A Path to Space-Based Power Transmission Using Space Resources: Additive Manufacturing Demonstration of a Cavity Magnetron for Solar Power Satellites

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1. Introduction

The main challenges faced with the implementation of Solar Power Satellites (SPS) as a renewable energy option are the immense costs and size associated with manufacturing and transportation [1]. A potential solution to this issue would be to manufacture the SPS in space using lunar resources and additive manufacturing (AM) methods. While AM methods are viable for the structural components of the SPS, the challenge comes with using AM to manufacture the active components. In microwave SPS systems, solid-state power amplifiers (SSPAs) are considered the optimal transmission devices when coupled with antenna arrays [2]. This research focuses on a different method of microwave generation in the form of the magnetron. These devices are a more suitable option when attempting to be made using AM in space. This research provides a proof of concept for using AM to manufacture a cavity magnetron.

2. Background

The cavity magnetron is a vacuum tube that is composed of an anode and a cathode that are sandwiched between two external magnets as shown in Fig. 1. These magnets form a magnetic field with flux lines parallel to the cathode [3]. The anode is usually manufactured from a cylindrical copper block and has cavities and resonators machined into it [4]. The cathode is formed by a thoriated tungsten filament that is electrically heated to emit electrons [5]. When the electrons experience a Crossfield between a parallel electric field and a perpendicular magnetic field, they begin to spiral away from the cathode. The electrons interact with the anode cavities and oscillate at microwave frequencies [5].

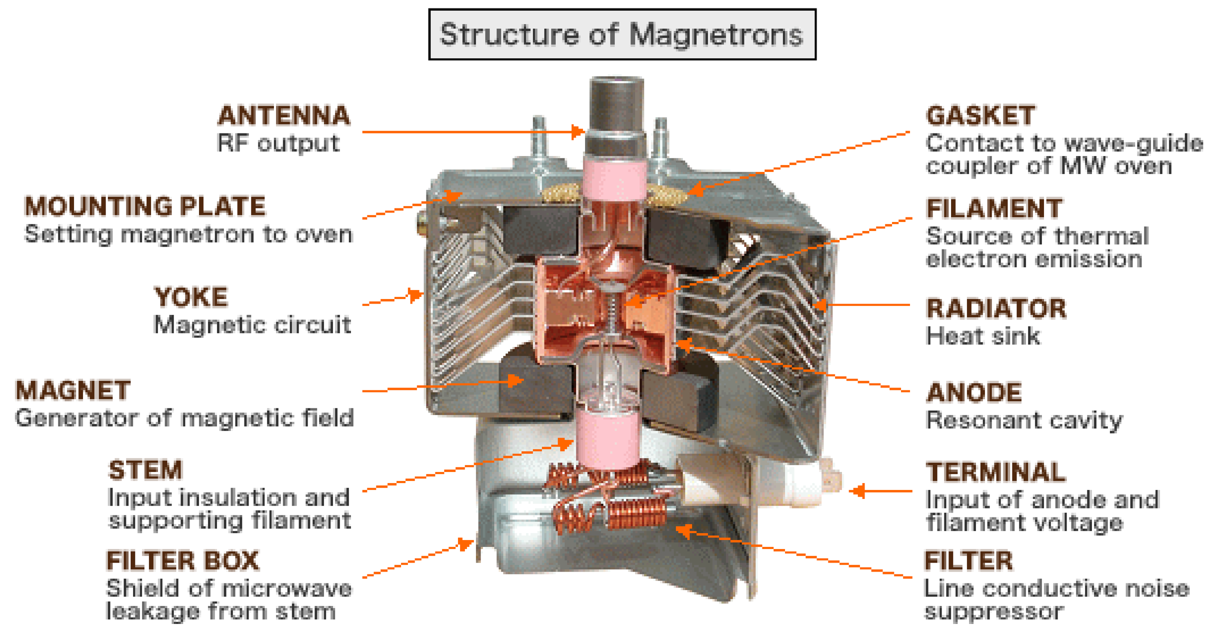


Fig. 1 Structure of a Commercial Magnetron [6]

3. Magnetron Lunar Resource Use

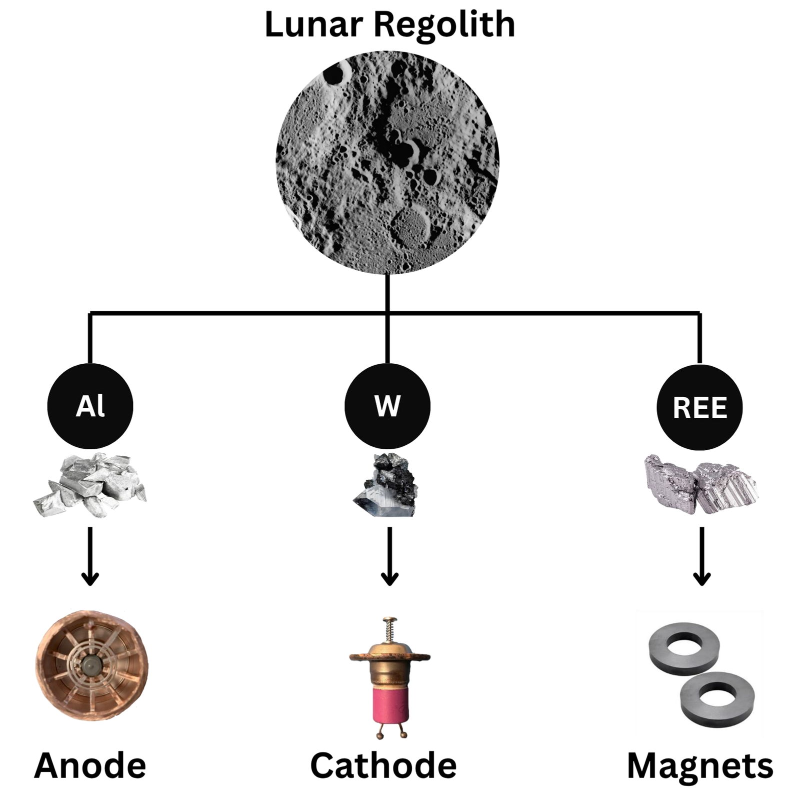


Fig. 2 Potential Extracted Elements for Magnetron Manufacturing Using Lunar Resources

4. Magnetron Design and Simulation

When designing the AM magnetron, a commercial magnetron from a microwave oven was dissected and used as a reference point. Using the dimensions of the commercial magnetron as a starting point, design calculations were used to determine the applied voltage and the applied magnetic field. These parameters were used to create a 3D model of the AM magnetron (see Fig. 3) which was then simulated in CST Studio Suite to verify the calculations and the dimensions.

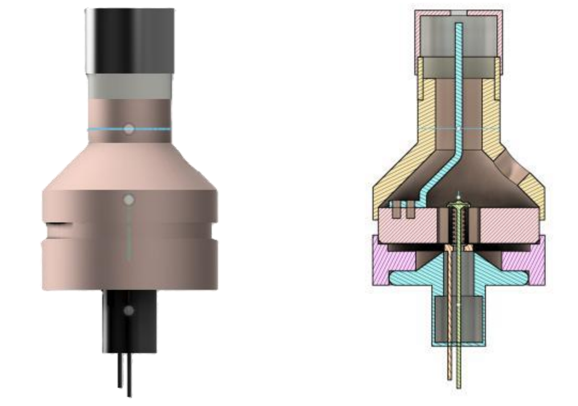
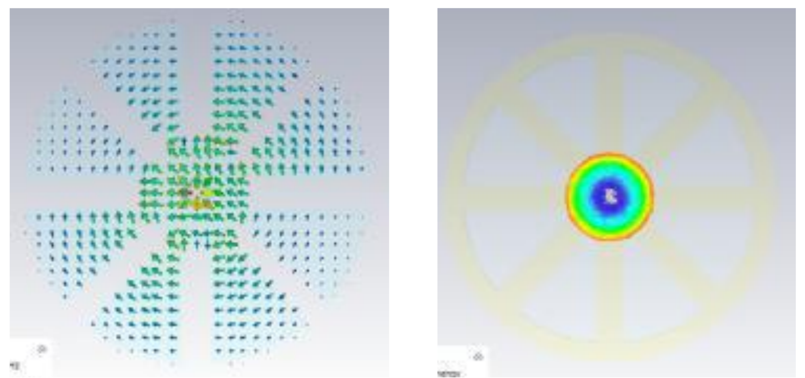


Fig. 3 3D Model of the AM Magnetron

Two types of simulations were performed: **Eigenmode Analysis** for mode verification and **Particle Tracking** to verify electron motion as seen in Fig. 4. An iterative process was used, and the magnetron model was adjusted until an appropriate response was identified. For the final model, the strapping rings were removed for easier printing and the number of vanes were reduced to 8.



(a) (b)

Fig. 4 Magnetron Simulation Results: (a) Eigenmode Analysis, (b) Particle Tracking

5. Additive Manufacturing Process

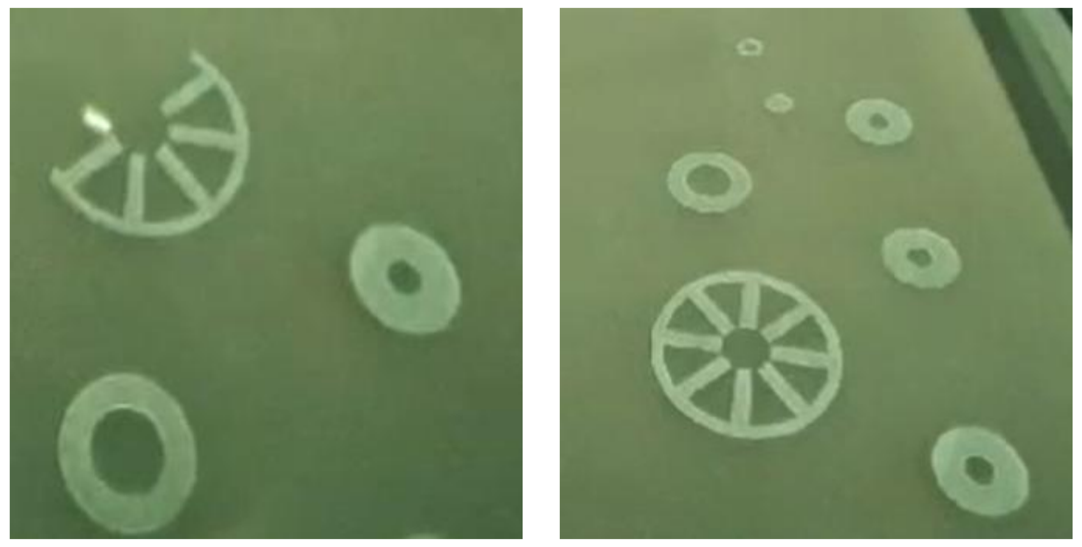


Fig. 5. Laser Powder Bed Fusion Printing of the AM Magnetron

The AM magnetron was printed using Laser Powder Bed Fusion (LPBF). This is because it allows printing of highly dense, complex shaped parts with detailed features and requires minimal post-processing [7]. The LPBF experiments were carried out at the University of Waterloo's Multi-Scale Additive Manufacturing Lab using Cu14500 powder and an EOS M290 Printer. The prints were turned on a lathe and cleaned to ensure that they fit in the specified tolerances. The anode, antenna, anode caps were printed. The cathode and magnets of a commercial magnetron would be used for the AM magnetron but could be produced via AM methods in future prototypes.

6. The AM Magnetron

The assembly process of the AM magnetron consisted of securing the antenna to the anode using small screws, joining the cathode, cathode adapter, anode and anode top cap using silver solder, and securing the antenna cap and ceramic insulator ring to the rest of the structure using ceramabond. The final AM magnetron tube is shown in Fig. 6. This magnetron will operate in a vacuum chamber that is evacuated to 8 x 10^{-7} Torr. The testing of the magnetron will take place using a microwave oven attached to the chamber.

Fig. 6 Parts of the Magnetron Tube and the Final Assembled AM Magnetron

7. Conclusion and Future Work

This research has provided a proof-of-concept on the use of AM methods to manufacture a cavity magnetron. This provides the groundwork for potentially being able to manufacture the active components of an SPS in space and indicates how lunar resources can be used to facilitate this process. The next steps in the research would be to determine the RF power output and verify proper operation. Future work can investigate replicating the design using materials extracted from lunar regolith.

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