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MICROWAVE POWER TUBES FOR SPACE APPLICATIONS

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MICROWAVE POWER TUBES FOR SPACE APPLICATIONS*

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The advent of the space age created and necessitated a number of applications and requirements for high power microwave amplifiers which are somewhat new or different from the conventional Earthbound approaches. Presently considered uses may be divided into the following four groups:

1. TWT's for deep space and interplanetary telemetry and data transfer.
2. Super high frequency (around 12 GHz) TWT's in the 100 to 700W range for TV broadcasting from synchronous orbit.
3. TWT's and/or klystrons in the 42 to 44 and 83 to 85 GHz frequency range at 100 to 200W CW power output for broadcasting from space of data, wide band video and high quality audio signals.
4. Amplitrons and klystrons at 5kW to hundreds of kW CW power level for transmission of solar power from synchronous orbit to Earth (SSPS).

A brief description of more important electrical and mechanical design features follows.

Deep Space TWT

The tubes to be discussed in this group are not high power amplifiers in the true meaning of the word. They are mentioned here due to their role in many history making missions: to the moon, the planets, and outside our solar system. A list is shown in figure 1.

Presently two different TWT's operating at frequencies of 2.295 GHz and 7.4 GHz midband, respectively, are planned for deep space missions, such as the Mars-Jupiter-Saturn project. The tubes are TWT's developed by Watkins-Johnson Co., at 25W and 22W CW, respectively. There is, in addition, a large number of space qualified tubes which had been flown on previous planatary missions at S-bands with power levels between 10W to 23W, CW. All these tubes have efficiencies in excess of 40 percent, augmented by a single stage depressed collector and were developed mainly by Hughes and Watkins-Johnson.

Super High Frequency Tubes for Broadcasting from Space

TWT's in this class are shown in figure 2 and are designed for multichannel broadcasting of television from space at frequencies around 12 GHz. Four different developments with more than 100W CW output power are known to this author: The CTS-TWT developed by NASA/Litton at 200W nominal power output and 85 GHz bandwidth. This tube is already in

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synchronous orbit and performs well at an overall efficiency above 50 percent.

It is important to note that the performance of the CTS TWT is degraded by a factor of about 0.9 when operated in vacuum and a baseplate temperature of 70^{o}C as compared to operation under atmospheric conditions and room temperatures.

A 120W TWT was developed by Hughes for the National Television of Japan. This tube has been space qualified and exhibits an efficiency of over 50 percent at a bandwidth of more than 100 MHz with PPM focusing.

High power TWT developments were also carried out in Germany by Siemens and Telefunken Companies. The Siemens A. G. is developing a 700 W nominal TWT which employs a slot mode version of the coupled cavity circuit with a velocity taper. This structure may be thought of as a coupled cavity line with a coupling hole so large azimuthally that only a narrow wall segment remains. This circuit has a larger bandwidth and lower impedance than typical coupled cavities. A multistage depressed collector made of carbon is intended for direct radiation and efficiency enhancement above 50 percent. The development status of this tube is not known to this author.

The AGE-Telefunken Company developed two versions of space power tubes to be space qualified during 1977. The first, a coupled cavity TWT of 450W is a light weight, 800MHz bandwidth TWT with a self radiating 5 stage depressed collector. The second is a 200 watt, helical TWT with a 3 stage self radiating collector and also 800MHz bandwidth. Both these tubes represent an improvement in the state of art of TWT's in space applications in terms of bandwidth and weight at high overall efficiency.

TWT's and Klystrons for 43 and 84GHz

Planned applications will require future development of TWT's and klystron amplifiers. The TWT (fig. 3) approach offers a coverage of the entire 2GHz allocated band with single 100 to 200W tubes, all PPM focused and augmented with multistage depressed collectors. Prototype developments are in progress at Hughes utilizing coupled cavity approaches. The voltages are: 17 and 25kV; electronic efficiencies 5 and 10 percent; $\gamma a = 1.5$ and 3.0 for the two frequency bands, respectively. Mild velocity tapers are planned in both cases.

The klystron (fig. 4) approach has only a 120MHz-1 dB bandwidth (which is sufficient for many applications) but it offers a much less expensive, smaller size (1 in.) and much more efficient solution than a TWT. Because unloaded Q's of only 1600 and 1000 (at 85GHz), respectively, can be expected, high circuit losses would be associated with conventional designs. If, however, the output cavity is overcoupled lower Q_L/Q_o, lower electronic efficiency, $\eta_e \approx 0.25$, but a higher circuit efficiency = $1 - Q_L/Q_o$, result. This fact is important because it leads to a higher overall efficiency with a depressed collector. Permanent magnet focusing is envisaged.

Amplitrons and Klystrons for Transmission of Power from Space (SSPS)

Limited feasibility studies of the concept for conversion of solar power in synchronous orbit into microwave power at 2.4GHz and transmission to Earth were carried out. These studies indicate that only amplitrons and klystrons achieve efficiencies in excess of 80 percent, which are necessary to be considered for potential applications in the SSPS.

We will review now the major features of the amplitron and klystron amplifiers. Figure 5 shows a summary of amplitron design parameters.

Raytheon arrived at an optimum amplitron design in which the output power level of 5 kW is determined by the upper limit of temperature on the vane tips, set for 350°C. Passive radiation cooling of the anode and cathode are proposed. A platinum cold cathode with a high secondary emission yield and very long life is employed. The DC voltage of 20 kV is selected to assure an easy cold cathode operation. Sa Co_5 magnets provide the magnetic field. An efficiency of 85 to 90 percent and a gain of 6 to 7 dB are expected. Since a 5 GW array requires 10^6 amplitrons, phase alignment is necessary which is to be accomplished by mechanically perturbing the magnetic field. Output filters may also be required for noise and harmonic reduction.

Figure 6 is a summary of potential advantages and disadvantages. It should be stressed that future developments may or may not change present evaluations. Figure 7 is a table of proposed klystron parameters.

Preliminary evaluation of a klystron amplifier for the SSPS concept at Varian and LeRC indicates that its overall efficiency with a depressed collector augmentation. can be as high as 80 to 85 percent, if the power output is kept higher than 50 kW. This is so because klystrons need a beam-focusing field. It turns out that a body wound solenoid provides the best solution. Narrow bandwidth requirements permits a low perveance design of 0.3 unperv. and a low cathode loading of 0.5 A/cm^2. An M-type Phillips cathode produces this density at temperatures of approximately 850°C. Actual emission tests predict a potential life of 20 to 40 years. However, extrapolations of that magnitude may not be valid.

A summary of potential advantages and disadvantages follow in figure 8. The advantages of a klystron are its high gain of 40dB or more, permitting phase control at drive levels of 1W; very low noise, higher power per tube and bake out in space with its own solenoid. The operating voltage of 30 kV, the tube size, the hot cathode and the requirement of a depressed collector to exceed 75 percent efficiency are some of its disadvantages.

High power communication tubes are presently being developed for frequencies up to 85GHz. Plans include applications of power amplifiers up to 300GHz. The expansion of the power and frequency domain never stops. This is the challenge for us, the tube people.

MISSION	YEAR	TUBE TYPE	P_o, W	F_c, GHz	MODEL	MFR	NO. OF FLIGHTS	
PIONEER 1-9	58-69	TWT	8	S	214-H	HAC	9	
10-11	72-73	TWT	9	S	274-10	WJ	2	
RANGER	62-65	TRIODE	3	L	ML-6771	MAC	6	
MARINER VENUS	62	TRIODE	3	L	ML-6771	MAC	1	
MARS	64	TWT	10	S	216-H	HAC	1	
		TRIODE	10	S	7H7C	SIEMENS	1	
VENUS	67	TWT	10	S	216-H	HAC	1	
		TRIODE	10	S	7H7C	SIEMENS	1	
V/M	69-73	TWT	20	S	242BH	HAC	4	
SURVEYOR	66-68	TWT	10	S	216-H	HAC	7	
LUNAR ORBITER	66-67	TWT	20	S	WJ-274	WJ	5	
APOLLO	65-70	TWT	5/20	S	394-H	HAC	14	
LEM		AMPLITRON	20	S	QKS-1300	RAY	?	
SATURN		TWT	23	S	WJ-274-1	WJ	7	
HELIOS	75	TWT	10/20	S	WJ-274-12	WJ	2	
SKYLAB	73-74	TWT	5/20	S	395-H	HAC	3	↑
VIKING	75	TWT	20	S	242-BH	HAC	1	
ERTS A & B	?	TWT	10/20	S	WJ-274	WJ	2	PAST
MJS-77	77	TWT	25	S	WJ-274	WJ	1	FUTURE
		TWT	22	X	WJ-3616	WJ	1	↓

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Figure 1. - Spacecraft transmitters for deep space missions.

COMPANY	TYPE	P_o/W	FREQUENCY, GHz	WT/kg	EFF, %	COLLECTOR STAGES	YEAR DEVELOPED	COOLING
LITTON/NASA	CC	200	12.04-12.12	12	>50	8	1974	RAD
HUGHES	CC	120	11.95-12.13	8	54	3	1976	RAD
AEG-TELEFUNKEN	CC	450	11.7-12.5	5	50	5	1977	RAD
AEG-TELEFUNKEN	HELIX	200	11.7-12.5	2.6	45	3	1977	RAD
SIEMENS	CC	500	11.7-12.5		52	5	1976	RAD

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Figure 2. - High power TWTs for broadcasting from space.

DESIGN NO.	1	2	3	4
CENTER FREQUENCY, GHz	42	42	85	42.25
OUTPUT POWER, W	100	200	200	100
BANDWIDTH, GHz	2	2	2	0.5
SATURATED GAIN, dB	44	47	47	44
DESIGN LIFE, yr	2	2	2	2
OTHER	SPACE QUALIFIABLE			
OPTIMUM BEAM VOLTAGE, kV	17	21	*25	15
APPROX BASIC EFF, %	14	15	5	16
APPROX OVERALL EFF, %	40	45	25	45

*MAX ALLOWABLE BY NASA.

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Figure 3. - Coupled cavity PPM focused TWTs at 42 and 85 GHz.

43 GHz KLYSTRON AMPLIFIER

V_0, kV	5
PERVEANCE, MICROPERV	0.6
1 dB BW, MHz	110
GAIN, dB	>30
γa, rad	1.5
Q_0	1600
R/Q	90
NO. OF CAVITIES	5
CIRCUIT LENGTH, cm	1.2
η_{el}	~0.25
$\eta_{CT} = 1 - Q_L/Q_0$	0.8
η_{ov}	>0.5 (ASSUMING $\eta_{col} \geq 0.7$)
FOCUSSING	PERMANENT MAGNET

85 GHz KLYSTRON AMPLIFIER

γ_a	~3.0
Q_0	1000
R/Q	60
η_d	0.10-0.2
η_{ov}	0.3-0.4

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Figure 4. - 43 and 85 GHz klystron amplifiers.

FREQUENCY, MHz	2450
DC VOLTAGE, kV	20
DC CURRENT, mA	287
RF POWER ADDED, W	5000
EFFICIENCY, %	85-90
GAIN, dB	7
INTERNAL LOSSES, W	750
MAGNETIC FIELD, G	2940
NO. OF VANES	17
COOLING	CATHODE RADIATOR ANODE RADIATOR

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Figure 5. - Proposed high efficiency crossed-field amplifier for satellite solar power station.

ADVANTAGES

1. HIGH EFFICIENCY (85-90%)
2. COLD METAL CATHODE
3. USE OF PERMANENT MAGNETS
4. LOW VOLTAGE (COMPATIBLE WITH PRESENT SPACE-BORNE POWER CONDITIONING TECHNOLOGY)
5. PASSIVE COOLING (HIGH EFFICIENCY ENABLES COOLING BY CONDUCTION & RADIATION)
6. LONG LIFE (MAJOR CAUSE OF TUBE FAILURE IS CATHODE HEATER)
7. LIGHT WEIGHT (ANTICIPATED DESIGN FOR SSPS IS 3.56 lb/TUBE)
8. SIMPLICITY OF DESIGN

DISADVANTAGES

1. NOISE (FILTERS PROBABLY NECESSARY)
2. HIGH RF DRIVE REQUIRED (LOW GAIN)
3. MECHANICAL PHASE & AMPLITUDE CONTROL REQUIRED
4. PROXIMITY OF PERMANENT MAGNETS TO REGIONS OF HIGH TEMP (300-350° C) (ADVERSE EFFECT ON SmCo MAGNET LIFE)
5. SMALL POWER/TUBE/LARGE NO. OF TUBES IN SYSTEM

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Figure 6. - High-efficiency crossed-field amplifier for satellite solar power station.

FREQUENCY, MHz	2450
BANDWIDTH (3 dB), MHz	3
BEAM VOLTAGE, kV	34-40
BEAM CURRENT, A	1.8-2.4
BEAM PERVEANCE, μP	0.3
POWER OUTPUT, kW	48-77
BEAM EFFICIENCY, %	75-80
OVERALL EFFICIENCY[1], %	84-86
SATURATED GAIN, dB	40-50
AM NOISE[2], dB	-130
PM NOISE[2], db	-115
HEATER POWER, W	40
ELECTROMAGNET POWER, kW	-1
COOLING	RADIATION

[1] INCLUDES HEATER & ELECTROMAGNET POWER & REQUIRES DEPRESSED COLLECTOR.

[2] MEASURED IN 1 kHz BANDWIDTH 50 kHz FROM CARRIER.

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Figure 7. - Proposed high efficiency klystron CW amplifier operating characteristics.

ADVANTAGES
1. HIGH GAIN AMPLIFIER
    A. LOW RF DRIVE
    B. PHASE CONTROL AT LOW RF LEVEL
2. HIGH POWER OUTPUT
3. HIGH EFFICIENCY (OPTIMUM IN NARROW BANDWIDTH KLYSTRON)
4. LOW NOISE OUTPUT (AMPLIFIED SHOT NOISE)
5. HARMONICS OVER 30 dB DOWN
6. LONG LIFE
7. BAKEABLE SOLENOID (TUBE BAKEOUT WITH SOLENOID POWER)
8. SMALL EFFICIENCY CHANGE WITH TEMP
9. CONTROL & PROTECTIVE ELECTRODES

DISADVANTAGES
1. REQUIRES SOLENOID & HEATER POWER
2. REQUIRES PHASE CONTROL (MULTIPLE TUBE USE)
3. MAY REQUIRE TUNER TRIMMING CONTROL
4. HIGH BEAM VOLTAGE
5. REQUIRES DEPRESSED COLLECTOR FOR HIGHEST EFFICIENCY
6. EFFICIENCY SOMEWHAT LOWER THAN CROSSED-FIELD DEVICES

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Figure 8. - High-efficiency klystron CW amplifier for space applications.