Virtual Prototype of a Dielectric Window for High Power Microwave Tubes

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Outline

- Motivations
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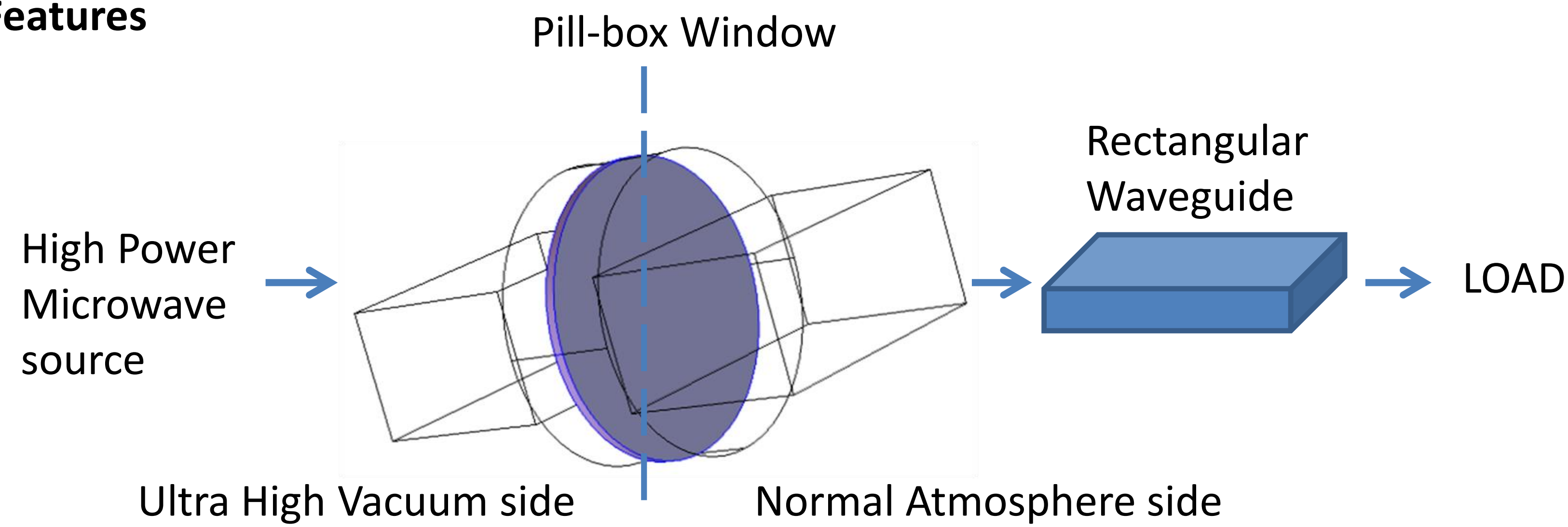
- Electromagnetic optimization
- Virtual prototype set-up
- Results
- Conclusions

Motivations

Window Features

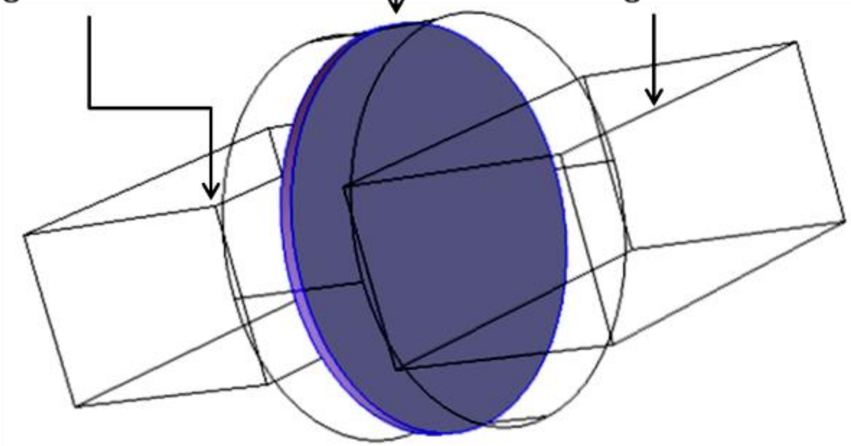


MICROWAVE VACUUM TUBES are the principal sources adopted where High Power signals are needed. Such devices employees Dielectric Windows (DW) to separate their Ultra High Vacuum (UHV) atmosphere to the normal atmosphere in the transport waveguide (which connects the device to the load), ensuring the microwave power transmission. These windows are often interposed between microwave power sources and LINAC's. DW are made by a waveguide section, in which a solid dielectric medium is inserted. Typically, energy transport system are based on rectangular waveguide (RWg) and, due to technological reason, dielectric windows are based on circular waveguide (CWg) sections and the most common kind of window is the pill-box type.

Motivations

Window: Design Target

PILL-BOX WINDOW

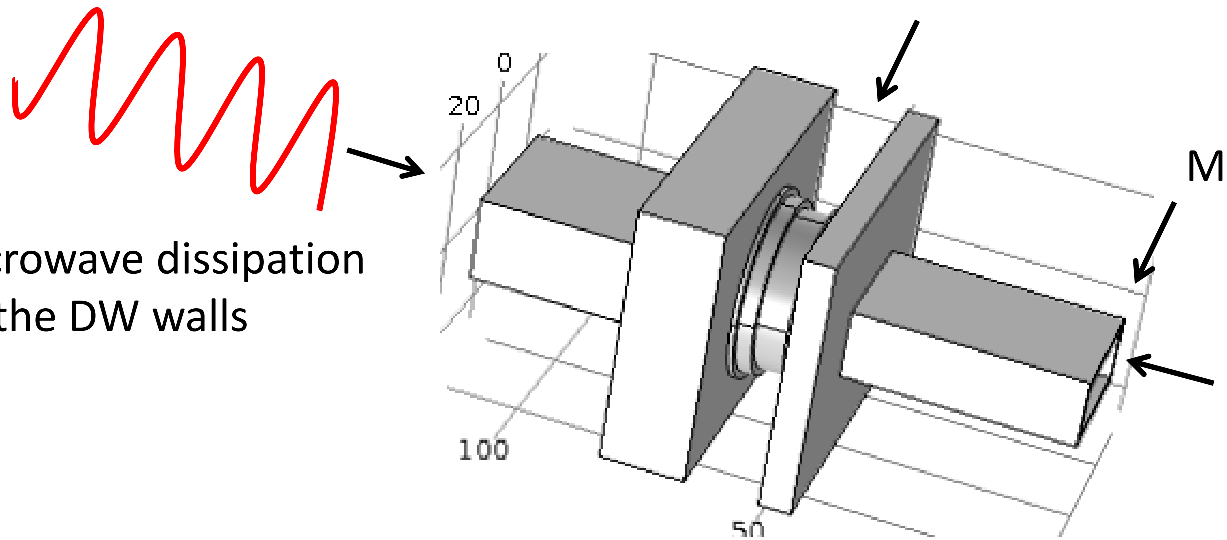


DIELECTRIC WINDOWS presents a certain Insertion Loss (IL) and Return Loss (RL) due to the change of the fields morphology between RWg and CWg and the permittivity step of the dielectric medium and its transparency to the microwave.
In this study we propose the design of a low Insertion Loss Pill-box Window: a new formula for the calculation of the Pill-box radius is proposed and other formulas, taken from literature, are reported and a numerical optimization is shown.

Motivations

Multiple Physic influencing factors

External environment



Mechanical Costraints

Microwave dissipation on the DW walls

Thermal contact with Microwave Power Tube

During the DW operation, multiple physical effects occur. Joule Effect is induced by the Electromagnetic (EM) Power Dissipation of the microwave which cross the device. Moreover, since the device is connected to a High Power Microwave (HPM) Tube, it experiences a further temperature increase, due to the thermal contact with the tube, which have a controlled constant temperature over its surfaces. These multiple effects induce some alterations of the EM behavior of the DW. The resulting virtual prototype shows a negligible decrease of the EM Performance while these multiple physical factors exerts their effects over the DW operation.

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Motivations

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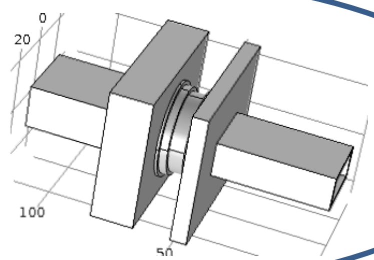
Opportune Shape to Re-increase thermally-altered perfomance

Thermal effects → Shape deformations → Electromagnetic performances Re-increase

Electric conductivity alteration

Electromagnetic performances degradation

Opportune shape and material



In this study, we show how to compensate the thermal induced degradation of the device performances, by exploiting the consequent Thermo - mechanical deformation of the opportunely designed device shape, which modify constructively the electromagnetic (EM) fields to re-increase performances. The global degradation of the performances due to the alteration of the electric conductivity induced by the temperature increase, can be mitigate by choosing a device shape and material which, when deformed by its temperature, modify constructively the EM fields re-increasing performances.

Theory and Design

Pill –box Window Design: Circular section radius

$$\lambda_{gC} = \frac{\lambda_0}{\sqrt{\epsilon_r - \frac{\lambda_0^2}{\lambda_{cC}^2}}} \qquad \lambda_{cC} = \frac{2\pi r}{p'_{11}\sqrt{\varepsilon_r \mu_r}}$$

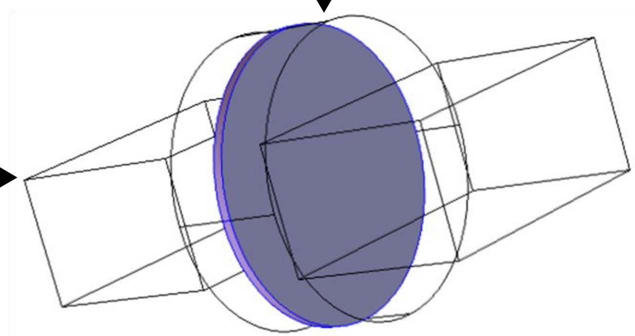
Invisible Discontinuity & Effective Permittivity

$$\lambda_{gR} = \lambda_{gC}$$

$$\varepsilon_r \leftarrow \varepsilon_r'$$

$$\lambda_{gR} = \frac{\lambda_0}{\sqrt{\epsilon_r - \frac{\lambda_0^2}{\lambda_{cR}^2}}}$$

$$\lambda_{cR} = 2a\sqrt{\varepsilon_r \mu_r}$$



Circular Section Radius

$$r = \frac{\lambda_0 \; p'_{11}}{2\pi\sqrt{1 - \frac{\lambda_0^2}{\varepsilon'_r \; \lambda_{gR}^2}}} \qquad (1)$$

Each discontinuity may insert evanescent modes, reducing transmitting and reflecting performances. The discontinuity will result locally invisible if the RWg fundamental mode wavelength will remain the same in the CWg. Since the CWg is partially filled with alumina ceramic, this may be treated as a uniformly filled with a effective relative permittivity ε_r'. Since the power transport system is based in RWg, we can consider λ_{gR} as a known value.

Theory and Design

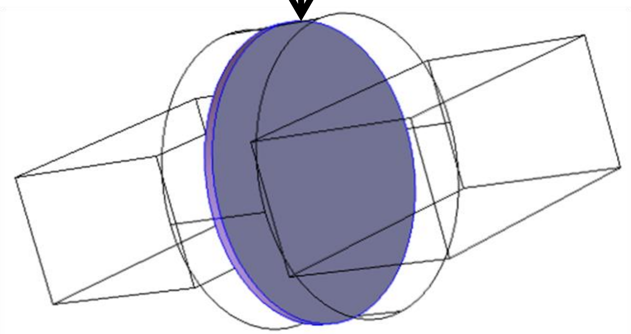
Pill –box Window Design: Dielectric disk

Maximum direct stress

$$\sigma = \frac{F_n}{\pi r^2} = P$$

Effective Permittivity

$$\epsilon_r' = 1 + \frac{t}{L}\left(\epsilon_r^{disk} - 1\right)$$

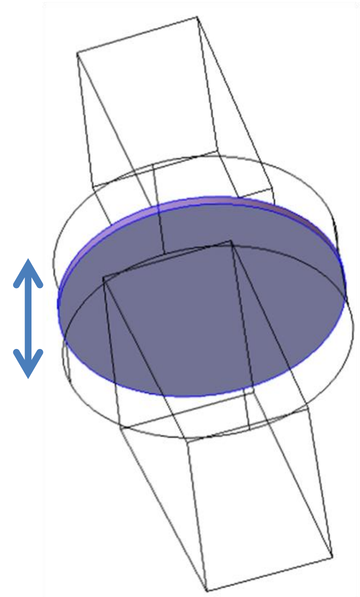


The disk should be designed with the minimum thickness which ensures the structural capacity to endure the direct stress σ applied from the atmosphere normal force. The mechanical characteristics of the dielectric medium are to be provided by the vendor. Assuming the gas permittivity very similar to the vacuum, the effective permittivity of the whole CWg section may be evaluated as the average value with respect to the volumes occupied by the disk and the vacuum or gas.

Theory and Design

Pill –box Window Design: Circular section length

$$L = \lambda_{gR} \frac{\sqrt{\varepsilon_r'}}{2} \frac{b}{a} \qquad (2)$$



In order to transfer maximum of microwave power from rectangular to circular and then vice-versa for downward transmission, it is required that at the junction, impedance of the rectangular waveguide should match with the impedance of circular waveguide both in the input & output side: By manipulating the design formulas reported in [4], the total length of the CWg section can be calculated. For most of the high power pill-box windows, the value of ε_r' will vary between 1.0 and 2.0. A value of 1.5 is reasonable for ε_r' [4].

Theory and Design

Analytical calculations

f = 9 GHz

WR09 (a = 22.86 mm, b = 10.16 mm)

λ_{gR} = 49 mm and λ_0 = 33 mm

ε_r'=1.5

⇒

L = 13 mm

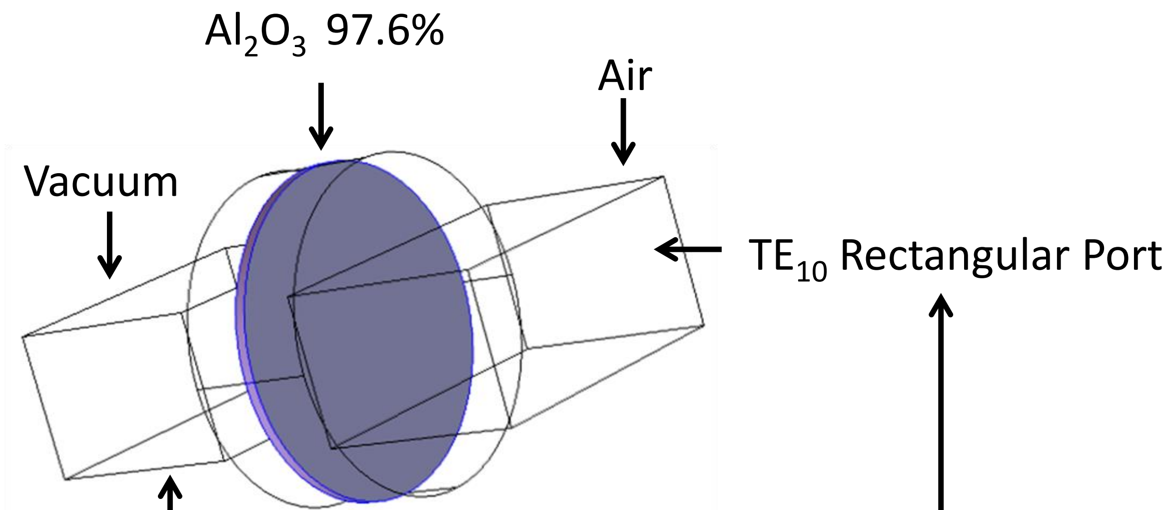
r = 12 mm.

For an X-Band Power Tube operating at f = 9 GHz and driven through a RWg WR90, which have a = 22.86 mm and b = 10.16 mm, according to [1] with ε_r =1 we obtain λ_{gR} = 49 mm and λ_0 = 33 mm. The DW can be dimensioned as follows: By applying the (1) with ε_r'=1.5 we obtain a radius of r = 12 mm. From the (2) results that the total length of the CWg is L = 13 mm.

Electromagnetic Model

Electromagnetic simulation Set-Up

- Electromagnetic Waves *(emw)*
  - Wave Equation, Electric 1
  - Perfect Electric Conductor 1
  - Initial Values 1
  - Impedance Boundary Condition 1
  - Port 1
  - Port 2

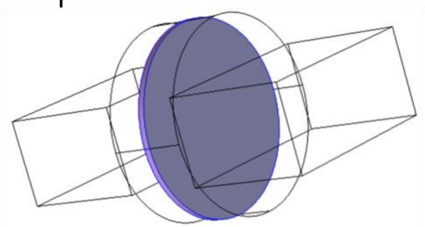


EM simulation has been performed setting two vacuum circular section of radius *r* and variable length *L,* which enclose the dielectric plate with a variable length *t.* Two standard RWg WR90 sections are connected at the open faces of the CWg section. All the waveguide boundaries are made of copper with an Impedance Boundary Condition which consider the field penetration inside the conductor, according to its skin depth. At the RWg's external faces, TE ports are placed.

Electromagnetic Model

CAD optimization

Al_2O_3 97.6% plate
ε_r = 9.0 in S band

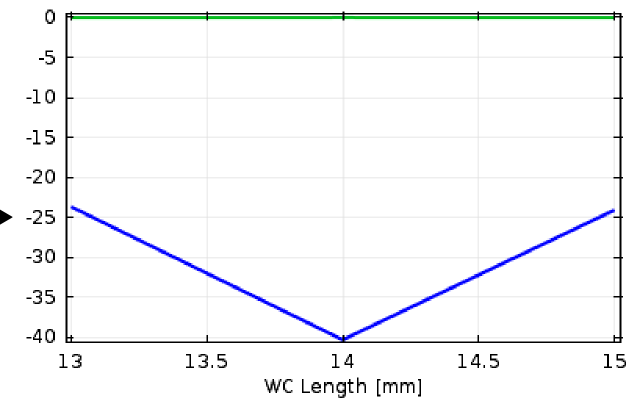


→

CWg Lentgh & Plate thikness Sweep

$$\nabla \times \mu_r^{-1}(\nabla \times \overline{E}) - k_0^2(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0})\overline{E} = 0$$

→



Optimal Values: *L* = 14 mm *t* = 0.7 mm

The analytical design procedure, is a simplification of the real dimensioning problem, in which we have more difficulties given mostly from spatial distribution and complex value of dielectric constant. In fact, effective dielectric constant depends by the length of the CWg and the portion occupied by the disk, resulting in a recursive problem, thus we need to set a value of ε_r', and a numeric optimization is mandatory. Length *L* of circular waveguide sections as well as thickness *t* of dielectric plate have been optimized in order to provide the minimum reflection parameter $S_{11}$and the maximum transmission parameter S_{21} at the two ports. Optimization has shown as optimum values *L* = 14 mm and *t* = 0.7 mm.

Virtual Prototype Set-Up

Multiphysics Ambient:

CAD

Electromagnetic Waves

$$\nabla \times \mu_r^{-1}(\nabla \times \overline{E}) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\overline{E} = 0$$

Postprocessing

Surface current J

Temperature T

Joule Heating and Thermal Expansion

$$\nabla \cdot \overline{J} = \overline{Q}_J \qquad \overline{J} = \sigma\overline{E} + \overline{J}_E$$

$$\overline{E} = -\nabla V \qquad -\nabla \cdot \sigma = \overline{F}_V$$

$$\rho C_p \overline{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

Displacement $\overline{u}$

Geometry $\overline{X}$

Moving Mesh

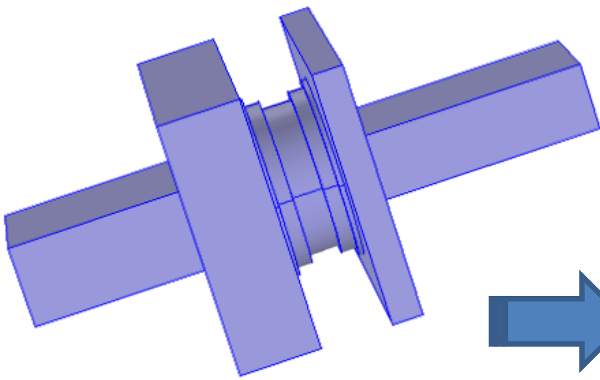
$$\overline{X} = \overline{X}_0 + \overline{u}$$

The model employee the Elecectromagnetic Waves (EMW), Moving Mesh (MM) and Joule Heating and Thermal Expansion (JHTE) Modules.

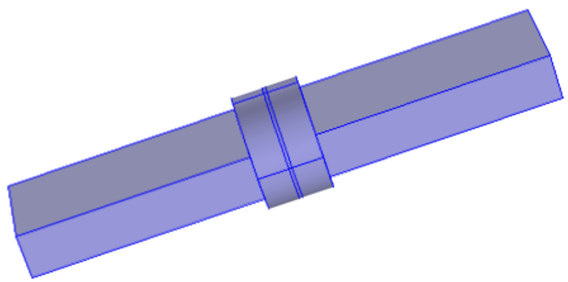
Virtual Prototype Set-Up

Electromagnetic Waves:

Whole structure



EMW applied only
to the dielectrics.



Performed 2 times

1st step, receiving:
- power at the input port

2nd step, receiving:
- power at the input port
- Temperature (JHTE)
- Deformed geometry (MM)

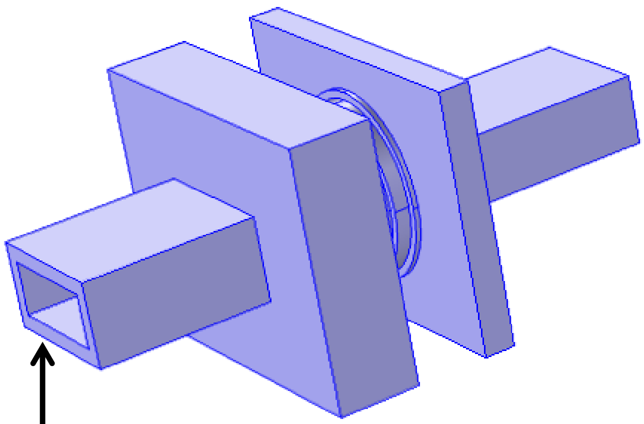
This module works two times: First, a frequency domain analysis to compute the Electric Field by receiving the power at the input port. The ultimate EM analysis has been performed on the moved meshes, considering the temperatures computed by JHTE study. The wave equation in the frequency domain (4) is solved again. Since Impedance boundary condition is applied on the wall shared between dielectrics (included vacuum and air) and external carrier such analysis is applied only to the dielectrics; copper an steel volumes are excluded.

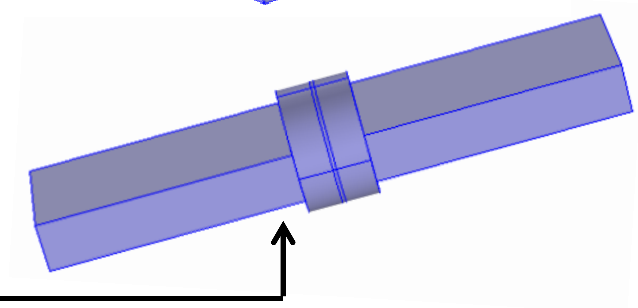
Virtual Prototype Set-Up

Joule Heating and Thermal Expansion – Electrical features:

- Joule Heating and Thermal Expansion *(tem)*
  - Thermal Linear Elastic Material 1
  - Joule Heating Model 1
  - Electromagnetic Heat Source 1
  - Boundary Electromagnetic Heat Source 1
  - Free 1
  - Electric Insulation 1
  - Thermal Insulation 1
  - Initial Values 1
  - Convective Cooling 1
  - Temperature 1
  - Ground 2
  - Normal Current Density 1
  - Fixed Constraint 1

From EMW →



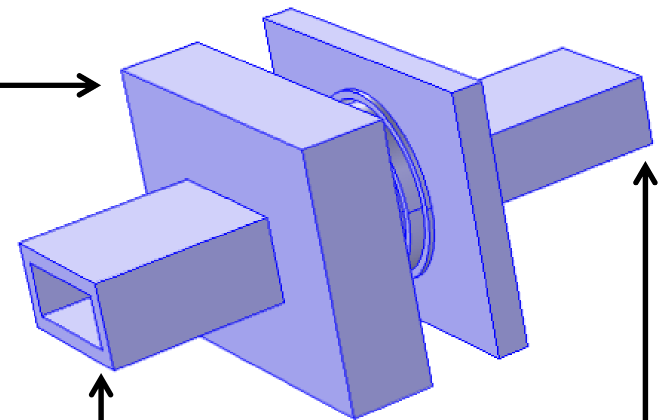


Such module computes the temperature and the displacement fields due to the thermal expansion. The joule effect is calculated by receiving the surface currents related to the electric field (from EMW) on the walls shared with the dielectrics. Such analysis is applied only on the DW carrier walls and alumina excluding air and vacuum, since the currents are on the surfaces shared between carrier walls and dielectrics. Ports are connected to the ground as in the reality.

Virtual Prototype Set-Up

Joule Heating and Thermal Expansion – Mechanical features:

- Joule Heating and Thermal Expansion *(tem)*
  - Thermal Linear Elastic Material 1
  - Joule Heating Model 1
  - Electromagnetic Heat Source 1
  - Boundary Electromagnetic Heat Source 1
  - Free 1
  - Electric Insulation 1
  - Thermal Insulation 1
  - Initial Values 1
  - Convective Cooling 1
  - Temperature 1
  - Ground 2
  - Normal Current Density 1
  - Fixed Constraint 1

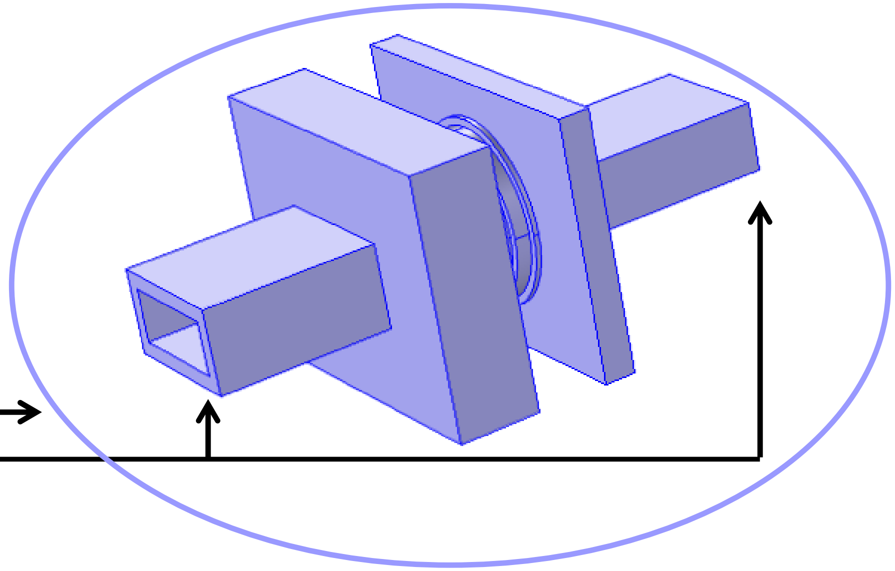


Solid model is isotropic and the structural transient behavior is quasi-static. The non ideal vacuum and the air atmospheres inside the DW volume are excluded from moment computations. The external metallic surface of DW waveguide input port is locked to the rigid structure of the vacuum tube to support the device. Thus it represents fixed constraints for the generation of the compressive forces induced by the thermal expansion.

Virtual Prototype Set-Up

Joule Heating and Thermal Expansion – Thermal features:

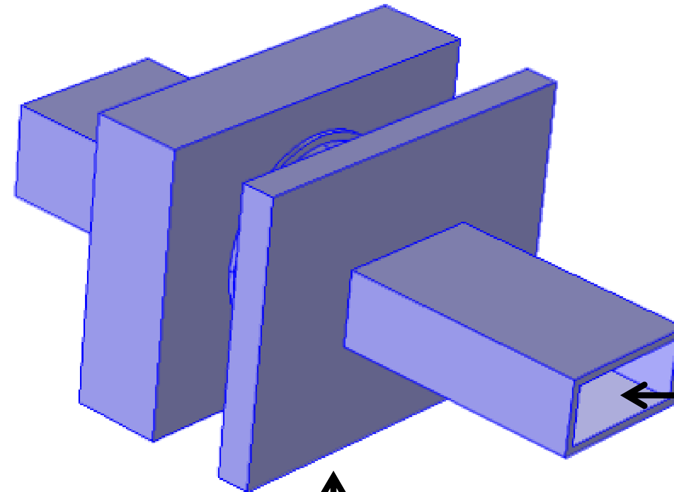
- Joule Heating and Thermal Expansion *(tem)*
  - Thermal Linear Elastic Material 1
  - Joule Heating Model 1
  - Electromagnetic Heat Source 1
  - Boundary Electromagnetic Heat Source 1
  - Free 1
  - Electric Insulation 1
  - Thermal Insulation 1
  - Initial Values 1
  - Convective Cooling 1
  - Temperature 1
  - Ground 2
  - Normal Current Density 1
  - Fixed Constraint 1



Together with the currents, this analysis take in input the temperature of the surface connected to the vacuum tube. This temperature has been set to set to 35°C, since many vacuum tubes such as Magnetrons or Klystrons and also their loads as LINAC's are thermostated at this value. The dielectrics are modeled only to consider the heat transfer through them.

Virtual Prototype Set-Up

Moving Mesh – Computation Set-Up:

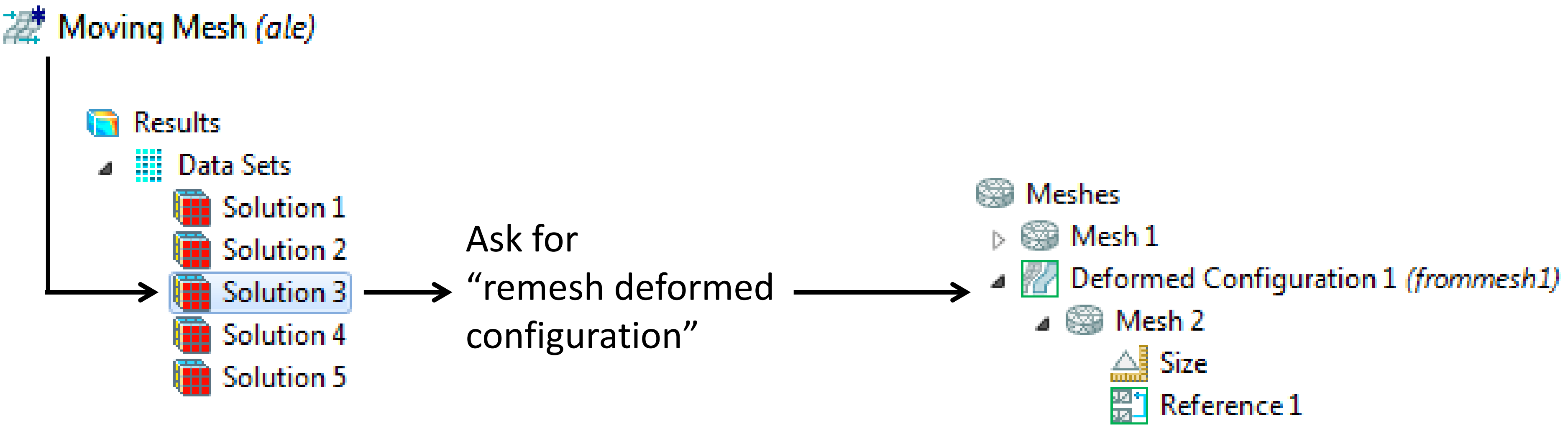


- Moving Mesh *(ale)*
  - Fixed Mesh 1
  - Prescribed Mesh Displacement 1
  - Prescribed Deformation 1 → Copper and steel external carriers
  - Free Deformation 1 → Air and vacuum
  - Prescribed Mesh Displacement 2 → Surfaces shared between carrier walls and dielectrics

copper and steel external carriers represent the volumes subjected to structural formulation by TS analysis. Air and vacuum volumes are free to move, since excluded from moment computations. surfaces shared between carrier walls and dielectrics, adjacent to the carrier volumes are deformed by the thermal stress computation and, by the MM computation, they can stretch the free deformable air meshes. Such meshes are used for the ultimate EMW analysis.

Virtual Prototype Set-Up

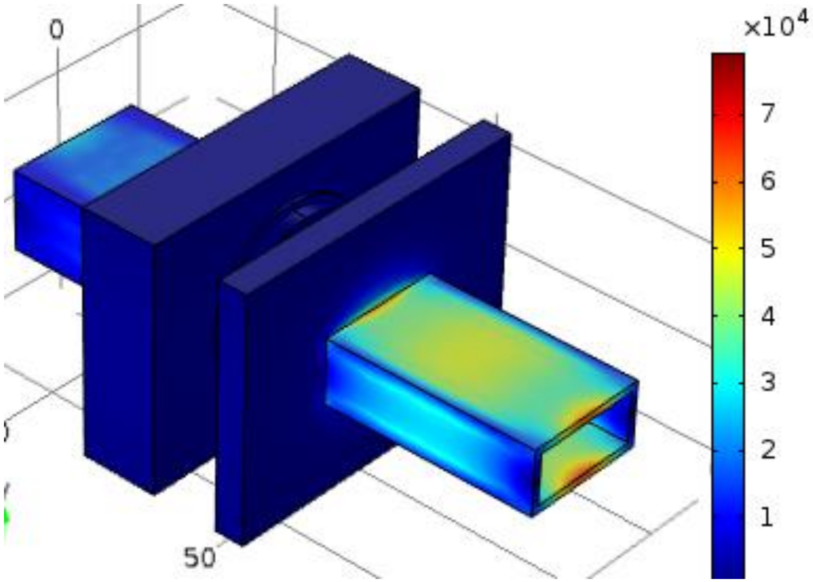
Moving Mesh – Remeshing:



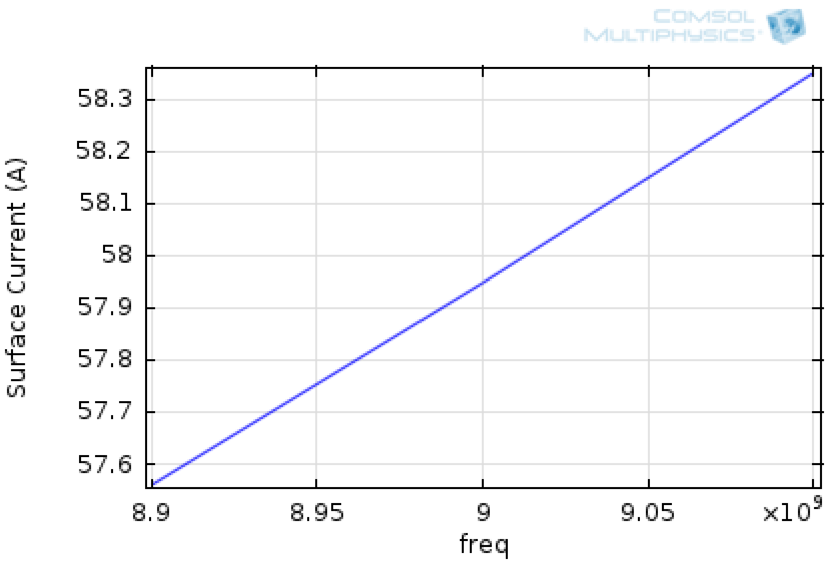
In order to search for the opportune shape which wen deformed, re-increase electromagnetic performances, the deformations of the whole structure have been considered by performing th e EMW study on new meshes: After MM study, new mesh configuration has been produced. In the solution related to the MM study, it has been asked to the calculator to remesh deformed configuration. A "deformed configuration" sub-node appeared in the "Mesh" node on the model three. In such sub-node, has been asked to "build all". New meshes have been produced. In the Frequency Domain study related to the final EM analysis the new meshes have been selected as the mesh in the "Mesh Selection" box.

Results

Surface current



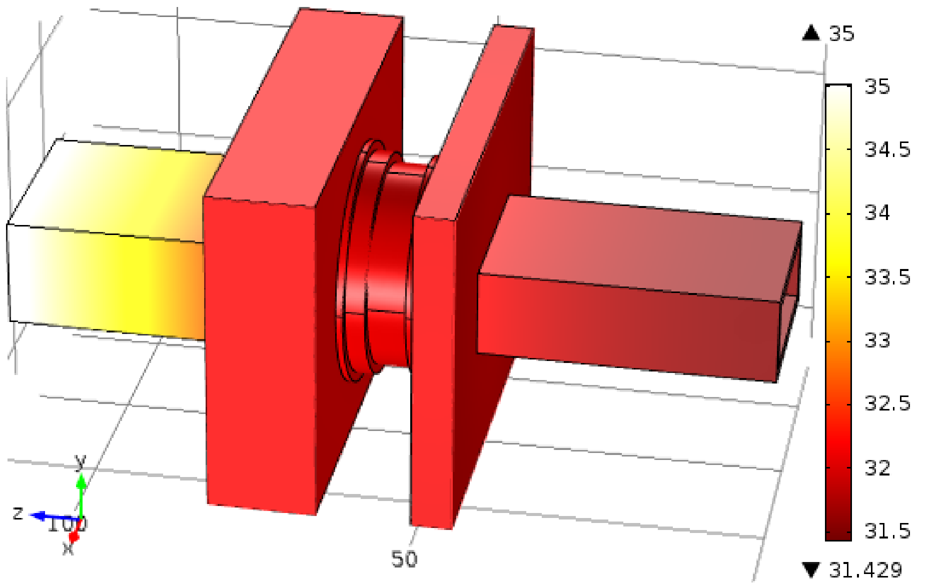
Surface Current Densisty (A/m²)



The proposed DW may operate connected with a Magnetron at a maximum power input of P_{peak}=3MW pulsed with a duty Cycle of δ=0.004%. By imposing a Power input of average power Pave = δ·P_{peak} = 120W, the EM FD stationary analysis has shown a maximum surface current density of I_s=58.3 A.

Results

Temperature

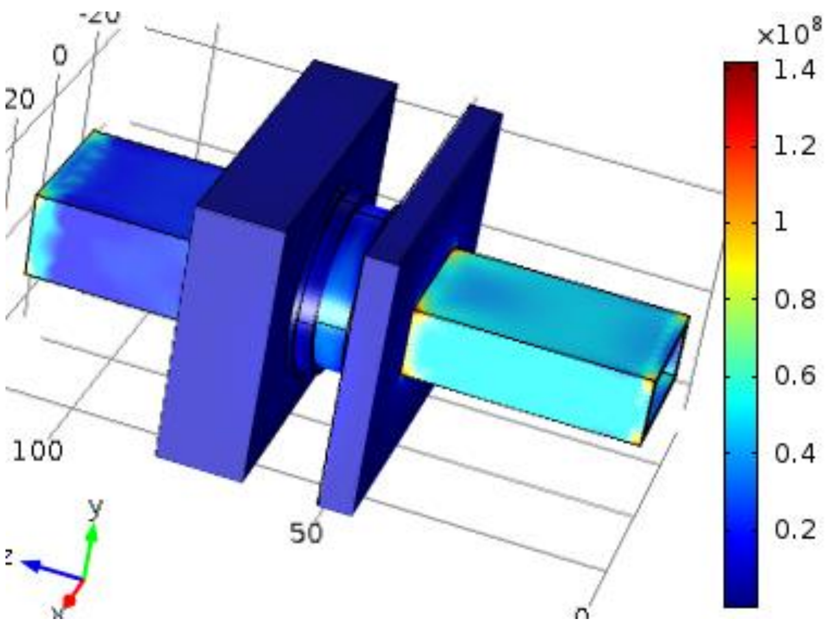


Temperature (°C)

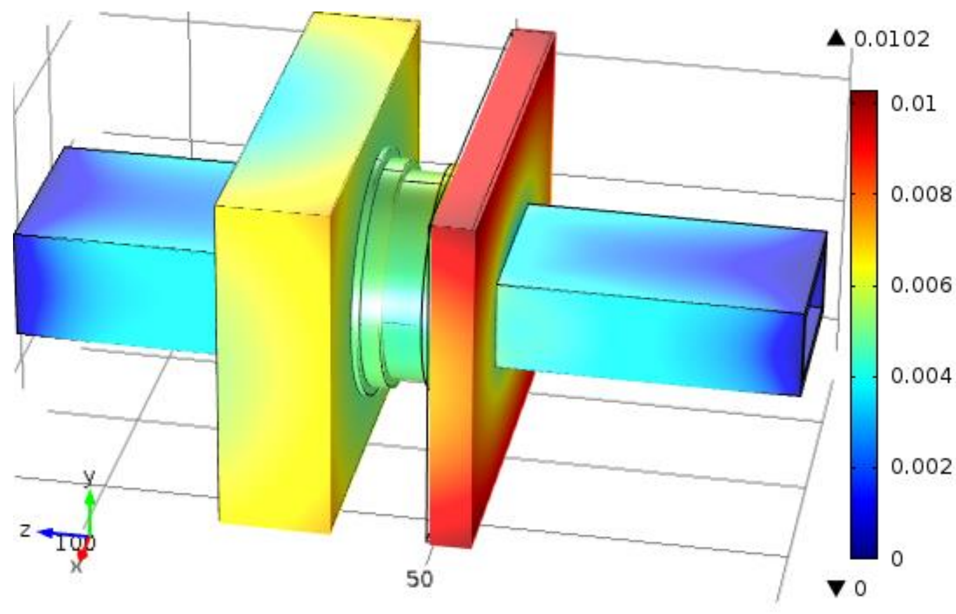
By receiving the current density shown above, at the maximum frequency, the JHTE analysis have given a maximum temperature of T = 35°C. This temperature induces the thermal expansion of the material with consequent compressive forces applied to the surfaces. The opportunely designed shape provide a certain deformation in order to mitigate the thermally degraded performances of the DW.

Results

Stress **Displacement**



Stress (N/m^2)

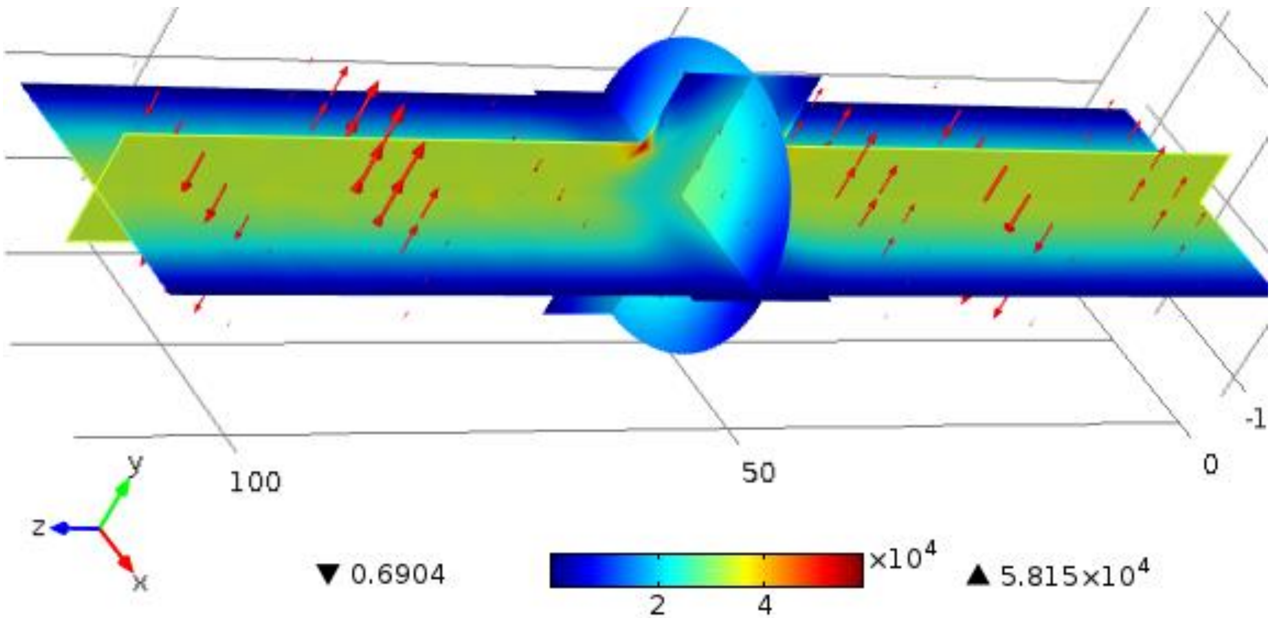


Displacement (mm)

The maximum stress is located at the junctions between the RWg and the flanges which connect the circular section of the DW. Since the input and output ports are fixed constraints and the whole DW is the heat source. Maximum stress is about 0.14 [GNm^{-2}]. The maximum total displacement is located on flange surface connected to the vacuum tube interface, this result is due to the further heating of the power tube. Such maximum displacement is about 10 µm

Results

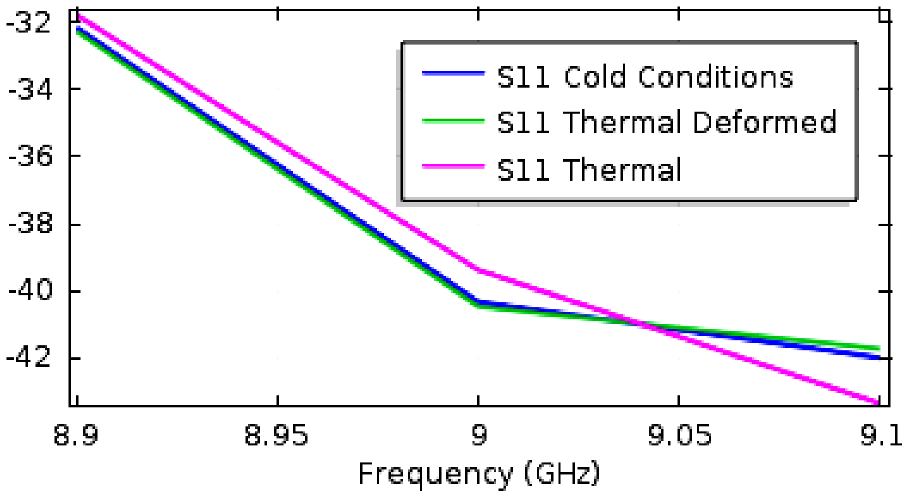
Electric field in thermo – mechanical subjected operative conditions

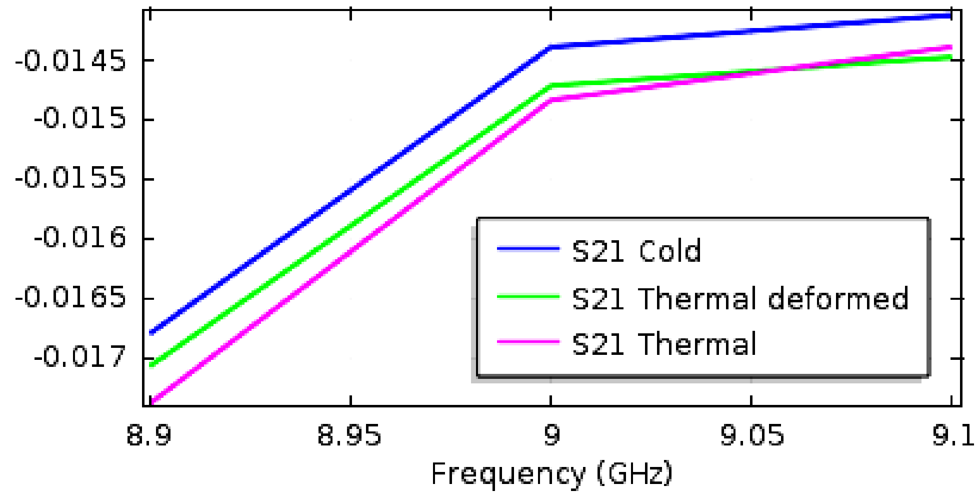


The simulation output shows the field power density distribution of the electric field under the thermal working condition imposed by the surface heating produced by the contact with the warm power tube and by the joule effect induced by the surface currents.

Results

Scattering Parameters





Scattering Parameters in cold condition (cold), and in operating condition by considering all the thermo mechanical conditions (Thermal Deformed) and by considering only the heating (Thermal). Scattering parameters at the DW ports shows how is possible, by adopting the multiphysics modeling based design of the DW, to ensure the mitigation of the power losses due to the surface currents. This results is evident by observing the improvement of the scattering parameters when the deformation is considered hence the EMW analysis is performed on the deformed meshes (Thermal deformed).

Conclusions

The DW design has been studied using **COMSOL**, and many aspects has been investigated, such as the **Joule effect** induced by the **dissipation of the electromagnetic power** traveling in the device and **the thermal contact with the High power source and the load** in addition to the **mechanical constraints** imposed by the physical support.

The **scattering parameters** and the **electric fields in cold and in thermo mechanical operative conditions** have been documented by considering the electromagnetic heating due to the joule effects induced by the power dissipation of the signal carried through the DW.

We have shown how to **mitigate the degradation of the performances**, induced by the thermal losses, by choosing an **opportune device shape** which, **when deformed** by its temperature, **modifies constructively the EM fields to re-increase performances**.

According to this study, the **appropriate materials have been chosen** in order to ensure the correct operation of the device in thermal stress critically affected working conditions.

The proposed device can ensure a minimum return loss of RL=32 dB with an maximum Insertion Loss IL=0.017 dB when it is carrying a pulsed power of P_{peak}=3MW with a Duty Cycle of δ=0.004%. provided by an X-Band Magnetron or Klystron.

It operates at the center frequency f=9 GHz with 200 MHz of Bandwidth.

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References

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