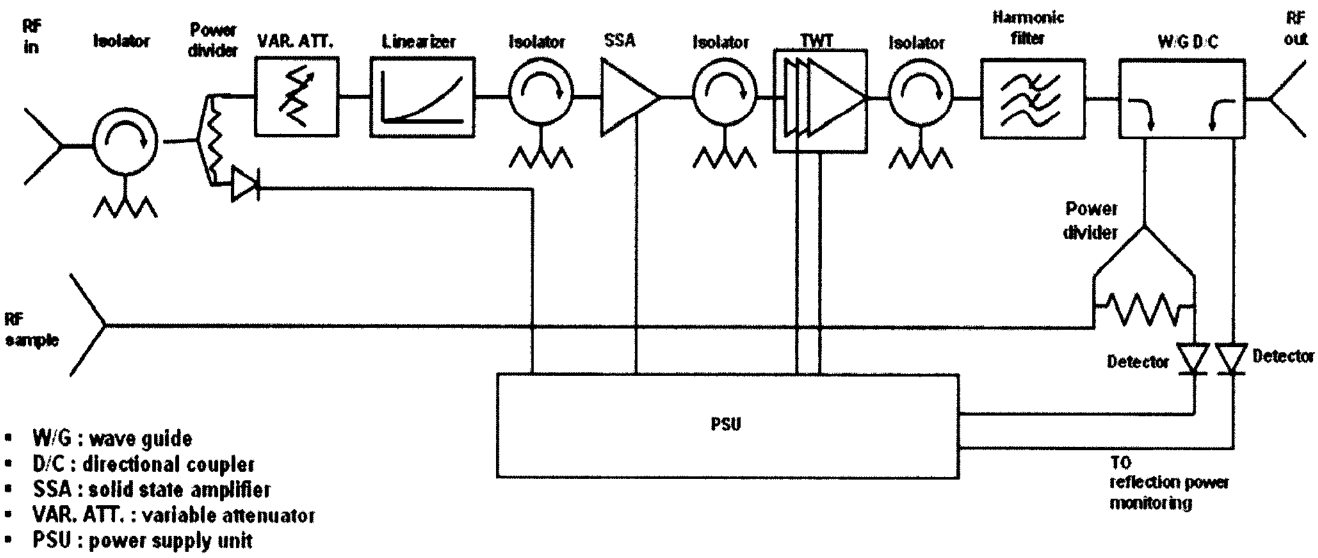


Fig. 3. Functional diagram of TWTA.

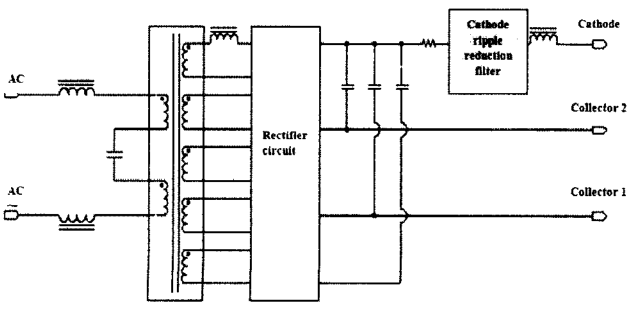


Fig. 4. Block diagram of high voltage module.

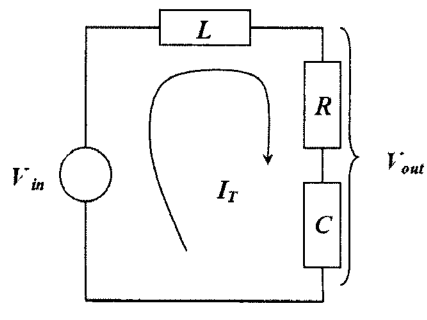


Fig. 5. Cathode ripple reduction filter circuit.

To obtain R, L, and C values, we can define generally the transfer function of R-L-C circuit in Fig. 5 as follows.

$$V_{in} = (sL + R + \frac{1}{sC}) \times I_T$$

$$V_{out} = (R + \frac{1}{sC}) \times I_T$$

$$H(s) = \frac{V_{out}}{V_{in}} = \frac{sRC + 1}{s^2 LC + sRC + 1} \quad (1)$$

where $s=j\omega=j2\pi f$.

As the transfer characteristics is derived from the absolute value of transfer function, it is given by

$$|H(s)| = \left| \frac{sRC + 1}{s^2 LC + sRC + 1} \right| = \frac{\sqrt{1 - (\omega RC)^2}}{\sqrt{(1 - \omega^2 LC)^2 - (\omega RC)^2}} \quad (2)$$

In order to remove properly the cathode ripple of switching frequency, we should design a low pass filter and produce optimum R-L-C values. As we can not calculate R, L, and C values simultaneously, we calculate a value while the other two values are fixed; for example, we calculate a C value while R and L values are fixed. So we try to do for this case as follows.

In order to get a C value, equation (2) can be rewritten as

$$\left(H^2\omega^4 L^2 + \omega^2 R^2\right)C^2 - (2H^2\omega^2 L + H^2\omega R)C + (H^2 - 1) = 0 \quad (3)$$

The RF characteristics, such as cathode ripple, FFT spectrum, and residual AM, especially depend on rectifier and filter circuits at high voltage module. The output voltage of full-wave bridge rectifier circuit is the effective value of input voltage. The output ripple voltage (V_r) is as a following equation:

$$V_r = I_c/(4\ f_{AC}\ C_o), \quad (4)$$

where I_c is cathode current, f_{AC} is the frequency of AC input voltage, C_o is the capacitance at output of rectifier circuit.

The output ripple voltage of full-wave bridge rectifier circuit is reduced by 0.8 times as that of the full-wave voltage doubler circuit, if they have identical output current, frequency, and capacitance. In the test, the full-wave voltage doubler circuit can not satisfy the specification for residual AM. We choose consequently the full-wave bridge rectifier circuit through analysis and experiments. We find out that the RF characteristics depend on cathode filter type reducing ripple voltage. Namely, it is improved the residual AM and phase noise performance. Also, as the result of analyzing and experimenting for the unexpected noise, we get an idea that it can be induced by the ripple voltage of auxiliary power (+15 V, −15 V, +5 V) supplied to RF module. To remove it, we make the output waveform of auxiliary power flat by using electrolytic condenser.

As mentioned above, there are close relationships between cathode ripple voltage, residual AM, and phase noise. Namely, cathode ripple reduction can improve the efficiency of residual AM and phase noise.

2-3 Implementation

Using the various principles mentioned in previous Sections, we now present an overview of the results obtained in the current study. The TWTA designed and implemented in this paper is an amplifier, which is called as ETWTA. It consists of RF module, TWT, PSU, and cooling module as Fig. 2. Table 1 illustrates its design specifications.

To select optimal RF part products that meet the design specifications and parameter values, we calculate the TWT flange output and TWTA rated power values through power budget for RF module including TWT. By using Table 2 and 3, we can get the result as Fig. 6. Then, ETWTA rated power is about 532 Watt.

Table 1. Main design specifications for ETWTA.

Item	Specifications
Frequency range	7.9∼8.4 GHz
Output power	TWT output flange power: >600 W (57.8 dBm) TWTA rated power: >57.3 dBm
Gain	At rated power: 60 dB Small signal gain: >65 dB
Intermodulation	<−19 dBc (4 dB back off) <−25 dBc (7 dB back off)
Harmonic distortion	<−60 dBc
AM to PM conversion	<−2.5 °/dB (6 dB back off)
Noise & spurious	<−65 dBW/4 kHz @ 7.25∼7.75 GHz <−65 dBW/4 kHz @ 7.9∼8.4 GHz
Group delay	Linear: 0.01 ns/MHz @ 50 MHZ Parabolic: 0.005 ns/MHz^2 @ 50 MHZ Ripple: 1 ns/peak to peak (p−p) @ 50 MHZ
Residual AM noise	<−50 dBc @∼10 kHz <−20(1.5+log f(kHz)) dBc @ 10∼500 kHz <−85 dBc @ 500 kHz∼
Phase noise	10 dB below Intelsat earth station standards(IESS) phase noise profile Sum of all spurious: <−47 dBc

Table 2. Specifications for components in RF module of ETWTA.

Item	Parameter	Specifications
Input isolator	Isolation	>20 dB
Variable attenuator	Attenuation variable range	>60 dB
SHF band linearizer	C/I ratio	>25 dB@ 3dB back off
		>30 dB@ 4dB back off
	AM/PM conversion	<2 °/dB
	Group delay	<1 ns/60 MHz
Drive amplifier	P1 dB	>14 dBm
	Small signal gain	>24 dB
TWT input isolator	Isolation	>20 dB
TWT output isolator	Isolation	>20 dB
Harmonic filter	Attenuation value	45 dB(@15.8~16.8 GHz)
Dual directional coupler	Directivity	≥20 dB

Table 3. TWT specifications using in ETWTA.

Item	Specifications
Output power	>600 Watt
Small signal gain	≥57 dB
Intermodulation	−25 dBc(@40 Watt)
Maximum harmonic output	≤−15 dBc
Spurious	<−60 dBc
Maximum AM to PM conversion	<2.5 °/dB@6 dB back off
Maximum noise output	−68 dBW/4 kHz (7.9~8.4 GHz)
Maximum group delay	Bandwidth: any 50 MHz Linear: 0.01 ns/MHz Parabolic: 0.005 ns/MHz^2 Ripple: 0.5 ns/p−p

PSU provides voltages to all parts in ETWTA. Table 4 is the electrical specifications for TWT operation. Then, we can generate the design specifications for PSU as Table 5. As is stated above, we design and implement the ETWTA that satisfies the design specification. Fig. 7(a) shows the appearance of ETWTA and Fig. 7(b) illustrates its inside. The major portion of phase noise for TWT is due to PSU, which affects seriously the RF signal quality of TWT. Because the ripple voltage and noise occurred by PSU affect electron beams and result in the phase noise for RF output signal of TWT. The cathode ripple voltage induces the worst case. To solve the problem for cathode ripple voltage of TWT, this paper makes the cathode ripple reduction filter at the output of high voltage module, which is depicted in Fig. 4 and 5.

Table 4. Electrical specifications for TWT operation.

Item		Voltage	Current
Heater		−6 Vdc	1.25 A
Helix	W/RF	Ground	3 mA
	W/O RF	Ground	0.5 mA
FE ON		−6 Vdc	0.01 mA
FE OFF		−1,600 Vdc	0.01 mA
Cathode(V_c)		−10.95 kV	338 mA
Collector W/ RF	# 1	6.132 kV	42 mA
	# 2	4.380 kV	293 mA

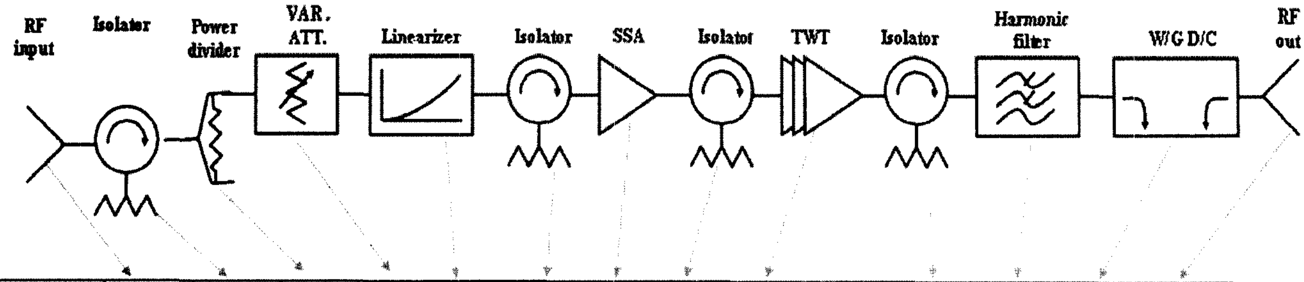
Table 5. Design specifications of PSU.

Item		Minimum voltage	Maximum voltage	Ripple (peak-peak)	Maximum current
Heater		−5.8 Vdc	−6.5 Vdc	50 mV	2 A
Helix	W/ RF	Ground			10 mA
	W/O RF	Ground			10 mA
FE ON		−5 Vdc	−10 Vdc		1 mA
FE OFF		−500 Vdc	−2,000 Vdc		0.2 mA
Cathode(V_c)		−10.5 kV	−11.1 kV	150 mV	340 mA
Collector W/RF	# 1	61 %×V_c±2 %		10 V	125 mA
	# 2	40 %×V_c±2 %		5 V	340 mA

To remove the cathode ripple of switching frequency (77 kHz), we design a low pass filter and produce optimum R-L-C values using equation (3) as Table 6.

Then, we select C value of 5 nF. The simulated H values(based on the selected values R=10 Ω, L=3 mH, and C=5 nF) are listed in Table 7.

According to the Table 7, the improved ripple value is −8 dB; we assumed it is −9 dB as we calculat R-L-C values.



							SHF_EIRP_BUDGET							
Input	Connector	Isolator	Power divider	VAR. ATT.	Linearizer	Isolator	SSA	Isolator	TWT output (dBm)	RF gasket	Isolator	Harmonic Filter(dB)	Directional coupler(dB)	TWTA output (dBm)
GAIN(dB)	-0.20	-0.40	-4.25	-3.00	0.00	-0.40	24.00	-0.40	57.00	0.00	-0.20	-0.12	-0.20	
OP1dB(dBm)					-16.00		14.00		57.782					
VSWR	1.10	1.25	1.35	1.80	1.35	1.25	1.25	1.25	2.00		1.15	1.10	1.05	
-50	-50.00	-50.20	-50.60	-54.85	-57.85	-57.85	-58.25	-34.25	-34.65	22.35	22.35	22.15	22.03	21.83
-30	-30.00	-30.20	-30.60	-34.85	-37.85	-37.85	-38.25	-14.25	-14.65	42.35	42.35	42.15	42.03	41.83
-10	-10.00	-10.20	-10.60	-14.85	-17.85	-17.85	-18.25	5.75	5.35	57.78	57.78	57.58	57.46	57.26
-5	-5.00	-5.20	-5.60	-9.85	-12.85	-12.85	-13.25	10.75	10.35	57.78	57.78	57.58	57.46	57.26

Fig. 6. Power budget for RF module including TWT of ETWTA.

2-4 Test and Evaluation

We now present and discuss an overview of the test results for the ETWTA implemented in Section 2-3. Fig. 8 is the waveform of cathode output with no filter at high voltage module. Measuring the ripple voltage, we use 20 V/division at high voltage probe of 1000:1. Its value is 17.6 Vp-p and then it should be removed to the negligible value consequently.

Table 6. Derivation of R-L-C values.

Item	Values	Remark
R	10 Ω	Fixed
L	3 mH	Fixed
ω	483805.27	$\omega=2\pi f$; f=77,000 Hz
H	0.3548	$H=10^{(V_R/20)}$; V_R=ripple improvement value=−9 dB
C	5.44 nF	

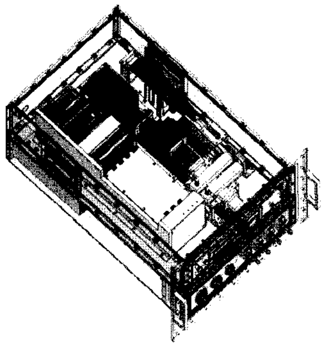
Fig. 9 shows the frequency spectrum of cathode ripple voltage. There is no component at switching frequency (77 kHz), 8 dBm at 96.9 kHz, and around −10 dBm at other harmonic frequencies. In high frequency, there are a few harmonics at 9 MHz and 11 MHz. But their magnitudes are around −8 dBm. So, they are too small to measure the residual AM at RF test. Namely, the harmonics at 96.9 kHz is induced by linking heater power & transmission control module and high voltage module and is found out to be a switching frequency of FE voltage. Its residual AM noise is −93.16 dBm at 96.6 kHz.

Fig. 10~12 are final RF test results in the case of using cathode ripple reduction filter. They satisfy the specifications for the residual AM, phase noise, and rated power at all frequency bands.

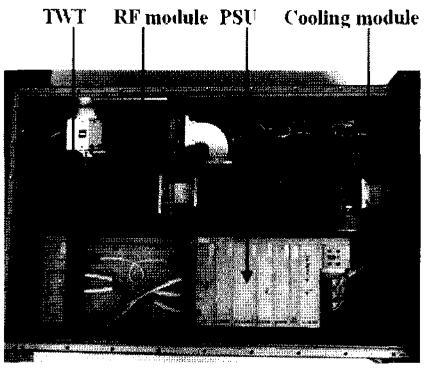
Also, the unexpected noise, which is illustrated in Fig. 13, is occurred at intervals of approximately 100 kHz between 500 kHz and 2 MHz. It is analyzed to be in-

Table 7. The H values for R=10 Ω, L=3 mH, and C=5 nF.

f(Hz)	ω	$\lvert V_{out}\rvert$	$\lvert V_{in}\rvert$	H	H(dB)
1,000	6283.18531	0.99999995	0.99940777	1.00059253	0.01
3,000	18849.5559	0.99999956	0.99466997	1.00535815	0.05
10,000	62831.8531	0.99999507	0.94077713	1.06294577	0.53
30,000	188495.559	0.99995559	0.46694626	2.14147896	6.61
77,000	**483805.269**	**0.99970737**	**2.51089655**	**0.39814758**	**−8.00**
100,000	628318.531	0.9995064	4.92166237	0.20308309	−13.85
300,000	1884955.59	0.99554877	52.2957788	0.01903689	−34.41



(a) Appearance



(b) Inside photograph

Fig. 7. ETWTA.

duced by the ripple voltage of auxiliary power sources supplied to RF module. Fig. 14(a) is the ripple voltage for a typical power source of +15 V among auxiliary power sources supplied from PSU to RF module. Its value is 200 mVp-p. Shown in Fig. 14(b) is a result of making it smooth by using electrolytic condenser of 470 uF. Namely, this technique can remove the unexpected noise and improve the RF characteristics. The residual AM noise after improvement is as Fig. 10. In Fig. 14, the upper waveform is the enlarged one of the lower. The scale of the upper one is 0.2 dB/division and that of the lower one is 20 V/division[7].

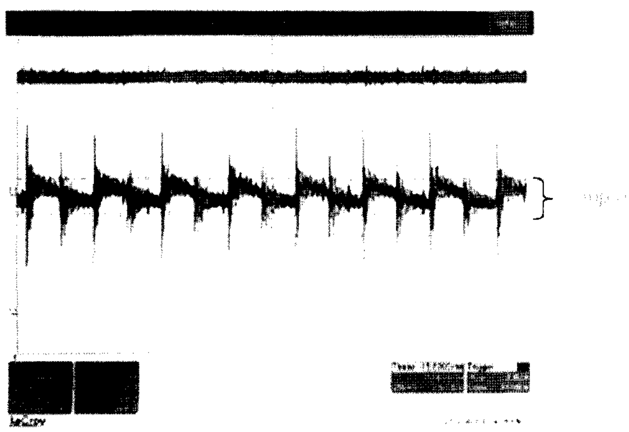


Fig. 8. Cathode ripple waveform in case of no filter.

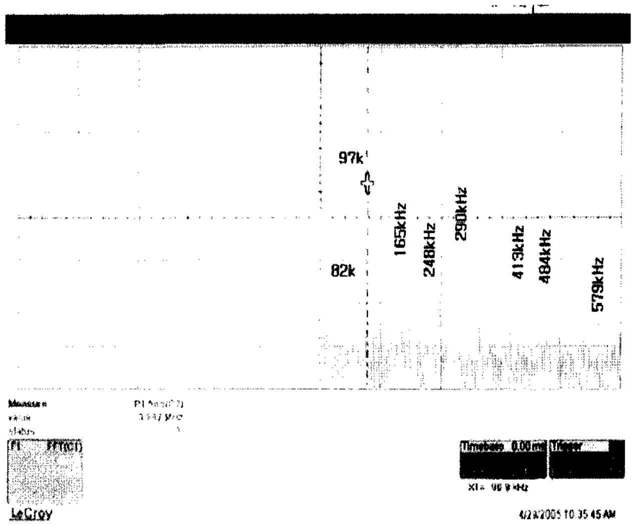


Fig. 9. FFT spectrum of cathode ripple voltage.

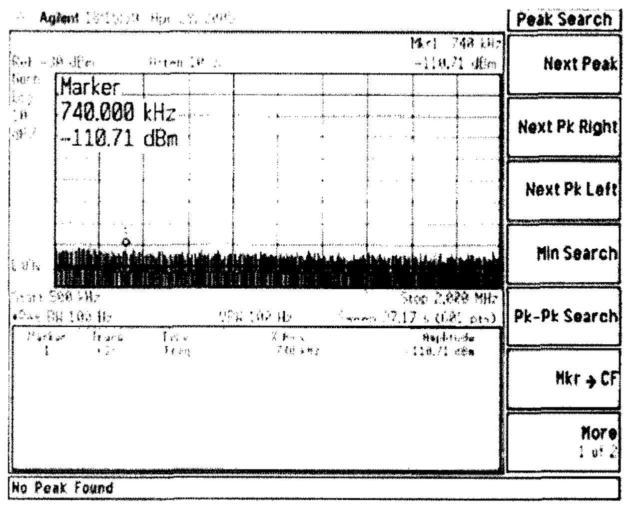


Fig. 10. Residual AM noise(500 kHz~2 MHz).

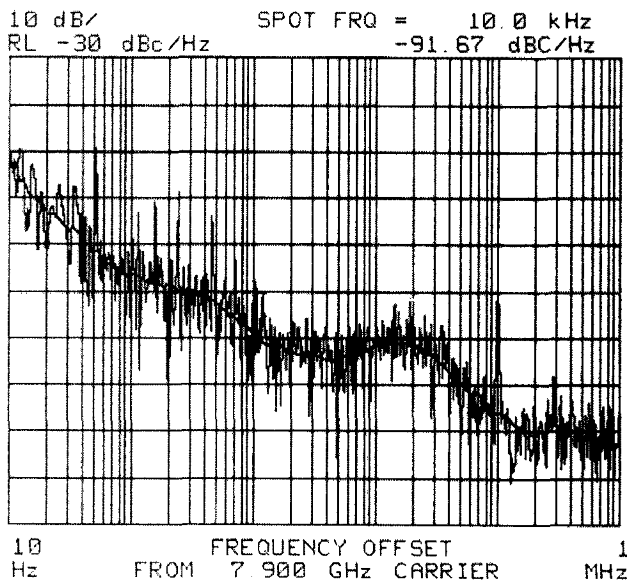


Fig. 11. Phase noise.

Table 8. The performance comparison of ETWTA and another TWTAs.

Item	ETWTA	TWTA1	TWTA2
Frequency range(GHz)	7.9~8.4	7.9~8.4	7.9~8.4
Output power(dBm) -TWT output flange power -TWTA rated power	 57.8(600 W) 57.33(540 W)	 57.4(550 W) 57(500 W)	 55.44(350 W)
Gain(dB) -At rated power -Small signal gain	 65.9 68	 70 75	 65
Intermodulation(dB)(with linearizer) -4 dB back off at output power -7 dB back off at output power	 −27 −30	−26(without linearizer)	−24
Harmonic distortion(dBc)	−78	−60	Harmonic filter dependent
AM to PM conversion(°/dBmax) -At rated power -6 dB back off at rated power	2.1	2.5	6.0
Noise & spurious(dBW/4 kHz) -Receive band -Transmit band	 −77 −72	 −65 −65	 −65 −65
Group delay -Linear(ns/MHz) -Parabolic(ns/MHz^2) -Ripple(ns p−p)	 0.01@50 MHz 0.0008@50 MHz 0.646@50 MHz	 0.01@40 MHz 0.005@40 MHz 0.5@40 MHz	 0.05@40 MHz 0.01@40 MHz 0.5@40 MHz
Residual AM noise(dBc)	−59@~10 kHz −20(1.5+logf)@ 10~500 kHz −98@500 kHz~	−50@~10 kHz −20(1.5+logf)@10~500 kHz −85@500 kHz~	−50@~10 kHz −20(1.15+logf)@10~500 kHz −80@500 kHz~
Phase noise (dBc) -AC fundamental -Sum of all except AC fundamental	−49	−36 −42	IESS-308 profile

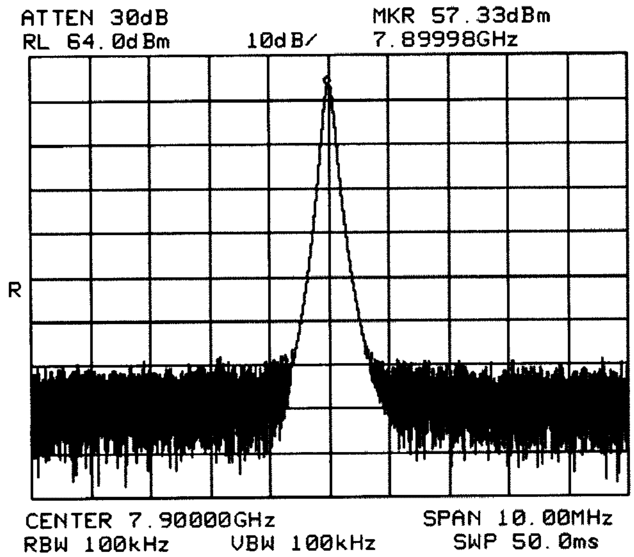


Fig. 12. Rated power.

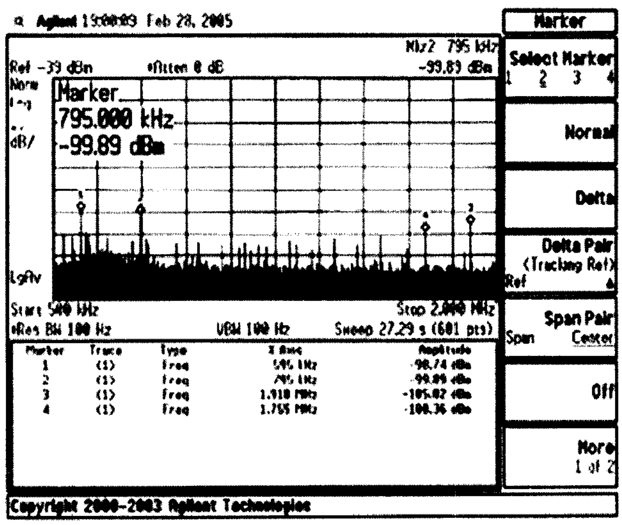
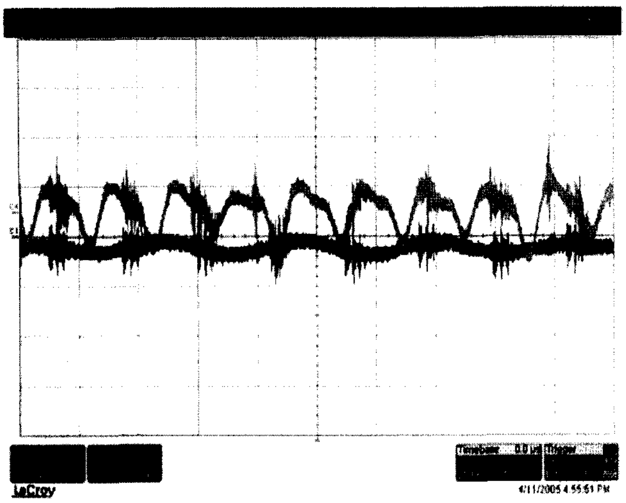
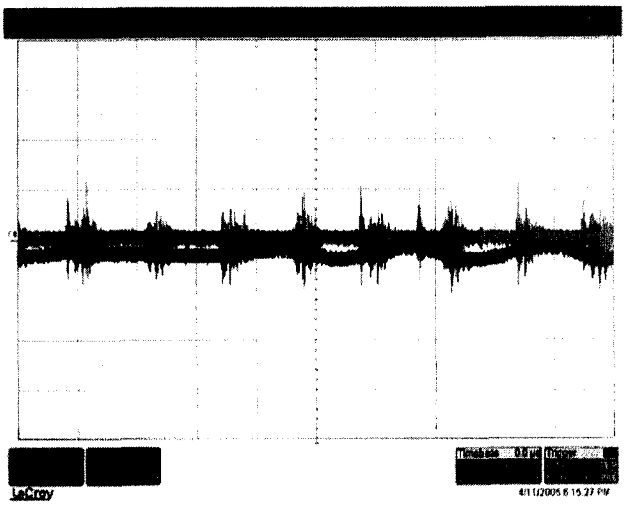


Fig. 13. Residual AM noise in case of no filter(500 kHz ~2 MHz).



(a) Before improvement



(b) After improvement

Fig. 14. Ripple voltage noise for +15V.

Through the experiment, it is found out that the cases using no filter and R-C filter do not satisfy the specification of residual AM noise but do the case using cathode ripple reduction filter. Also, as shown in Table 8, the RF performance of ETWTA is better than that of two existing TWTAs made by another company: 3~7 dB in phase noise, about 9 dB in residual AM noise.

Ⅲ. Conclusion

This paper proposes the developing procedure for TWTA. Using it, we develop a 600 W SHF TWTA called ETWTA, which has a full-wave bridge rectifier circuit in high voltage module and a cathode ripple reduction filter at cathode output to improve the RF characteristics such as phase noise and residual AM induced by ripple voltage effect. Through the test, it is proved that ETWTA satisfies the specifications for phase noise, rated power, and residual AM, which are main RF parameters. Also, the unexpected noise is removed by reducing the noise of auxiliary power sources supplied to RF module. It is very difficult to develop the 600 W SHF TWTA that satisfies the IESS specifications, because it is very hard to remove the harmonics and unexpected noise at high voltage, even though theories about TWTA characteristics are well known by publishing materials. So, this paper focuses on its design and test results instead of theory.

Through the test and analysis, it is found out that the RF performance of ETWTA is better than that of some other TWTAs: 3~7 dB in phase noise, about 9 dB in residual AM. Therefore, test proves this cathode ripple reduction technique to be useful and effective. Thus, this approach can be applied to developing similar equipments.

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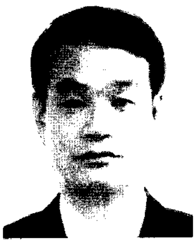

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