Miniature Klystron for CubeSats

Bernard Vancil
Jereme Shaver, Forrest Bishop
e beam, inc.
21070 SW Tile Flat Road
Beaverton, OR 97007 USA

Malcolm Caplan
Consultant
Fremont, CA 94536

Danilo Radovich
Consultant
Long Beach, CA 90807

Abstract: *We report results of a 3-year study to build a very small 35 GHz klystron for use in a cloud-imaging radar and deployed on a 1U (10 cm x 10 cm x 10 cm) CubeSat. Three klystrons and four beam testers were constructed. One device achieved 22 watts of saturated output power. DC beam transmission was 99 percent. The devices employed many innovative features, including glass rod fastening of gun, collectors, and circuit elements, a glass vacuum envelope for easy removal of heat by radiation, a novel permanent magnet focusing system and gun construction, a four-stage depressed collector of unprecedented compactness and simplicity, and a half-watt miniature scandate cathode. The paper describes the modeling tools used and compares their predictions to measured results.*

Keywords: klystron; linear beam amplifier; microwave tube; RF amplifier.

Introduction

CubeSat technology allows inexpensive access to space. Constellations of CubeSats flying in formation can be used for synthetic aperture radars for earth and cloud imaging [1]. CubeSats numbering in the thousands are now planned for earth-wide internet service [2]. Both radar and broadcasting will require amplifiers at 35 GHz, having substantial output power. Vacuum electron devices such as klystrons and traveling wave tubes are much more efficient than solid state power amplifiers. Moreover, they are about 35 times more efficient at radiating heat. A 32-watt klystron amplifier on a CubeSat will generate approximately 32 watts of heat, which it can easily radiate to space. A solid-state amplifier at just 7 watts output will also dissipate almost 32 watts, which it cannot easily radiate.

The challenge is whether VEDs can be built small enough to fit into a 1U CubeSat and be produced in volume at low cost. This project addressed these questions. Key to success is a construction technology validated on two previous projects [3][4]. It involves glass rod fastening of gun, collectors, and circuit elements, see Figure 1. This construction allows the utmost compactness because the gun and collectors are no longer separate modules but are integrated with the RF and focusing section. The collectors, in particular, are seamlessly integrated with the rest of the device. Collector parts are seen in Figure 2. The glass rodding technique allows automated production of the internal structure. The insertion into the glass envelope can also be automated in a carousel glass sealing system, such as is used in light bulb production.

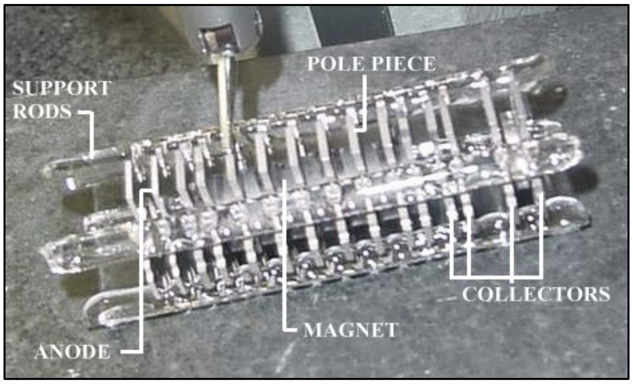

Figure 1. Glass rodded assembly with 4 cavities, magnets, pole pieces, and collectors

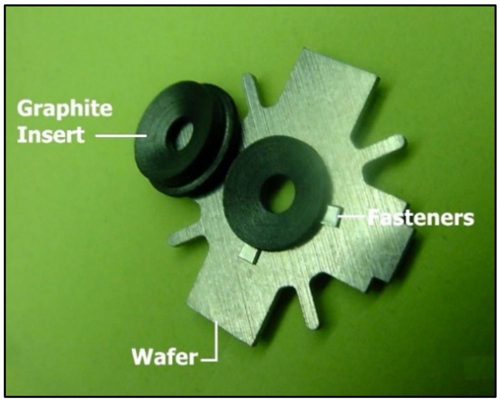

Figure 2. Collector graphite inserts and holding wafer

Construction

Magnet Stack. Annular, inexpensive off-the-shelf samarium cobalt magnets were used. These magnets were captured between iron pole piece wafers that were, in turn, held by glass rods. The pole pieces extended to within 0.025 inch of the beam tunnel axis. It was found that a half-thickness magnet was required at the beginning of the stack to nullify the magnetic field at the cathode.

RF Cavities. Cavities were three-piece, conventionally machined from copper, and brazed together. The beam tunnel was 0.020-inch diameter. The ferrule gap was 0.010 inch. The RF cavities were mechanically captured between the pole piece wafers along with the magnets.

Couplers, Windows, and Bellows. Off-the-shelf glass windows with 0.009-inch center pins were used. These were brazed to our couplers. The center pin was laser welded to the center wire of the coupler. The coupler center wire was made of copper-plated iron, flattened at one end and bent into a loop for magnetic coupling to the cavity. Coupling to the cavity was adjusted by moving the loop slightly into or out of the cavity.

Electron Gun and Cathode. The cathode was 0.050-inch planar scandia-doped tungsten emitting 3A/cm^2 at 830º C. A very small coil-on-coil ceramic-coated heater was slipped into a long heater enclosure laser welded to the cathode button. Thus, the heater required no potting. The cathode was held inside the focus electrode cup by mechanical capture. The focus electrode cup was held in place by metal spring clips. Consequently, every part in the focus electrode assembly was fastened either by mechanical capture or automated spot welds.

Four-Stage Collector. This consisted of graphite inserts machined to shapes that minimize beam reflections. These were captured in metal wafers, as seen in Figure 2. The wafers, in turn, are fastened to the glass rods. Glass rods give over three times as much voltage stand-off as ceramic.

Modeling and Data Comparisons

The Herrmannsfeldt EGUN modeling program was used for gun and e-beam simulations. PANDIRA was used to model the magnets and periodic focusing structure. TESLA, SUPERFISH, and AJ DISK were used for RF modeling and cavity design. A proprietary code was used to model and optimize the four-stage depressed collector. Figure 3 shows beam transmission to the collectors.

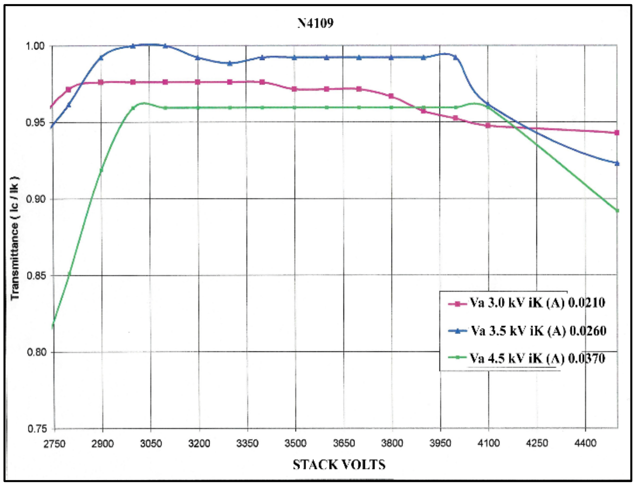

Figure 3. Beam transmission vs. stack voltage vs. beam current

Table 1 shows tube performance parameters, actual vs. predicted. We achieved 22 watts on one tube, but gain was only 22 dB vs. 31 predicted. Low gain can be explained as follows: Ohmic Q was close to the correct value in the output cavity, but it was low in cavities 1, 2, and 3. Consequently, there was poor beam bunching in those cavities. At this frequency, ohmic losses can easily account for 20-40% of total dissipation.

Table 1. Klystron Performance

BEAM VOLTAGE	4.25 kV
BEAM CURRENT	39 mA
BEAM POWER	165 watts
FREQUENCY	35.54 GHz
OUTPUT CAVITY OHMIC Q	1843 (max. theoretical: 1900)
POWER OUT (at saturation)	43 dBm (22 watts) (max. theoretical: 21.4 watts)
POWER IN (at saturation)	21 dBm
GAIN (at saturation)	22 dB (30.7 dB theoretical)
SMALL SIGNAL GAIN	28 dB (33.8 dB theoretical)
BANDWIDTH	40 MHz

Conclusions

High ohmic losses in the cavities degraded efficiency, power, and gain. This was seen in modeling and in actual devices. An extended interaction output cavity will reduce these losses. Also, the four-stage collector requires further optimization to recapture free energy left in the beam. The instability in coupler and tuner position will be solved by threading the couplers into a cavity coupling hole, moving the tuners inside the envelope, and using a remote adjustment technique. Stagger-tuning to increase bandwidth also lowered gain. The construction technology was validated. The project proves that a very small klystron can be produced in volume on automated equipment for less than $1,000. A miniature scandate cathode dramatically lowered electron gun size and dissipation. The natural advantage of VEDs in space, especially on CubeSats, has been confirmed. This project paves the way for miniature broad band devices of similar construction, such as TWTs and EIKs.

Acknowledgments

This work was funded by NASA Jet Propulsion Laboratory. Special thanks to Wayne Harvey at JPL.

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