# KU-BAND IMPATT AMPLIFIERS AND POWER COMBINERS

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## ABSTRACT

The feasibility of combining high-power, high-efficiency Ku-band IMPATT amplifiers in broadband hybrid-type combiners and the systematic design of the individual amplifiers are discussed. Experimental data are presented on uniformity of output power and phase tracking of the individual amplifiers and on overall combiner performance.

## Introduction

This paper presents results of a systematic study of broadband combining of high-power, high-efficiency GaAs IMPATT diode amplifiers. Objectives were to determine practical limitations and highest powers and efficiencies achievable at Ku-band and higher frequencies. Power levels of 10 to 30 watt cw were immediate goals. Waveguide combiner configurations were employed in these studies to obtain lowest dissipation losses. Experiments were performed with a two-amplifier magic-tee combiner and with a new eight-amplifier conical-waveguide combiner. The waveguide hat-circuit amplifier circuits investigated provide highest possible added power and efficiency which can be equal to that of an optimized high-power, high-efficiency reference oscillator. Amplifiers with broad 1 dB bandwidths were also investigated. Results indicate that diode uniformity, combiner VSWR and isolation are the principal factors limiting combiner performance. It is concluded that combiner characteristics can be controlled sufficiently, leaving diode uniformity as the ultimate limitation on combining efficiency. Our results also show that power degradation rate depends critically on the reflection phase difference between an active and failed amplifier.

## Amplifiers With Optimized Power And Efficiency

High-power, high-efficiency amplifiers can be derived directly from an oscillator by adjustment of only the fundamental-frequency impedance at the output port, provided harmonic output power levels are small, as must be the case in a well-designed oscillator. Under these conditions, a tuner at output port affects primarily fundamental impedance with little effect on harmonic impedances at the diode chip. Therefore, a high-power, high-efficiency oscillator can be transformed to an amplifier having added power and power-added efficiency equal to the output power and efficiency of the reference free-running oscillator. The oscillator and amplifier can then be said to be in same "oscillation state" i.e., equal dc voltage and current and identical harmonic impedances and diode waveforms.

Experiments were performed to demonstrate this principle using high-CW-power Ku-band waveguide hat-circuit oscillators[1] (2.2 watts, 18-percent efficiency).* In an initial experiment using crude 0-80 tuning screws close to the diode, output power of 2.75 watts was obtained, with added power of 1.75 watts and power added efficiency of 14 percent. Different gain and bandwidth values could be obtained by changing input power and fundamental impedance loading.

Having demonstrated the principle in above experiment, amplifiers employing no tuning screws were obtained by adjustment of hat diameter and back short position only from optimum free-running oscillator condition. An output power of 3.78 watts was obtained at 14.7 GHz representing added power of 2.26 watts and efficiency of 18.27 percent. This actually exceeds the recorded oscillator performance, and represents the highest power level reported to date for a Ku-band IMPATT amplifier. 1 dB bandwidths as high as 400 MHz with same gain have been obtained in later work.

When back short position and hat diameter are not the same for free-running oscillator and amplifier as in second experiment above, "oscillation states" as defined above are clearly not identical. However, the excellent amplifier results obtained indicate that small changes can be made in these "internal" parameters to accomplish optimum amplifier loading at the fundamental frequency without serious degradation of harmonic impedances presented to chip. Therefore, this appears to be a general method for obtaining a hat circuit amplifier with highly optimized output power and efficiency.

## Very Broadband Amplifiers

Broadband amplifiers were also developed systematically using the same principle of "identical states." In these experiments the packaged diode was placed in reduced-height waveguide (0.031" x 0.622"). Back short was set at an experimentally determined position to obtain a small initial gain $G_o$ at a frequency close to free running oscillator frequency. Initial gain $G_o$ was maximized by means of back short position, typical maximized values being ≈2 dB. With no additional tuning elements, input power was then increased until output power had a value equal to input power plus an added power corresponding to that of the desired oscillation state; that is, an added power equal to output power of the reference high-efficiency free-running oscillator. A standard Ku-band waveguide slotted line was employed directly in front of the amplifier (comprising the reduced height section with broadband multi-step transition to standard waveguide), to measure the complex admittance presented by the diode under high-power test conditions. These data were employed to determine additional tuning elements required to increase gain from initial value $G_o$ to desired value $G_a$ (e.g., 4 dB). Large bandwidths can result if the additional elements are placed close to the diode. Table 1 shows typical early results. Initial gain $G_o$ was 1.8 dB at 14.5 GHz with an input power of 3.096 watts, and the slotted-line data showed that a normalized capacitive susceptance of ~0.7 was required near the diode to obtain 3 dB gain. The resulting 1 dB bandwidth was 1.0 GHz.

*Raytheon MS-928-A and MS-50372 diodes were employed.

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TABLE 1

SUMMARY OF SYSTEMATIC BROADBAND AMPLIFIER EXPERIMENTS

| Tuning Condition | F (GHz) | $I_{dc}$ (ma) | $V_{dc}$ (volts) | Gain (dB) | $P_{in}$ (watts) | $P_{out}$ (watts) | Padded (watts) | Efficiency (percent) |
|---|---|---|---|---|---|---|---|---|
| Initial | 14.5 | 295 | 38 | 1.8 | 3.096 | 4.687 | 1.591 | 14.18 |
| First Design | 14.0 | 305 | 38.6 | 3.25 | 1.548 | 3.257 | 1.709 | 14.60 |
| Second Design | 14.5 | 290 | 37.9 | 3.5 | 1.375 | 3.080 | 1.705 | 15.51 |

## Amplifier Phase Tracking

Reflection coefficient (complex gain) was measured under high power test conditions to investigate the usefulness of these amplifiers for power combiner applications. Figure 1 shows measured data of positions of minima for a set of four diodes (employed singly) in one of the high-power, high-efficiency hat-circuit amplifiers. These data were obtained with a slotted line under high power conditions and used to calculate the phase of the complex reflection gain. The data points obtained at the center frequency of 14.6 GHz lie within a 0.1 mm band and track well over a broad frequency range. Random phase error are within $\pm 13°$. For these same amplifiers the output powers at 14.6 GHz were 3.56, 3.66, 3.68 and 3.61 watts for diodes 1, 3, 4 and 5 respectively representing gain values in the range $4.45 \pm 0.07$ dB. Power added efficiencies were $18 \pm 0.5$ percent. Under above conditions output power from an ideal hybrid-type combiner would be 13.74 watts compared to total power of 14.51 watts produced by all four amplifiers. Phase was relatively insensitive to

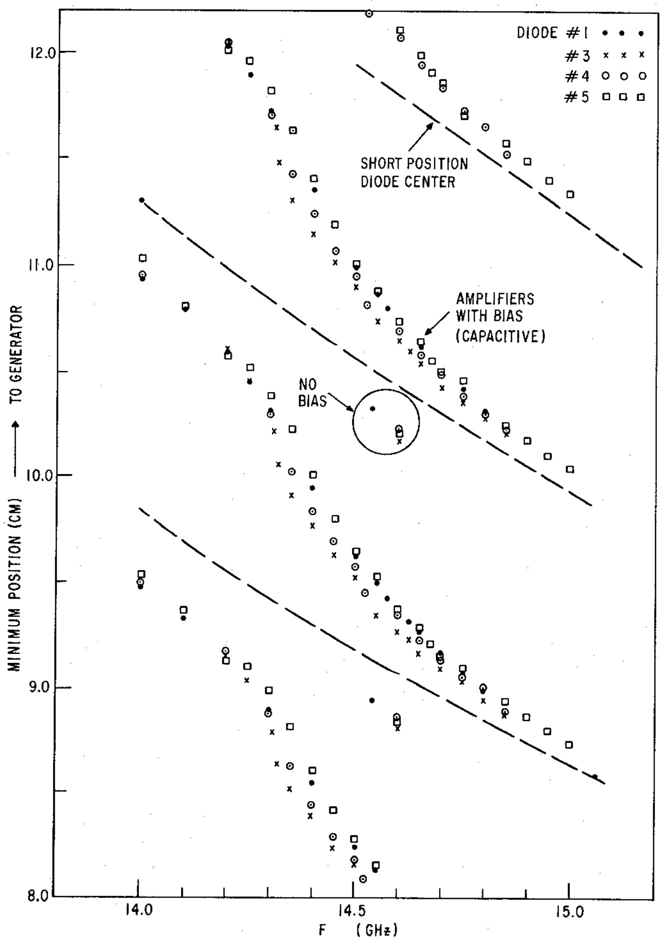


Figure 1 MEASURED POSITION OF MINIMA

dc bias and input microwave power. Data marked "no-bias" correspond to dc bias removed but with 1.3 watts input microwave power maintained. Our earlier results showed that no-bias condition closely simulates failed diode. Thus, reflection phase difference between active and failed diodes in power combiner would be 132°, indicating power degradation rate somewhat faster than square law.

## Single-Amplifier Load Sensitivity

A calibrated slide-screw tuner was placed in front of a high-power hat-circuit reflection amplifier and output power and reflection phase recorded as a function of tuner probe position. Only decreases in output power were observed relative to optimized power with no tuner. Minima of -0.25, -0.84 and 1.17 dB and phase deviations of 8.1°, 24.3° and 52° were obtained for tuner VSWR values of 1.07, 1.14 and 1.30 respectively. Adjustment of back short position would not always restore output power to maximum value. Furthermore, when back short was effective, power restoration was accompanied with significant phase deviation. These results indicate that VSWR values of 1.1 or less are required for the combiner.

## Optimized Magic-Tee Combiner

Two hat-circuit amplifiers were combined using a standard magic tee (Waveline Model 980). An 0-80 screw was placed close to the junction in H-plane to reduce H-port VSWR to less than 1.1 from 14.2 to 15.1 GHz. With shorts on side ports, round trip reflection loss in H-port was about 0.15 dB, indicating potential for high combining efficiency for two-amplifier combiner. The two individual amplifiers (denoted #1 and #2) had respectively, 14.66, 14.73 GHz center frequencies; 3.537, 3.417 W output powers; 5.56, 5.4 dB gains; 20.46, 19.53 percent efficiencies and 280, 260 GHz 1 dB bandwidths. Figure 2a shows the individual amplifier power and combined power. Reflection phases of the two amplifiers were made nearly equal (Figure 2b) by use of a 0.065" waveguide shim at output of amplifier #2. Note that combining efficiency at 14.66 GHz is 5.872/(3.537 + 3.42) or 84.4 percent.

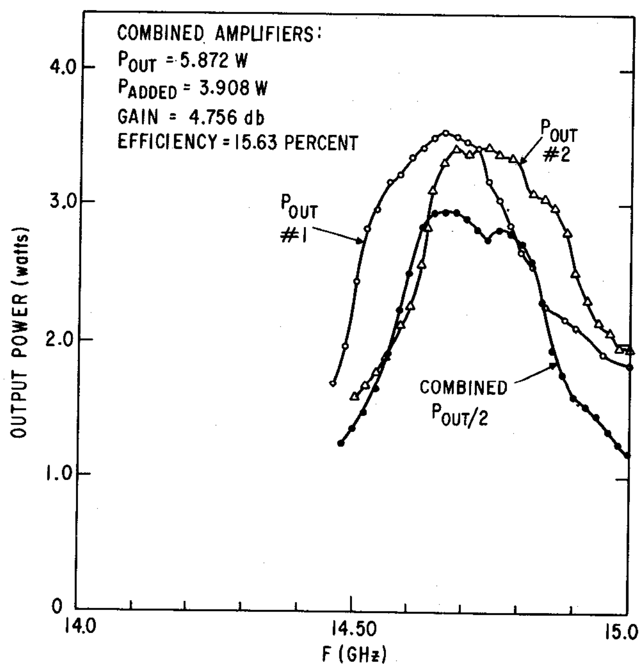


Figure 2a OUTPUT POWER CHARACTERISTICS FOR MAGIC-T COMBINER

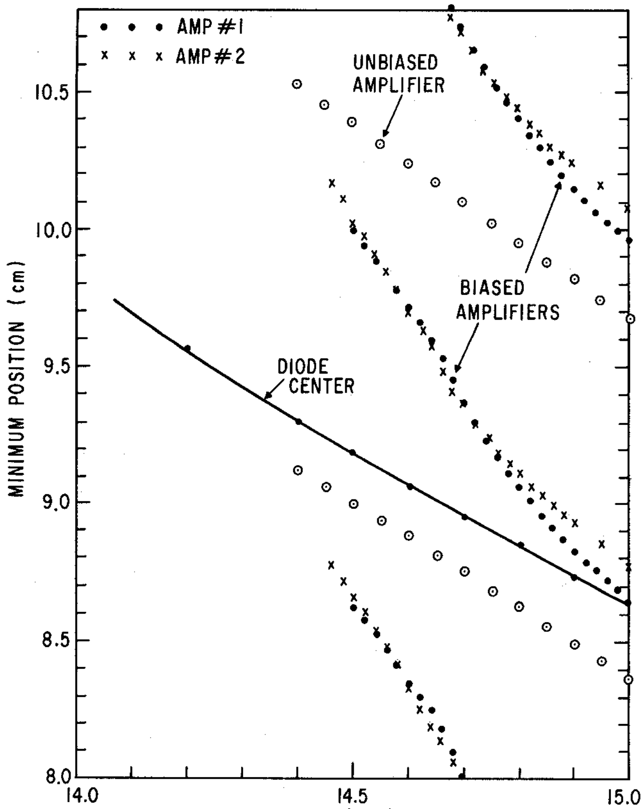


Figure 2b PHASE CHARACTERISTICS OF INDIVUAL AMPLIFIERS

## Conical Waveguide Combiners

One type of conical combiner is shown in Figure 3. The power from 8 full-height waveguide hat-circuit amplifiers are combined into a single coaxial line output port. The amplifier waveguides arranged in a circular array are machined in a flange connected to one end of a conical waveguide (pair of coaxial cones), having output coaxial line at the other end. An advantage of the conical waveguide configuration is the gradual transition to output port which allows sufficient length for radial slots for absorbing higher order combiner modes. Carefully designed radial slots partially filled with absorbing material are machined in outer cone. Waveguide spacing $S>\lambda/2$ is required to allow $\pi$-mode to propagate away from interface and be absorbed in slots. $S<\lambda$ is required to prevent grating waves. If the amplifier waveguide/conical waveguide interface has low VSWR for all combiner modes, a high degree of isolation results between individual amplifiers. Measured interface VSWR for desired mode with no additional matching is 1.35, and agrees well with a theoretical value of 1.30. Interface VSWR for the $\pi$-mode is inherently low, being well below that of desired mode. Desired mode VSWR was reduced below 1.1 with capacitive pins placed in front of interface along radials coinciding with common waveguide walls.* These pins have little effect on the $\pi$-mode. Measured round-trip reflection loss for desired mode at output port with a conducting-disc short circuit at interface was less than 0.25 dB with absorbing material in radial slots.

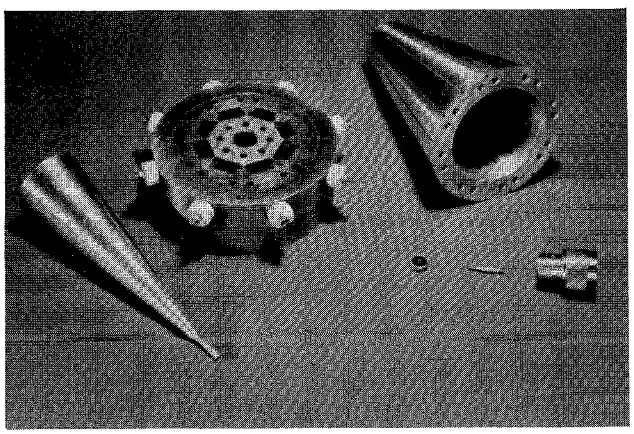

Figure 3. DISASSEMBLED VIEW OF CONICAL WAVEGUIDE COMBINER

Table II shows measured amplitude and reflection phase values for a set of eight amplifiers (in flange) measured with slotted line connected successively to each amplifier port. These tests termed "IN SITU" tests were performed prior to connection of flange to the combiner cones. Data in Table IIa show that all amplifiers were tuned for power greater than 3.2 watts with 1.3 watts input power. The first five amplifiers exhibited reflection phase values within $\pm 15°$ range. However, amplifiers 6, 7 and 8 exhibited large phase errors which could not be eliminated by changes in hat diameter or back short position. A Fourier analysis was employed to calculate power distribution among combiner modes from data in Table IIa. Results are shown in Table IIb. Total amplifier power was 28.204 watts, while power in desired mode m=0 was only 18.10 watts, the difference being principally a result of amplifier phase error. When the flange containing the eight amplifiers was connected to the combiner cones, measured combined output power was 17.9 watts at 14.6 GHz. 19.06 watts was obtained earlier with a different set of amplifier characteristics. The 17.9 watts measured is close to the 18.10 watts calculated, indicating phase errors are a principal problem. However, interface mismatch also may have contributed since these experiments were performed earlier with an interface VSWR of 1.35. This work is continuing.

TABLE II - FOURIER ANALYSIS OF INSITU TEST DATA

a) Measured Power and Phase

| Amplifier Position | Power (watts) | Reflection Phase (degrees) |
|---|---|---|
| 1 | 3.658 | 0 |
| 2 | 3.369 | +5.294 |
| 3 | 3.754 | -34.417 |
| 4 | 3.754 | -15.88 |
| 5 | 3.754 | -23.82 |
| 6 | 3.321 | +68.82 |
| 7 | 3.22148 | -71.47 |
| 8 | 3.3692 | -45 |

Total Power = 28.204 watts

b) Calculated Mode Power

| Combiner Mode Index, m | Power (watts) |
|---|---|
| 0 (Desired Mode) | 18.10236 |
| 1 | 1.24909 |
| 2 | 4.30158 |
| 3 | 0.86621 |
| 4 (Π-Mode) | 1.64410 |
| 5 | 0.94149 |
| 6 | 0.81884 |
| 7 | 0.28033 |

Total Power = 28.204 watts

The conical waveguide combiner can also have reduced cone spacing to accommodate reduced-height broadband waveguide amplifiers. Alternately, the waveguide walls can be eliminated and the diodes mounted directly in conical waveguide with radial slots extending between diodes. These configurations can also be employed at higher frequencies.

*Low-VSWR absorber strips placed along the sidewalls and used only during the interface reflection measurements can be seen in Figure 3.


1. I. S. Groves and D. E. Lewis, "Resonant cap structures for IMPATT diodes," Electronics Letters, 24 February 1972, pp. 98-99.



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