Homogeneous Heating in Microwave Sintering with Non-Resonant Slotted Waveguides and Granular Susceptor Material

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Introduction

Sinter based additive manufacturing of metal and ceramic parts includes a variety of techniques for manufacturing a three-dimensional part followed by a sintering process. In one technique, a 3D printer may extrude a feedstock composed of a metal or ceramic powder and a binder to create a green part without the need for a mold. The green part may then undergo a debinding and sintering processes to produce a solid metal or ceramic part. In another technique, a 3D printed part is produced by selectively spraying a binder into successive layers of a metal or ceramic powder material to form a green part. The green part is then subjected to a sintering process to produce a solid metal or ceramic part. Sintering processes play a major role in metal additive manufacturing and over the last 40 years the performance of conventional sintering processes has not significantly improved. Current conventional sintering processes for metal and ceramic additive manufacturing have slow heating rates (~ 5 deg. C/min), long sintering times (> 24 hrs.), high energy consumption and high equipment costs. Metallum3D is developing patent pending microwave sintering technologies that greatly improve the performance and economics of the sintering process including fast heating rates (5x to 10x faster), short sintering times (up to 90% reduction when compared to conventional sintering), lower energy consumption and lower equipment costs. Despite many advantages, there are two primary problems associated with microwave sintering. The first problem is that microwave sintering systems operating in a multi-mode resonant condition suffer from uneven microwave energy distributions due to the standing waves that are generated inside the microwave applicator, which in turn leads to non-uniform heat distributions in the form of hot and cold spots. The second problem is that parts undergoing microwave sintering exhibit volumetric heating resulting in a reverse heating profile where the inside of the part is hotter than the outside of the part. Since heat uniformity is one of the most critical sintering parameters, these two problems have prevented microwave sintering from being used on a large scale commercial basis. Metallum3D is developing two technical innovations that solve the above referenced problems First, Metallum3D is developing a microwave sintering system that utilizes non-resonant, cross polarized slotted waveguides to achieve a homogenous distribution of the microwave energy inside the microwave applicator. Second, Metallum3D is developing a granular microwave susceptor material that is used to equalize the heating profile of the parts, provide part support, and promote non resonant operation during microwave sintering. These two technical innovations provide our microwave sintering system with the required homogenous microwave energy distributions needed for the commercial use of microwave energy for sintering applications in metal and ceramic additive manufacturing.

Technical Innovation

Current microwave heating processes are primarily based on multi-mode resonant technology. This technology has found enormous success in low power, domestic microwave oven applications due to its robustness and simplicity. One major drawback of this technology is the uneven distribution of the microwave energy which leads to non-uniform heating during processing. Several methods including mode stirrers and turntables have been developed to improve microwave energy distribution, but these methods are marginally effective when applied to a microwave sintering processes. Metallum3D is developing innovative microwave heating technologies for microwave sintering by utilizing non-resonant, cross polarized slotted waveguides and granular susceptor materials. This combination overcomes the limitations of multi-mode resonant technology and provides for homogenous heat distributions during microwave sintering.

Metallum3D has developed a design methodology for non-resonant, cross polarized slotted waveguides that uses a combination of analytical and computer numerical simulations to calculate the size and location of the slots in the non-resonant slotted waveguides. Using the calculated slot sizes and locations, 3D CAD models of the slotted waveguides have been constructed and their performance has been evaluated using CST Microwave Studio, which is a high performance electromagnetic simulation software package.

Metallum3D has also developed a formulation for a granular susceptor material. The formulation was designed to provide the following characteristics: 1) heats at the same rate as the material being sintered 2) does not sinter or fuse to itself or the part being sintered 3) it is free flowing and 4) has spherical geometry. The materials in the formulation have been successfully mixed and agglomerated into spherical granules raging from 3mm to 5mm. in diameter.

Technical Development

Current state of the art microwave heating equipment is based on multi-mode resonant technology. The components of a multi-mode resonant system include a microwave source, a circulator, a water load, a tuner, a waveguide, a resonant applicator, and a mode stirrer or turntable. A typical system is shown in Figure 1 below.

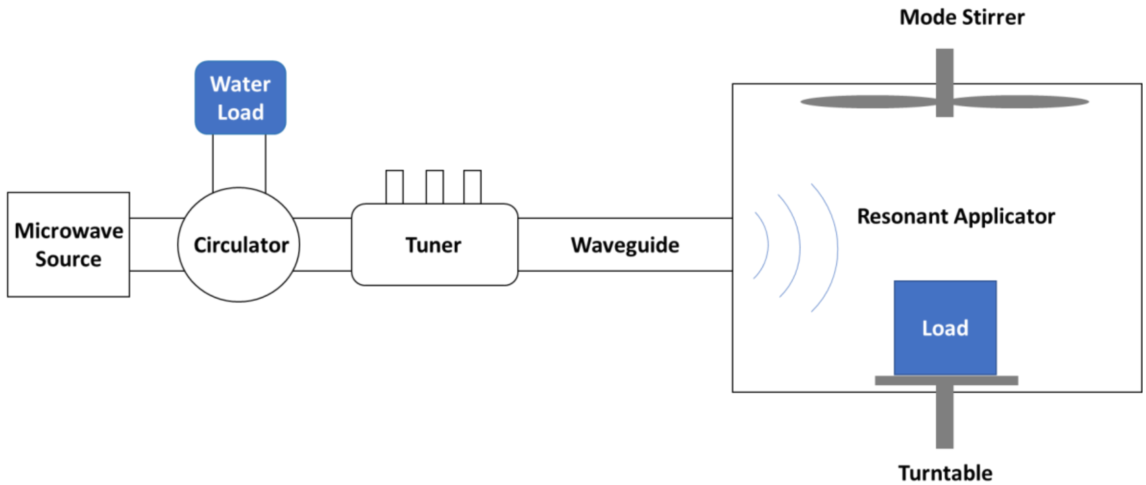

Figure 1

From 2017 to 2019 Metallum3D designed, built, and tested a prototype microwave sintering furnace based on multi-mode resonant technology. Figure 2 below shows a picture of the prototype microwave furnace and its specifications.

- Multi-mode resonant applicator
- 15.8” x 13.8” x 10.8 “ working volume
- Two independent 1 kw magnetrons
- Computer controlled
- Fiber optic pyrometer (1,200 Deg C)
- Vacuum atmosphere to 29 inHg
- Gas flowing atmosphere (argon, nitrogen)
- Configurable with Turntable or Mode Stirrer
- Cold Trap

Figure 2

The prototype microwave furnace was used to conduct multiple microwave heating and sintering tests which provided great insight into the microwave heating performance of a multimode resonant system. There were four primary problems that we encountered in our testing. 1) non-uniform distribution of microwave energy resulting in uneven heat distributions. 2) turntables and mode stirrers were only marginally effective in improving heat distributions 3) energy reflections back to microwave source and 4) reverse heating profile in parts due to volumetric heating.

When parts made from metal powder are heated with microwave energy, the heating mechanism is one of energy conversion rather than energy transfer. This results in volumetric heating, which heats the entire part simultaneously. Since only the part is being heated, the cooler environment around the part causes cooling of the outer surfaces of the part, which in turn results in a reverse heating profile. A comparison of the heating profiles for conventional heating and microwave heating is shown in Figure 3 below.

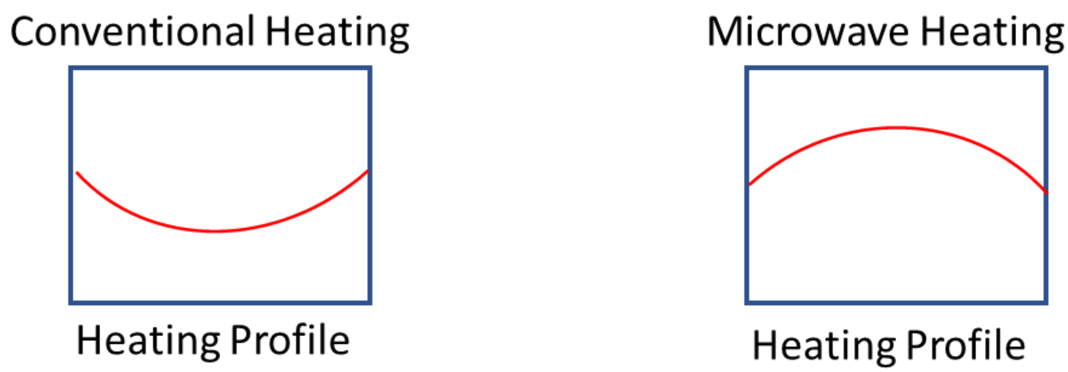

Figure 3

From our prototype microwave furnace test results, it was evident that new solutions would be needed to achieve a successful microwave sintering process. Our development efforts were focused on finding solutions to 1) achieving a homogeneous microwave field distribution with 1% or less of energy reflections back to the source and 2) achieving equalization of the part heating profile during microwave sintering.

Homogeneous Microwave Field Distributions

To achieve homogeneous microwave field distribution with less than 1% of reflected energy, Metallum3D is developing a novel non-resonant, cross polarized slotted waveguide array. This array performs distinctly different than traditional resonant slotted waveguides used in antenna applications. For comparison, we will first present the microwave radiation distribution characteristics for resonant slotted waveguides with longitudinal and transverse slots. Longitudinal slotted waveguides operate in resonant mode when the distance between the slots equals one half (1/2) of a waveguide wavelength. Transverse slotted waveguides operate in resonant mode when the distance between the slots equals one (1) waveguide wavelength.

Resonant Slotted Waveguides with Longitudinal Slots

Figure 4 shows a resonant slotted waveguide with 10 longitudinal slots and the corresponding 3D plot of the Farfield electric pattern at 2.45 GHz.

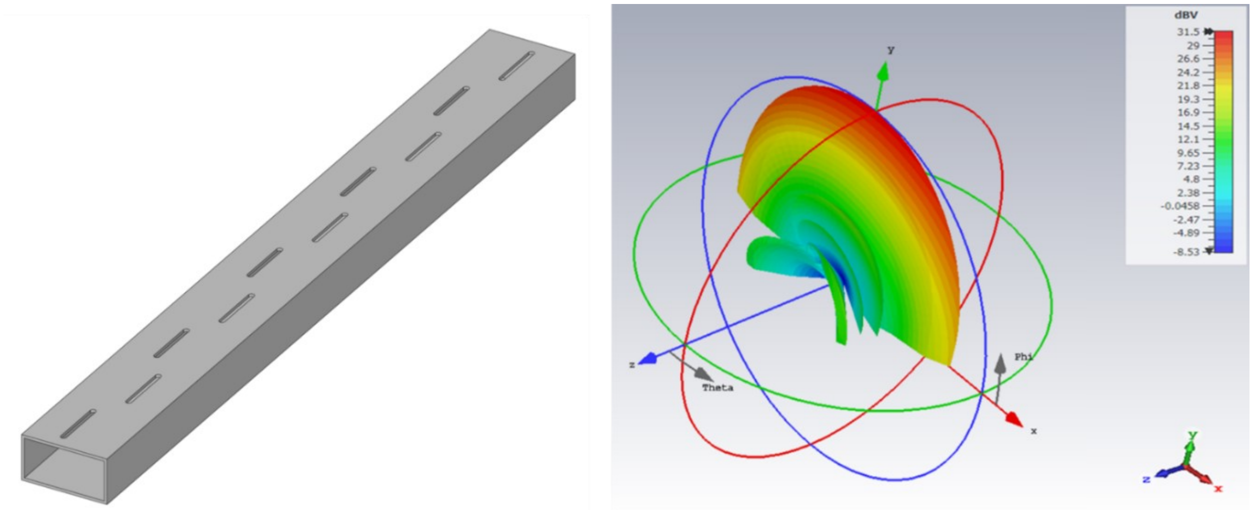

Figure 4

As can be seen in Figure 4, the microwave radiation pattern is highly directional as would be expected in an antenna application.

Further details of the radiation characteristics can be observed by looking at the plot of the microwave Farfield radiation pattern at 2.45 GHz as shown in Figure 5 below.

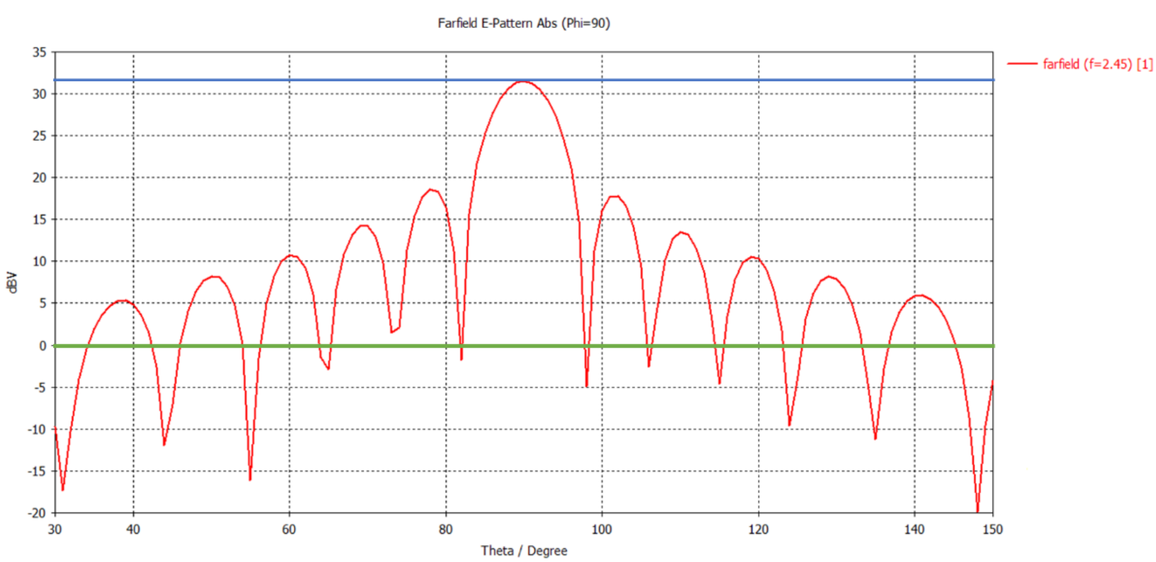

Figure 5

As can be seen in Figure 5, the microwave radiation distribution of the resonant waveguide with longitudinal slots is uneven with most of the energy being radiated in the main beam between 80 and 100 degrees. Due to the uneven radiation distribution pattern in the range from 30 to 150 degrees a resonant longitudinal slotted waveguide is not suitable for microwave heating applications. For a microwave heating application, the ideal microwave radiation pattern would follow the blue line shown in Figure 5.

Resonant Slotted Waveguides with Transverse Slots

Figure 6 shows a resonant slotted waveguide with 5 transverse slots and the corresponding 3D plot of the Farfield electric pattern at 2.45 GHz.

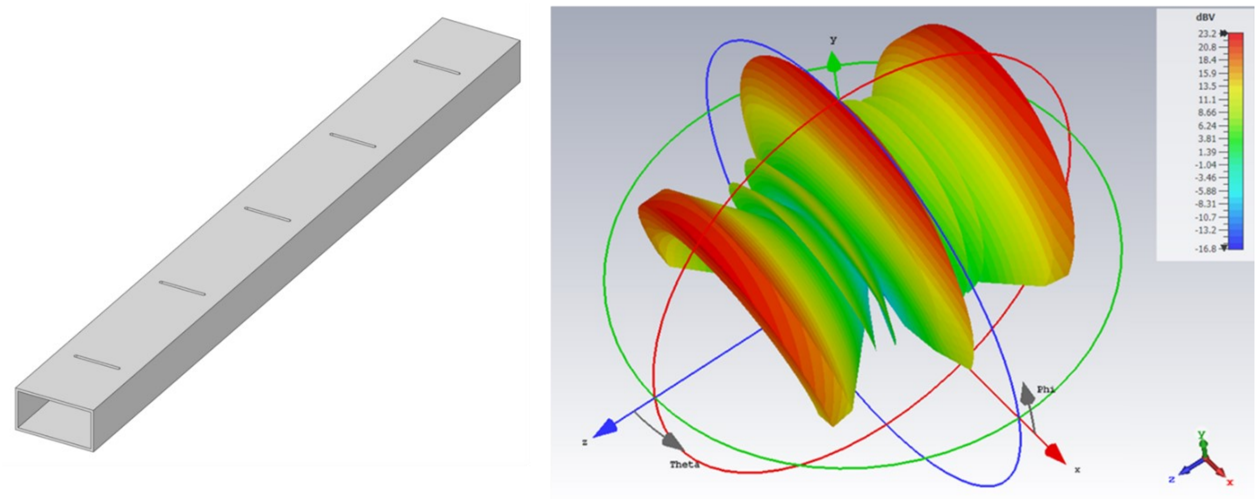

Figure 6

As can be seen in Figure 6, the microwave radiation pattern is highly directional. Further details of the radiation characteristics can be observed by looking at the plot of the microwave Farfield radiation pattern at 2.45 GHz as shown in Figure 7 below.

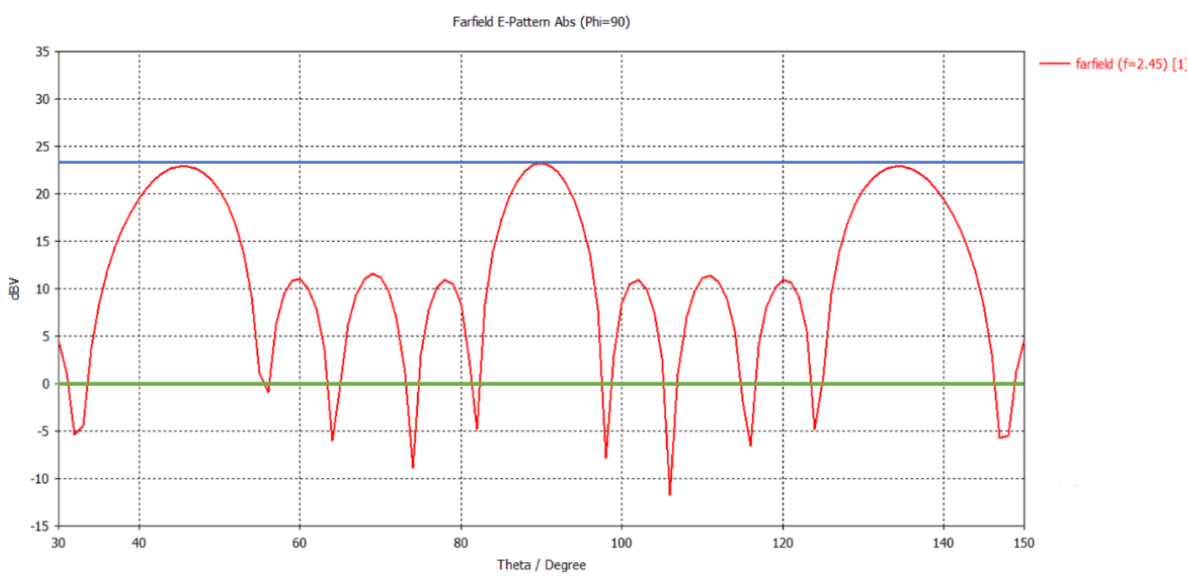

Figure 7

As can be seen in Figure 7, the microwave radiation distribution of the resonant waveguide with transverse slots is uneven with most of the energy being radiated in three main beams located between 35 and 55 degrees, 80 and 100 degrees and 125 to 145 degrees. Due to the uneven radiation distribution pattern a resonant transverse slotted waveguide is not suitable for microwave heating applications. For microwave heating applications, the ideal microwave radiation pattern would follow the blue line shown in Figure 7.

Metallum3D Non-Resonant Slotted Waveguides

To solve the problem of uneven microwave filed distributions in microwave sintering applications, Metallum3D has developed a design methodology for longitudinal and transverse, non-resonant slotted waveguides that utilizes analytical and computer numerical simulations to calculate the size and locations of the slots to achieve a homogeneous microwave radiation pattern.

Metallum3D Non-Resonant Slotted Waveguide with Longitudinal Slots

Figure 8 shows a non-resonant slotted waveguide with 10 longitudinal slots and the corresponding 3D plot of the Farfield electric pattern at 2.45 GHz.

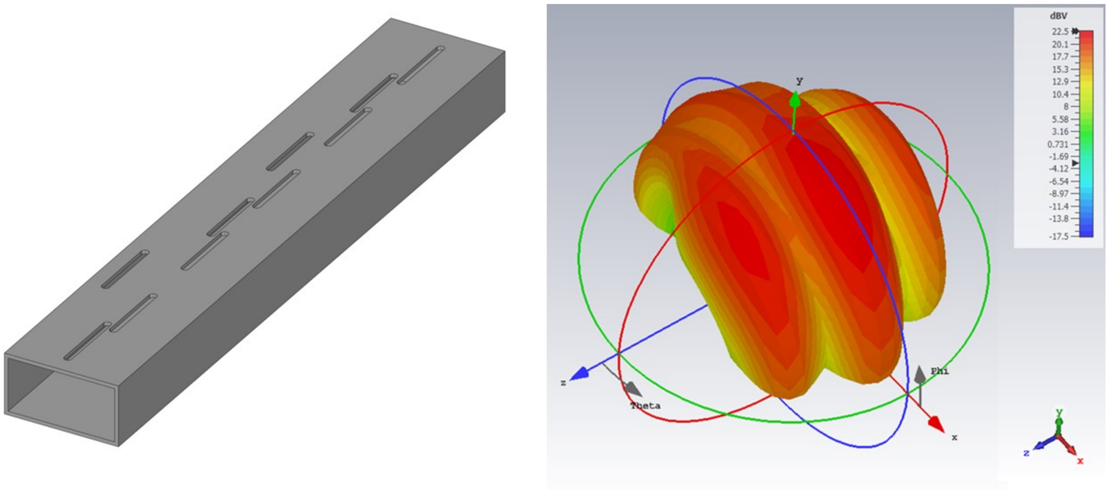

Figure 8

As can be seen in Figure 8, for the non-resonant longitudinal slotted waveguide, the microwave radiation Farfield pattern takes the shape of a cloud. Further details of the radiation characteristics can be observed by looking at the plot of the microwave Farfield radiation pattern at 2.45 GHz as shown in Figure 9 below.

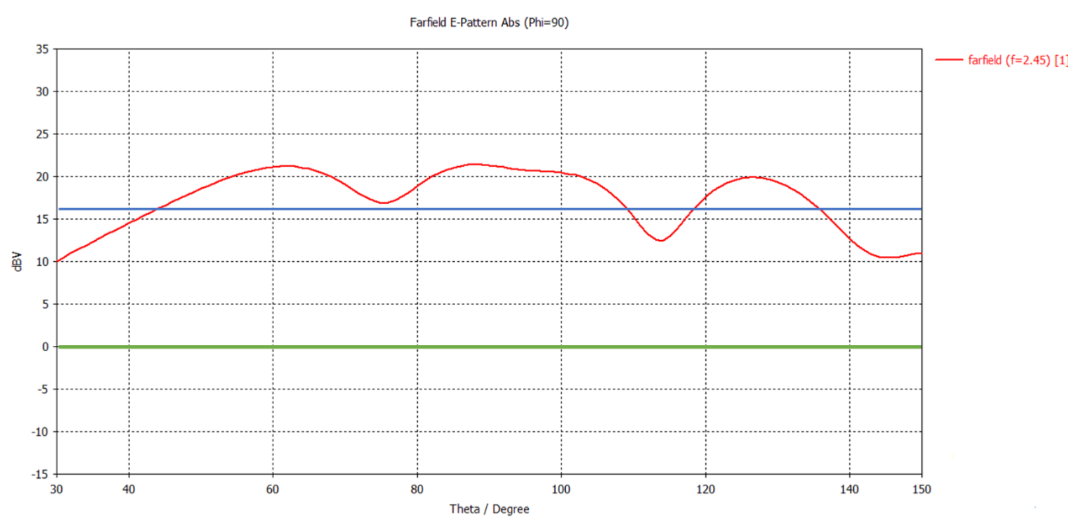

Figure 9

As can be seen in Figure 9, the microwave radiation distribution of the non-resonant waveguide with longitudinal slots has a relatively homogenous microwave radiation pattern, with most of the energy being radiated between 40 and 140 degrees within an acceptable deviation from the ideal radiation pattern shown by the blue line. This non-resonant longitudinal slotted waveguide is suitable for microwave heating applications.

A secondary and important objective in the design of non-resonant longitudinal slotted waveguides is reducing the reflections of energy to 1% or less. This implies that the slotted waveguide will operate with an efficiency of 99%. There are two methods to evaluate the operational efficiency 1) Calculation of the S_{11} parameter and calculation of the Voltage Standing Wave Ratio (VSWR). The design objective is to achieve an S_{11} parameter value below -20 dB and a VSWR value below 1.5. Figure 10 below shows that the non-resonant longitudinal slotted waveguide with 10 slots has an S_{11} parameter value of approximately -22 dB which exceeds the design goal of -20 dB.

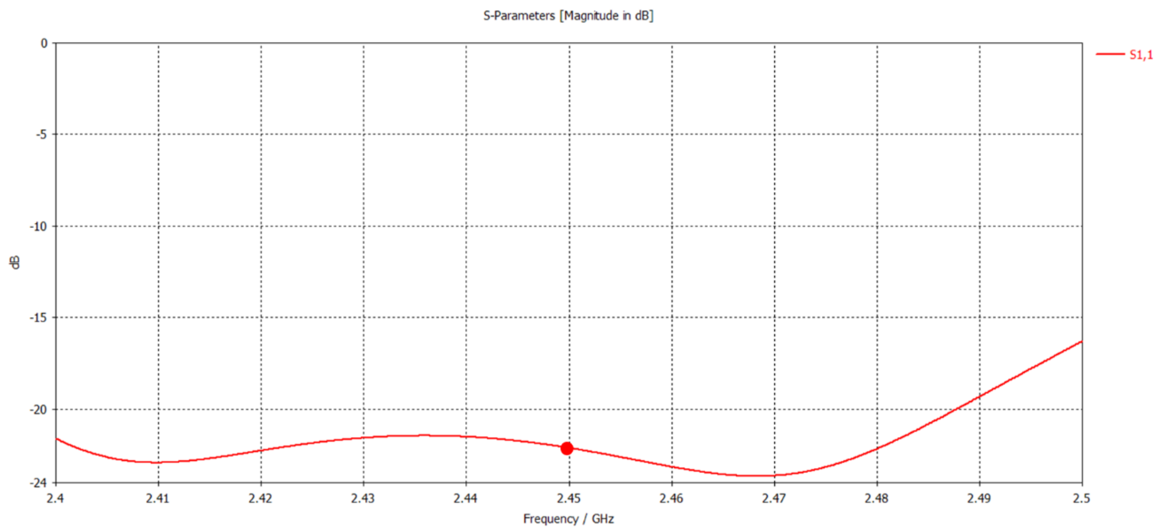

Figure 10

Figure 11 below shows that the non-resonant longitudinal slotted waveguide with 10 slots has a Voltage Standing Wave Ratio (VSWR) value of approximately 1.2 which is below the design goal of a VSWR value of 1.5

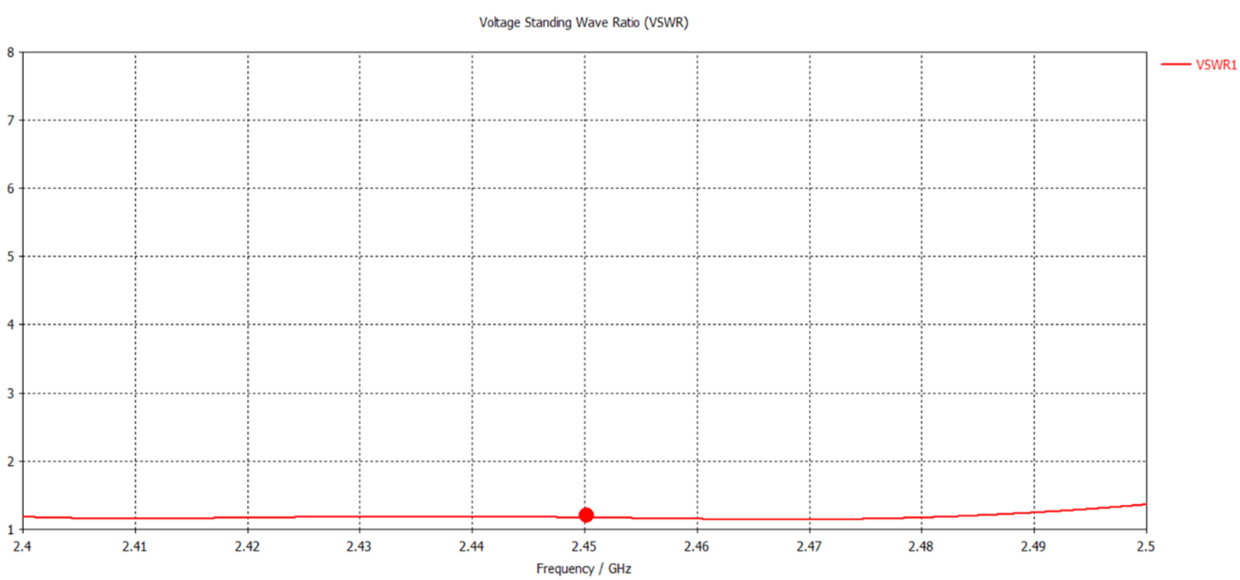

Figure 11

Metallum3D Non-Resonant Slotted Waveguide with Transverse Slots

Figure 12 shows a non-resonant slotted waveguide with 12 transverse slots and the corresponding 3D plot of the Farfield electric pattern at 2.45 GHz.

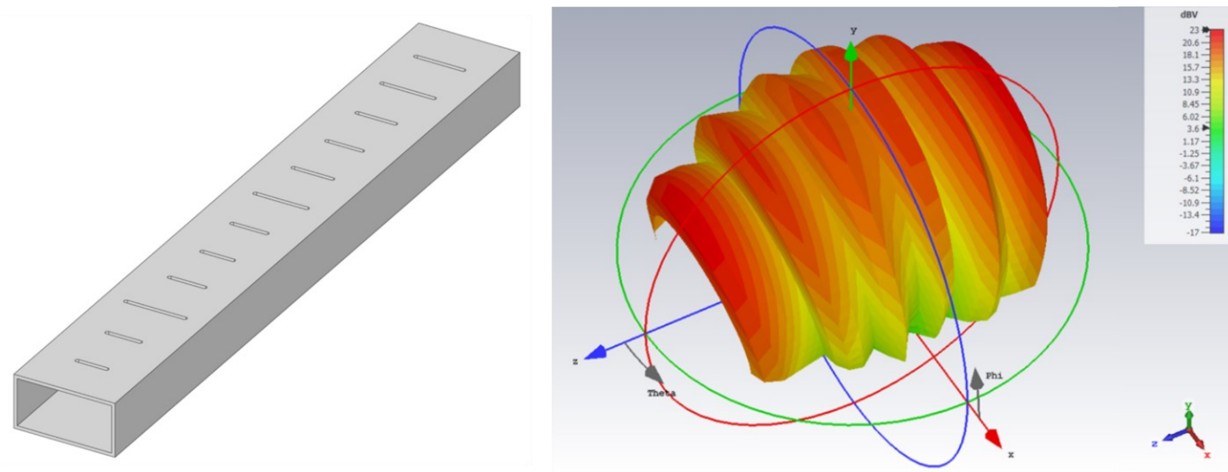

Figure 12

As can be seen in Figure 12, for the non-resonant transverse slotted waveguide, the microwave radiation Farfield pattern takes the shape of a cloud. Further details of the radiation characteristics can be observed by looking at a the 1D plot of the microwave Farfield radiation pattern at 2.45 GHz as shown in Figure 13 below.

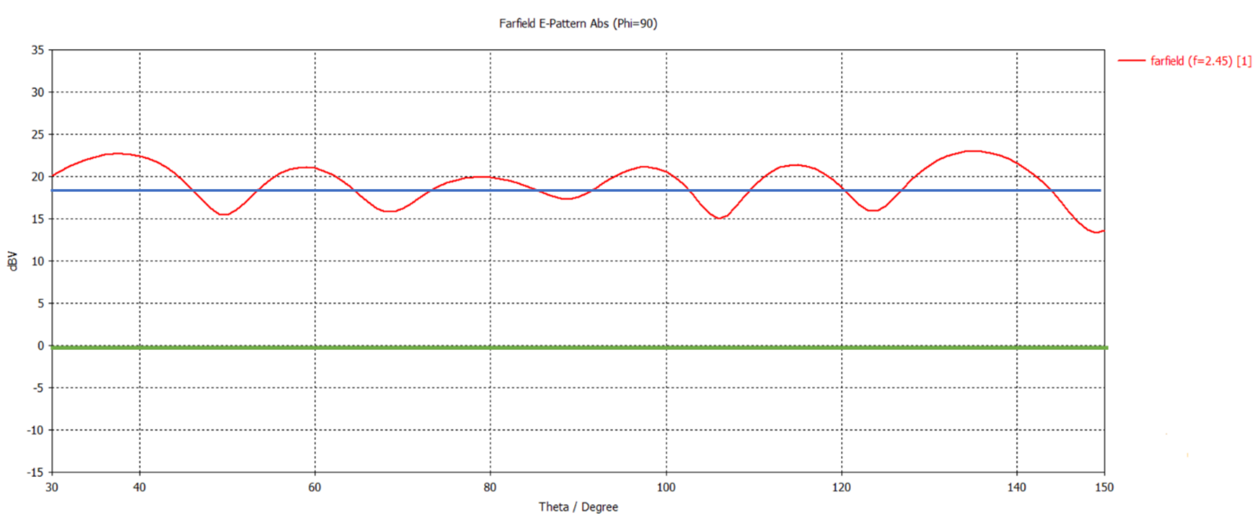

Figure 13

As can be seen in Figure 13, the microwave radiation distribution of the non-resonant waveguide with transverse slots has a relatively homogenous microwave radiation pattern, with most of the energy being radiated between 30 and 140 degrees within an acceptable deviation from the ideal radiation pattern shown by the blue line. This non-resonant transverse slotted waveguide is suitable for microwave heating applications.

A secondary and important objective in the design of non-resonant transverse slotted waveguides is reducing the reflections of energy to 1% or less. This implies that the slotted waveguide will operate with an efficiency of 99%. There are two methods to evaluate the operational efficiency 1) Calculation of the S_{11} parameter and calculation of the Voltage Standing Wave Ratio (VSWR). The design objective is to achieve an S_{11} parameter value below -20 dB and a VSWR value below 1.5. Figure 14 below shows that the non-resonant transverse slotted waveguide with 12 slots has an S_{11} parameter value of approximately -28 dB which exceeds the design goal of -20 dB.

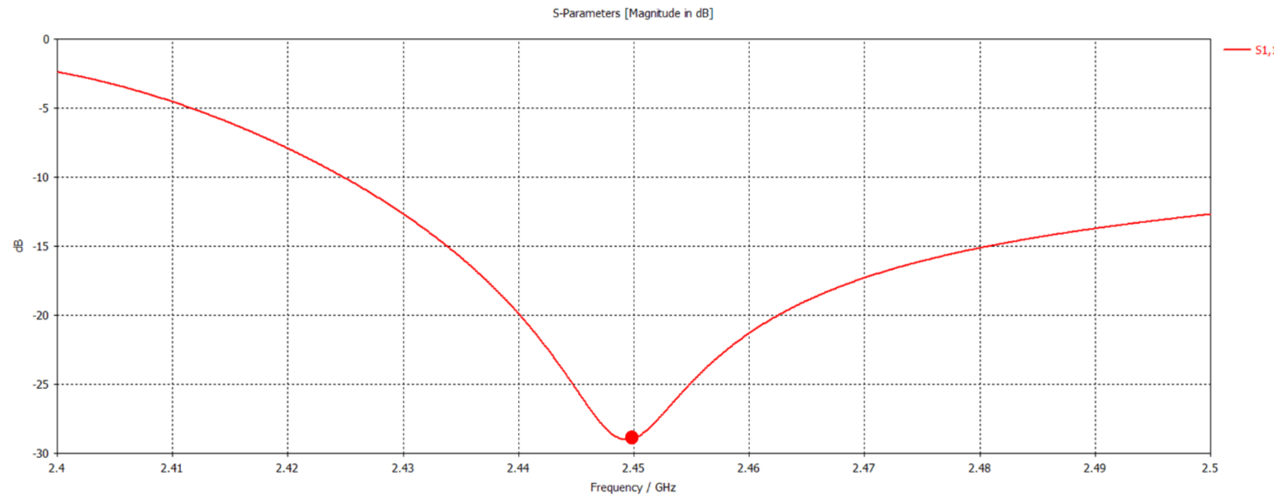

Figure 14

Figure 15 below shows that the non-resonant transverse slotted waveguide with 12 slots has a Voltage Standing Wave Ratio (VSWR) value of approximately 1.1 which is below the design goal of a VSWR value of 1.5

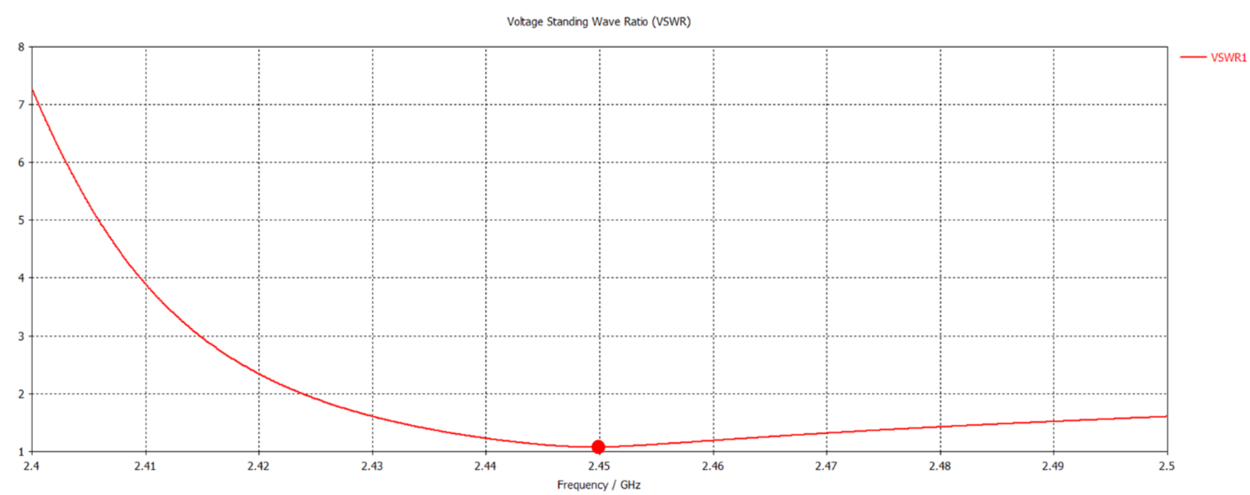

Figure 15

Metallum3D Non-Resonant Cross Polarized Slotted Waveguide Array

For microwave sintering applications the non-resonant longitudinal and transverse slotted waveguides are combined into a cross polarized slotted waveguide array. Figure 16 below shows the cross polarized waveguide pair array with and the corresponding 3D Farfield microwave radiation pattern resulting from the combined electric fields.

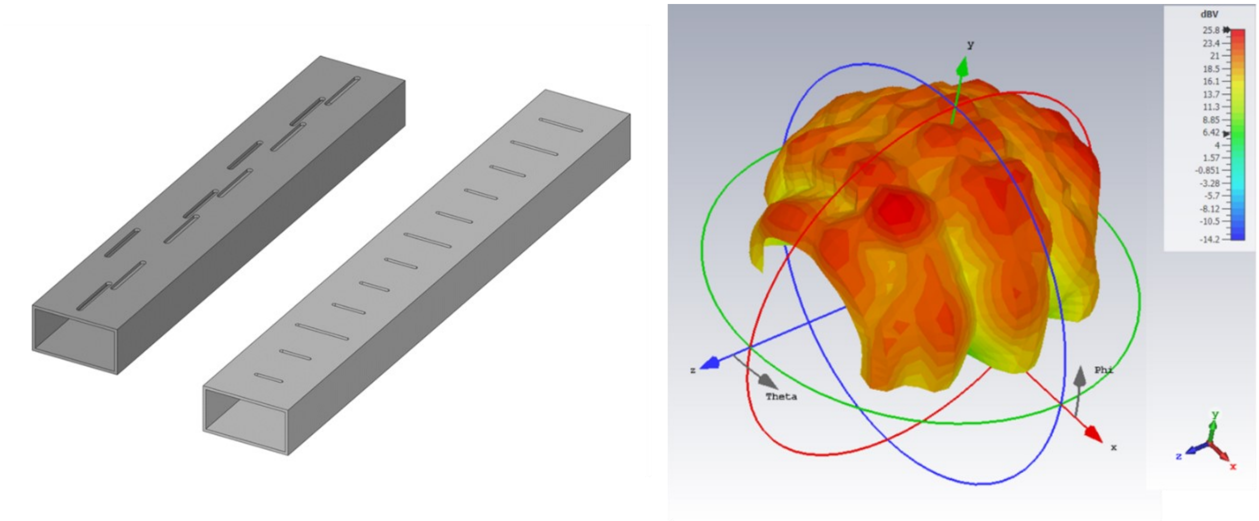

Figure 16

As can be seen in Figure 16, for the non-resonant, cross polarized slotted waveguide pair, the combined Farfield electric fields result in a microwave radiation pattern that takes the shape of a cloud. Further details of the radiation characteristics can be observed by looking at a the 1D plots of the microwave Farfield radiation pattern at 2.45 GHz as shown below in Figure 17 and 18

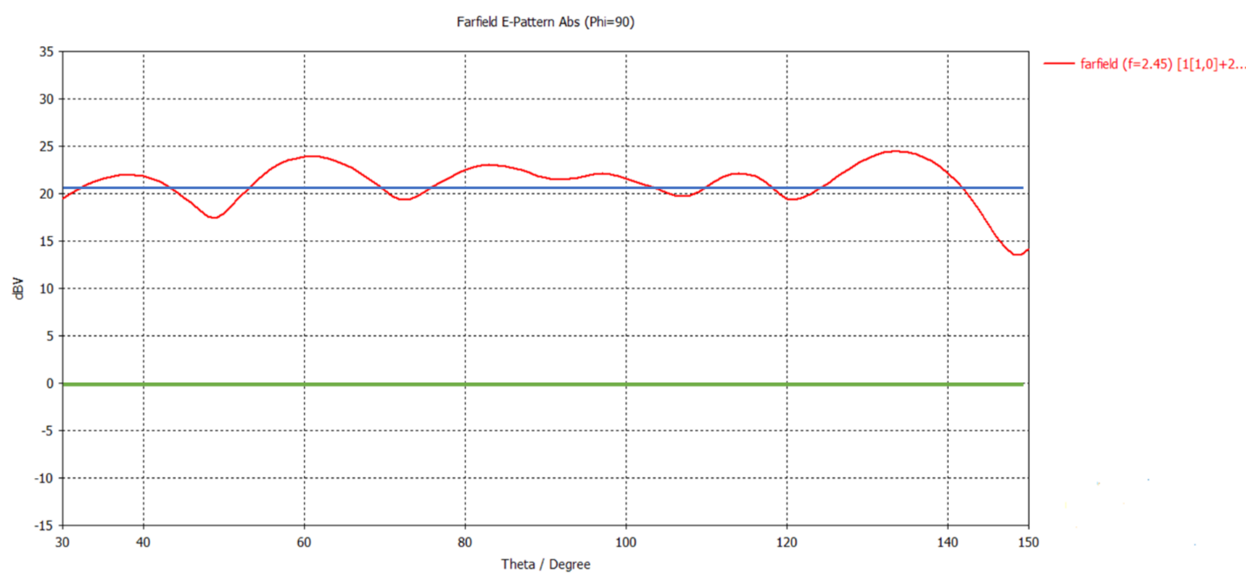

Figure 17

As can be seen in Figure 17, with the Phi angle held at constant of 90 degrees, the microwave radiation distribution of the non-resonant, cross polarized slotted waveguide pair has a relatively homogenous microwave radiation pattern, with most of the energy being radiated between 30 and 140 degrees within an acceptable deviation from the ideal radiation pattern shown by the blue line.

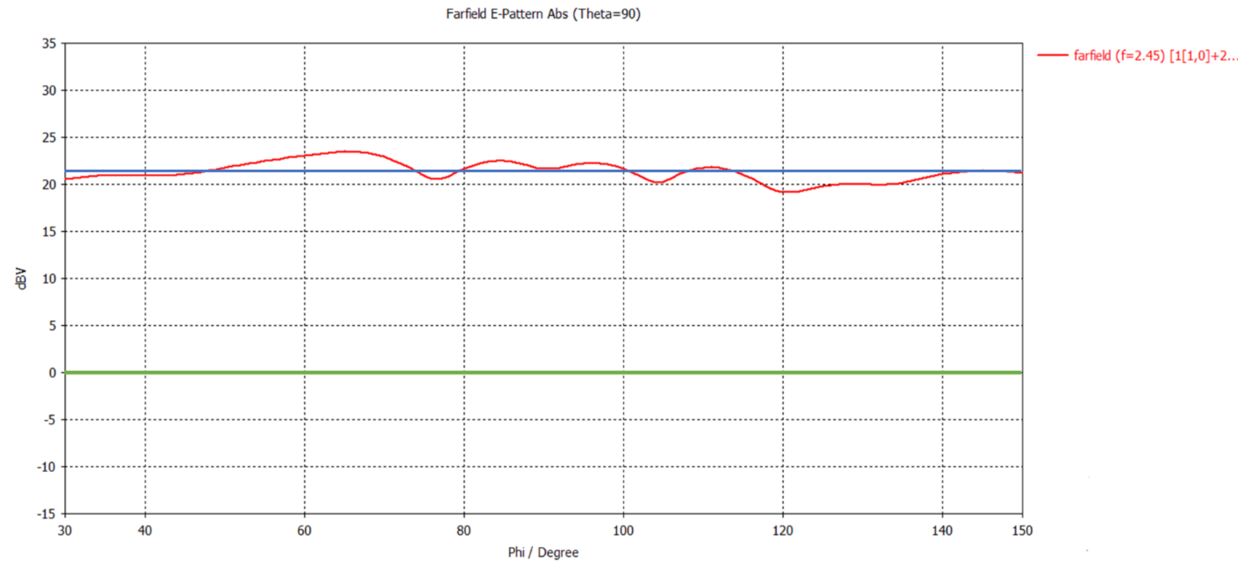

Figure 18

As can be seen in Figure 18, with the Theta angle held at constant of 90 degrees, the microwave radiation distribution of the non-resonant, cross polarized slotted waveguide pair has a relatively homogenous microwave radiation pattern, with most of the energy being radiated between 30 and 150 degrees within an acceptable deviation from the ideal radiation pattern shown by the blue line.

An additional and important objective in the design of non-resonant, cross polarized slotted waveguides arrays is minimizing the cross coupling between the waveguides. Cross coupling in the cross polarized slotted waveguide pair can be evaluated by calculating the S_{12} and S_{21} parameters. The design objective is to achieve S_{12} and S_{21} parameter values below -20 dB. Figures 19 and 20 below show the S_{12} and S_{21} parameter values for the wave guide pair.

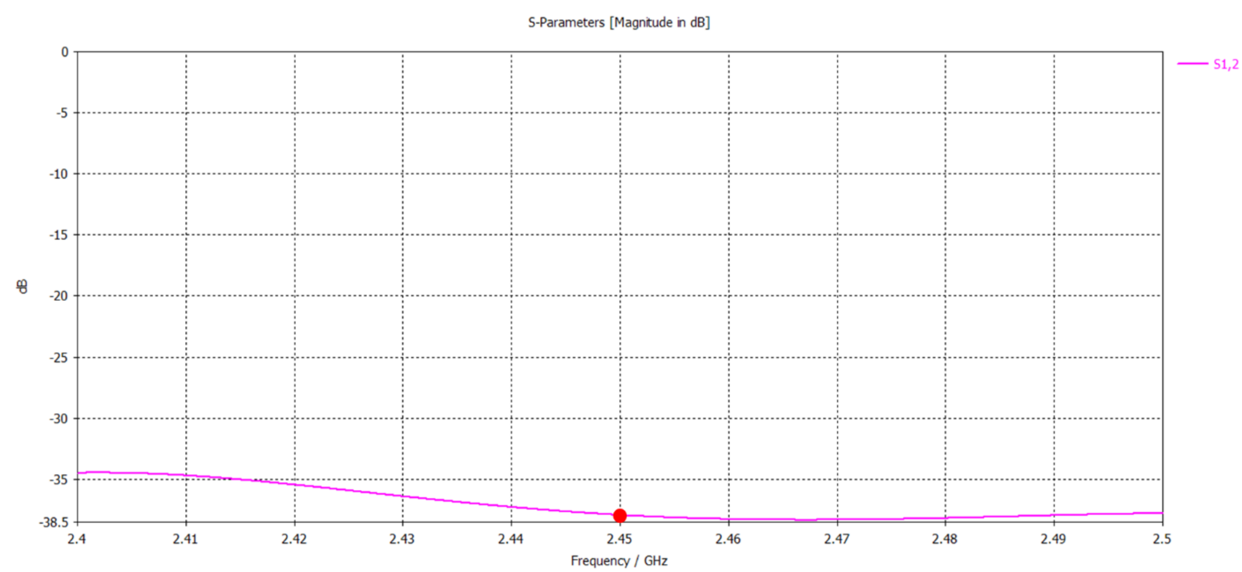

Figure 19

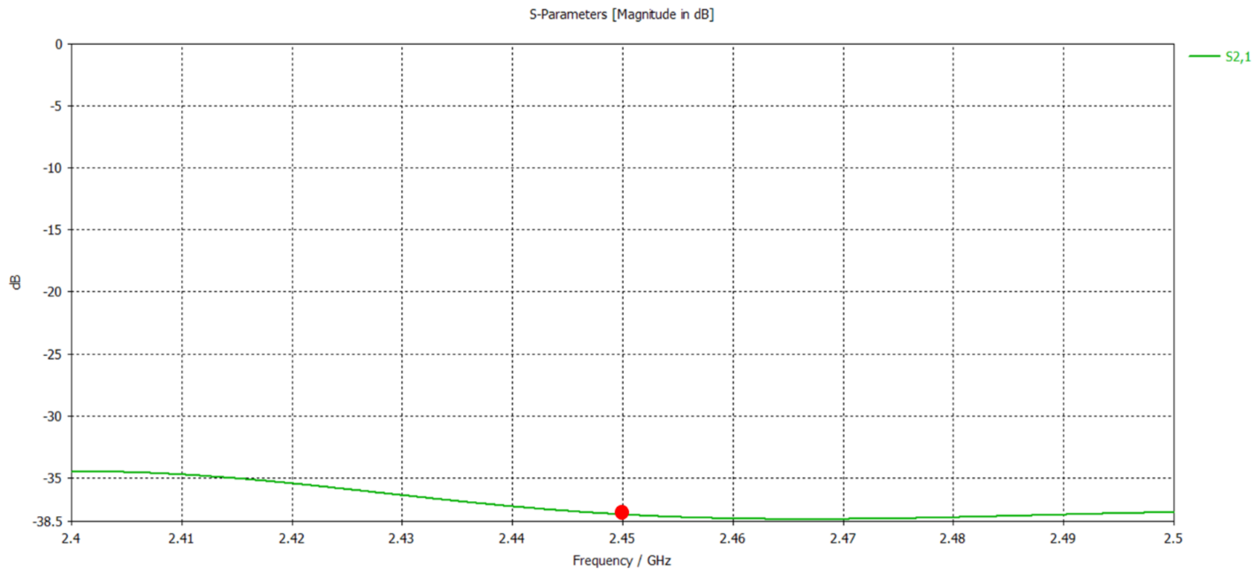

Figure 20

As can be seen in Figures 19 and 20 the S_{12} and S_{21} parameters for the waveguide pair have an approximate value of -38 dB which exceeds the design goal of -20 dB. These values mean that the cross coupling between waveguides is negligible.

Microwave Electric Field Cross-Section for Metallum3D Non-Resonant Waveguide Array

To assess the homogeneous distribution pattern of the non-resonant, cross polarized slotted waveguide pair, a simulation was executed to calculate the cross section of the electric fields at a distance of four (4) wavelengths from the radiating surface. The boundary conditions used resulted in an electric filed cross section with approximate dimensions of 1,700 mm x 1,300 mm.

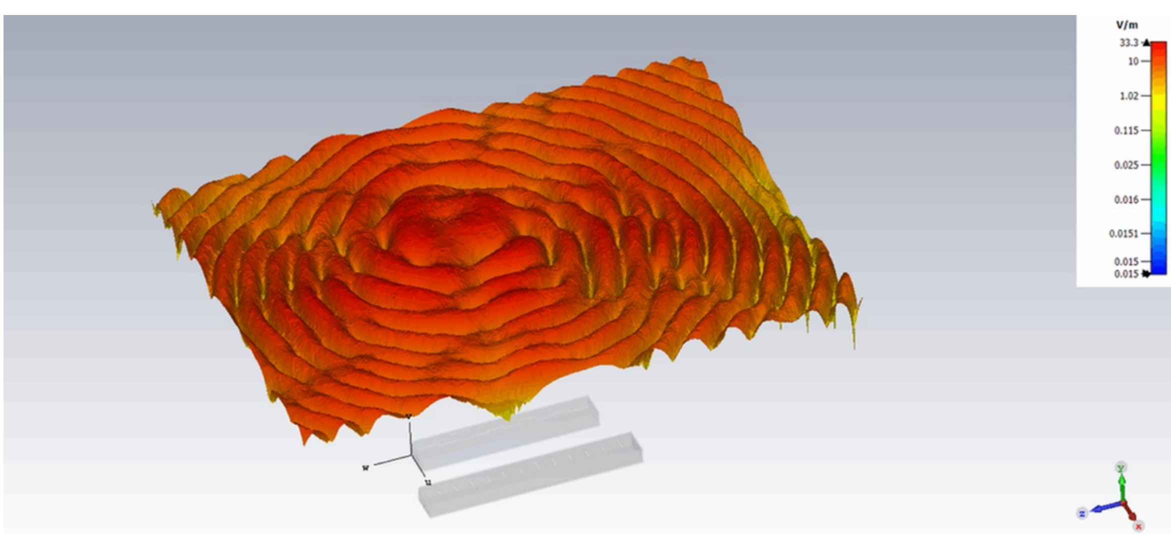

Figure 21

Granular Susceptor Material

To achieve equalization of the part heating profile during microwave sintering Metallum3D is developing a granular susceptor material formulation with the following characteristics, 1) heats at the same rate as the material to be sintered 2) does not sinter or fuse to itself or the part being sintered 3) it is free flowing and 4) has spherical geometry. The granular susceptor material is composed of a major amount of a ceramic material, a minor amount of a microwave absorbing material, a binder material and optionally a ceramic pigment. The ceramic material, microwave absorbing material and binder material are chosen such that the heating rate of the granular susceptor material closely matches the heating rate of the part being sintered. Figure 22 below shows a picture of a granular susceptor material agglomeration test, which resulted in the successful agglomeration of the material formulation into spherical granules ranging from 3 mm to 5 mm in diameter.

Figure 22

Metallum3D Microwave Sintering System

Figure 23 below shows a microwave sintering system based on non-resonant, cross polarized slotted waveguides with the parts to be sintered embedded in the granular susceptor to equalize the part heating profiles during sintering.

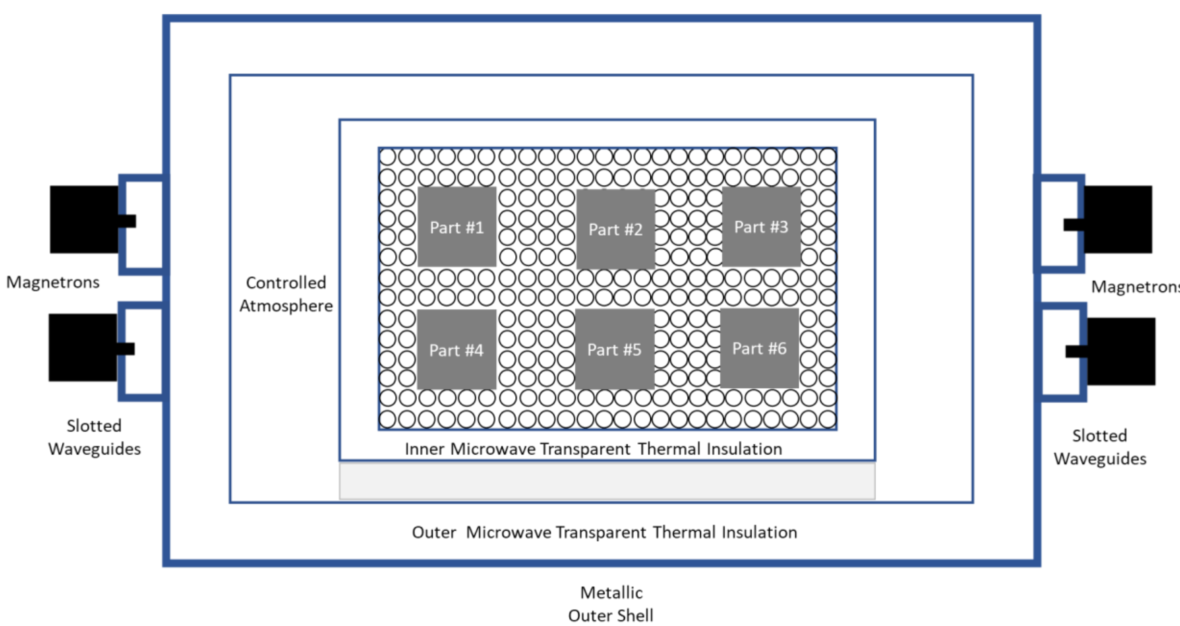

Figure 23