Design and fabrication of an E-band TWT for high throughout satellite links

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INTRODUCTION

The unstoppable demand of wireless ubiquitous high data rate is fostering the integration of 5G terrestrial networks and new dense high throughput satellite (HTS) constellations.

5G, and future 6G networks, will rely on the millimeter wave and sub-THz spectrum to support the huge data traffic increase, by wide multi-gigahertz frequency bands [1] [2] able to support tens of gigabit per second data rate (Gb/s), with the target of 1 Tb/s.

Substantial effort is devoted to create a new global architecture where NTN (Non Terrestrial Network) and terrestrial network are intimately connected for efficient, flexible coverage, with relevant enhancements such as security, resilience, smaller antennas, capacity. ESA Satellite for 5G initiative (S45G) is specifically devoted to a seamless integration of 5G terrestrial networks and satellite constellations, also for Radio Access Networks (RAN) and backhaul.

New LEO (low Earth orbit) satellite constellations, such as Oneweb and Starlink have started to provide large scale commercial distribution of internet from space. Hundreds of satellites are deployed and more will be deployed to provide ubiquitous Earth coverage, impossible to achieve by terrestrial networks. To note that the new coverage from space is eliminating the wide regions without coverage. The advantage of new LEO satellite constellations in comparison to geostationary satellites or the first constellations, such as Iridium or Globstar, is low latency and high throughput.

Ku-band (10.7 – 12.5 GHz) and Ka-band (17.8 – 30.0 GHz) are mostly used for uplink and downlink. However, the about 6 GHz aggregated bandwidth from the two bands is already not sufficient to respond to the traffic demand [3].

E-band (71 – 76 GHz, 81 – 86 GHz) is attracting substantial interest for satellite applications with its two 5 GHz sub-bands to provide additional tens of gigabits per second (Gb/s) data rate [4].

Extensive investigation in the past was conducted for E-band links, both for LEO and GEO orbit. The link budget is heavily affected by the free-space path loss that is predominant in comparison to the rain attenuation in the atmosphere leg of the link. To note that rain attenuation at 73 GHz is about 16 dB/km against 8 dB/km at 30 GHz. The downlink, due to the payload limitations and power supply requirements, requires technology advancement to be enabled. E-band antennas have shorter diameter and reduced footprint in comparison to Ku-band or Ka-band antennas with the same gain. However, the EIRP (Equivalent Isotropically Radiation Power) needed to operate an E-band link, due to the low available transmission power from solid state power amplifiers, about 2 - 3 W (33 - 34 dBm), requires large high gain antennas [5]- [8].

Recent technology advancements are supporting the development of a new generation of Traveling Wave Tubes (TWTs) at millimeter waves that can provide tens of Watt output power suitable to enable high capacity links with unprecedented data rate [9] - [11]. TWTs are wide band, high power amplifiers typically used for space applications at microwaves. A TWT consists of an electron gun, a slow wave structure (SWS), a collector, a periodic permanent magnets (PPM) system and RF windows. The electron gun generates an electron beam with given current, voltage and beam profile. The beam travels along the SWS in ultra-vacuum, confined by the magnetic field.

This paper describes the design and fabrication of a new compact 71 - 76 GHz traveling wave tube (TWT) amplifiers for the E-band satellite links [12]. The TWT uses the double corrugated waveguide (DCW) as slow wave structures. The TWT has been designed to provide about 70 W output power saturated with two DCW sections separated by a sever. A first test low power version with one section DCW is in its final assembly phase.

E-BAND TRAVELING WAVE TUBES DESIGN

The first step for the design of the E-band TWT is the calculation of the dimensions of the double corrugated waveguide on the basis of the beam parameters. A 12.2 kV beam voltage was selected to use an affordable power supply.

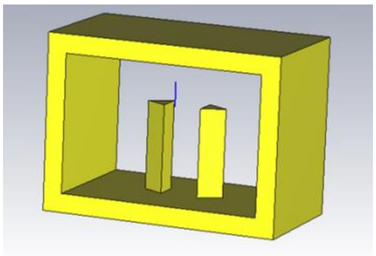
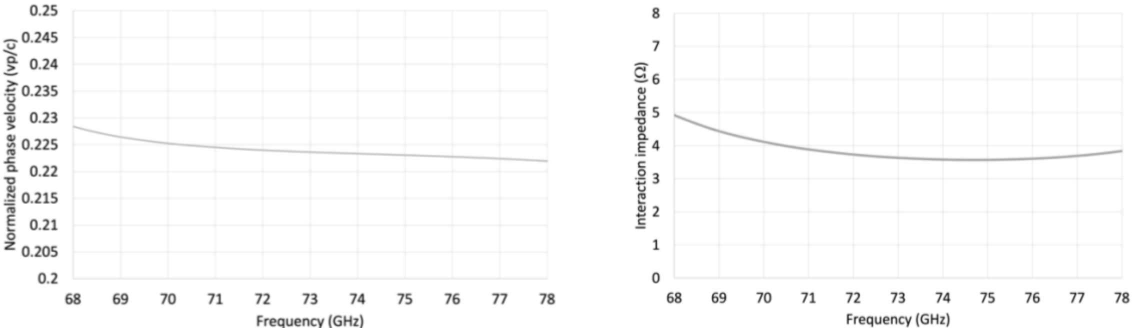


Figure 1 Triangular pillar double corrugated waveguide
(period 1.1 mm, pillar height 0.68 mm, pillar cross section 0.2 x 0.2 mm).

The DCW unit cell is shown in Figure 1. The triangular pillars ensure the higher interaction impedance among different pillar shapes.

The normalized phase velocity and the interaction impedance are shown in Figure 2a and 2b respectively. To note that the interaction impedance is better than 3.5 Ω over the full 71 – 76 GHz band.

The definition of the number of periods of the TWT sections to achieve about 70 W (48 dBm) and 35 dB gain was performed by an intensive campaign of Particle in Cell (PIC) simulations. A single section DCW, as first estimate, was simulated to achieve about 18 -20 dB gain. Then, the second section was added to rise the gain to 35 - 40 dB. After optimization, the required performance was achieved with a 30 periods first section and a 60 periods second section. The top view of the two sections DCW with sever and RF windows is shown in Fig. 3. Figure 4a show the simulated output power of the two sections TWT better than 48 dBm. As fabrication test, a single section TWT has been designed with one 45 periods DCW section identical to the two sections DCW. The gain is about 22 dB and the output power higher than 1.5 W (32 dBm) (Fig. 4b) with 10 mW input power. For this topology the sever is not used due to the low gain that prevent eventual oscillations.



a)

b)

Figure 2 Dispersion and interaction impedance

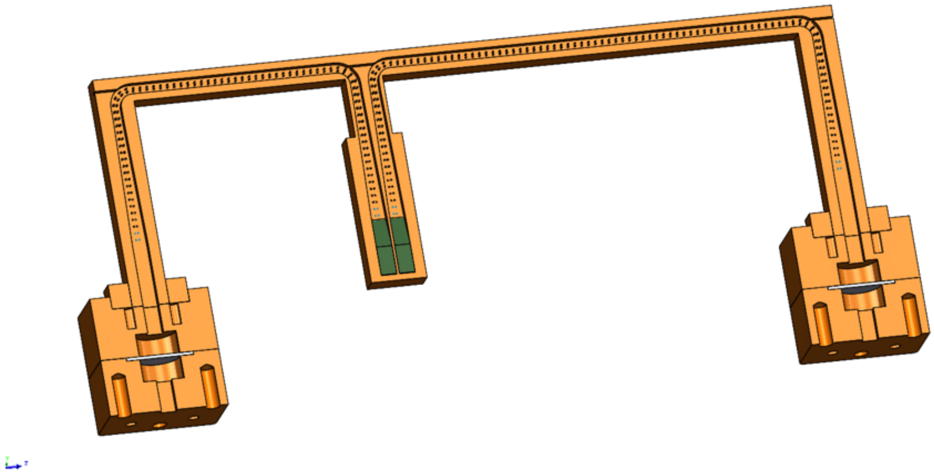
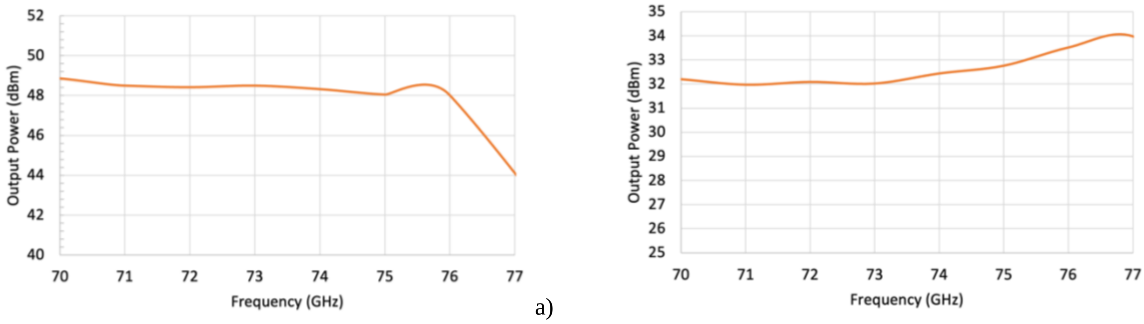


Figure 3 Schematic of the two sections TWT



a) b)

Figure 4 Output power E-band TWT a) two sections, b) one section.

E-BAND TRAVELING WAVE TUBES FABRICATION

All the parts of the single section E-band TWT have been fabricated, namely DCW circuit, electron gun and collector sub-assembly are completed.

Electron optics

The electron gun is a conventional Pierce gun with a very simple topology for low cost [23]. It has three high voltage feedthroughs for cathode, anode and beam focusing electrode (BFE). It has been designed to provide about 13 kV beam voltage and 90 mA current. The Permanent Periodic Magnet stack for beam confinement is mounted on a stainless steel pipe with iron pole pieces.

A single stage depressed collector is used for testing the single section TWT. A collector efficiency of about 50% is obtained. For the final two sections TWT will be considered two or three sections depressed collector with minimum 85% collector efficiency.

Double Corrugated Waveguide Interaction Circuit

The interaction circuit includes the DCW, the couplers, and the flanges to connect the electron gun, the collector and the RF windows. Millimeter wave SWSs, such as such as folded waveguides and DCWs, are usually made of metal, e.g. OFHC (Oxygen Free High Conductivity Copper), and usually fabricated in two split blocks by high accuracy CNC milling. The two split blocks then are bonded by diffusion bonding to make the structure vacuum tight. The resulting circuit is accurately machined to achieve the shape of a barrel to be enclosed in the PPM system. Due to the small dimensions, this process is very challenging and the quality of the diffusion bonding difficult to inspect. A not complete diffusion bonding makes the structure fragile with high risk of damage in the final CNC milling machining.

An innovative fabrication approach has been adopted to easily assess if the diffusion bonding is perfectly achieved prior to the final delicate machining phase. The blocks are designed with shape similar to the final DCW circuit. Figure 5 shows the four main fabrication steps. The DCW circuit is first etched in a copper block (Fig. 5a). Most of the copper around the etched DCW circuit is removed. A fixture with the exact shape of the of the DCW is produced (Fig. 5b). The DCW is inserted in the fixture and clamped where needed to remove the residual copper (Fig. 5c). Figure 5d shows the final structure after CNC milling. A flat lid with exactly the same perimeter of the DCW circuit in Fig. 5d is fabricated.

After polishing to improve the surface roughness and dimensional check with 3D Laser Microscope, the two parts are bonded by diffusion bonding. Diffusion bonding is a joining process for metal parts based on applying a high pressure at a temperature close to the melting point to permit the diffusion of atoms across the interface of the parts. The result is a structure without metallurgic discontinuities perfectly vacuum tight. This process requires a careful calibration of parameters to avoid deformation of the delicate copper structure due to excessive pressure.

After diffusion bonding and successful leakage test, the final machining is performed to produce the barrel.

Figure **6**a shows by the X-ray CT scan of portion of the DCW circuit, the excellent quality of the diffusion bonding. Figure 6b shows the barrel assembled by brazing with the flanges to connect the electron gun and the collector and the one block of the RF window. A second brazing step is performed to assemble the second block of the RF window with the Alumina sheet (500 micron thickness).

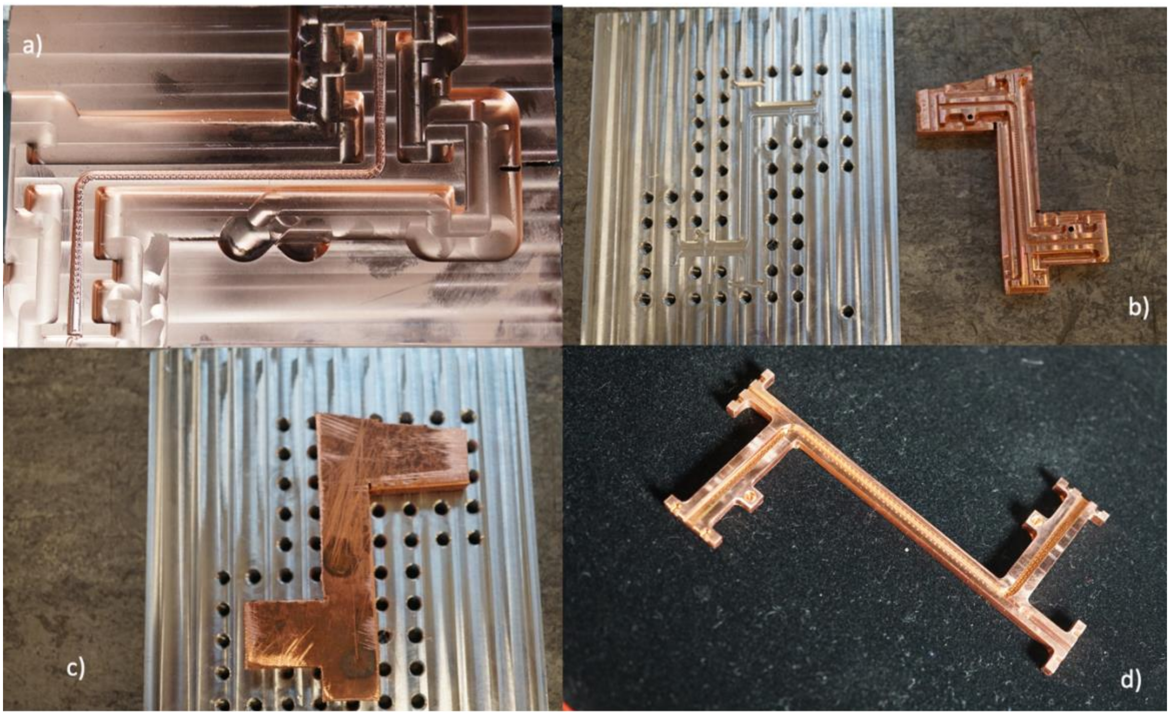
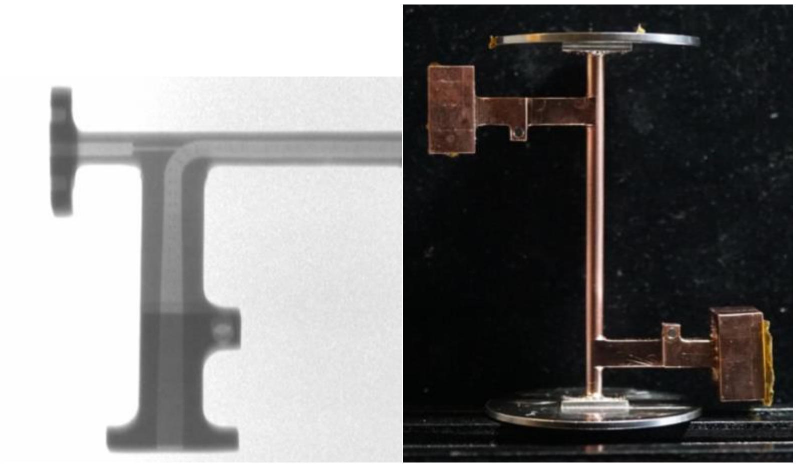


Figure 5 Four fabrication step of DCW block with waveguide and pillars by CNC machining: a) DCW machined, b) ficture and DCW with the copper block residual, c) DCW inserted in the ficture, d) final DCW block.



a) b)

Figure 6 Final DCW circuit a) X-ray CT scan of the bonded circuit, b) with brazed flanges and RF window blocks.

The full TWT is shown in Fig. 7. At the time of the image, the flanges at the collector and electron gun were not yet laser welded. The electron gun and the collector are built for testing purpose. A much more compact TWT can be produced with a proper optimization of shape and dimensions of the electron gun and collector.

CONCLUSIONS

The design and fabrication of the first European DCW TWT at E-band (71 – 76 GHz) with high gain and power for space applications and, more broadly for wireless long links, have been discussed. The TWT simple structure makes it compact and low cost. The processes developed for TWT fabrication are at the state of the art, but they do not require complex infrastructure. The fabrication of the DCW circuit requires good accuracy CNC milling and it is suitable for large scale fabrication. Diffusion bonding and brazing can be performed in large furnaces with substantial reduction of cost. Differently from helix TWTs, where the alignment of the helix especially in the millimeter wave frequency range is very

difficult, the DCW SWS is self-aligned, reducing substantially the assembly effort. The pole piece stack is also used for supporting the DCW copper structure and does not need to be vacuum tight making easier their fabrication.
The TWT will be assembled and measured. However, the progress so far achieved are already a substantial advancement in millimeter wave TWT technology for space applications.

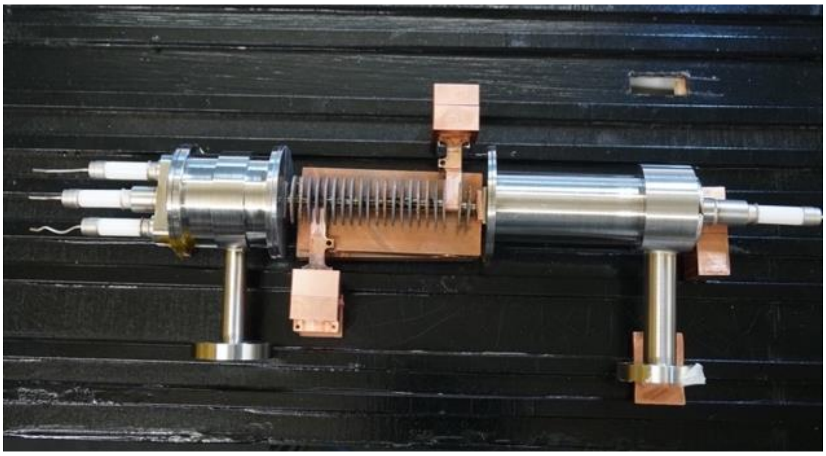


Figure 7 Single section E-band TWT partially assembled.

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