

Virtual Prototype of a Dielectric Window for High Power Microwave Tubes

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Abstract: This paper describes the Virtual Prototype of a Dielectric Window (DW) for High Power Microwave Vacuum Tubes and Linear Accelerators (LINAC). Design formulas are provided and Computer Aided Design techniques based on COMSOL Multiphysics are proposed. The virtual prototype considers the Thermo-mechanical effects due to the joule effect induced by the power which crosses the DW and the Thermal contact with the Tube connected to the device. The proposed analysis involves Electromagnetic Waves (EMW), Joule Heating and Thermal Expansion (JHTE) and Moving Mesh (MM) interfaces of COMSOL Multiphysics. 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.

Keywords: Dielectric Windows, High Power Microwave Tubes, Joule Heating and Thermal Expansion, Moving Mesh, Electromagnetic Waves.

1. Introduction

MICROWAVE VACUUM TUBES are the principal sources adopted where High Power signals are needed. Such devices employ Dielectric Windows 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. Dielectric Windows are made by a waveguide section, in which a solid dielectric medium is inserted.

Typically, energy transport systems are based on rectangular waveguide (RWg) and, due to technological reasons, dielectric windows are based on circular waveguide (CWg) sections. For

these reasons, the most common kind of window is the pill-box type which consists of a CWg section, at which centre a dielectric (typically ceramic) cylindrical plate is enclosed. CWg section terminates on both sides to two CWg to RWg transitions. Vacuum windows also enable the RWg to be filled with SF₆ for high-power transmission. Several technological solutions can be adopted, as for example long pill-box type windows, with a very long longitudinal size, or with oversized diameter.

Usually, design of Radiofrequency (RF) structure can be achieved by using a circuit model and in all cases RF analysis, using high-frequency simulation codes, allows to optimize properties of the RF structure. For high power transfer, oversized circular plates are sometimes employed in order to reduce the RF field strength on the ceramic surface by increasing the diameter of its ceramic part compared to an ordinary pill-box type window [1]. An image of such window is depicted in Fig. 1 and a schematization of its internal geometry with the fundamental electric fields is reported in Fig. 2.

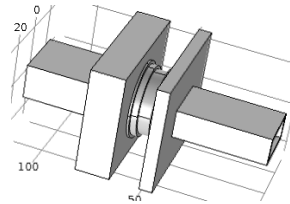


Fig. 1. A Pill-box Window inserted between two RWg sections. The larger RWg section (on the left) is the normal atmosphere side to be connected to the load.

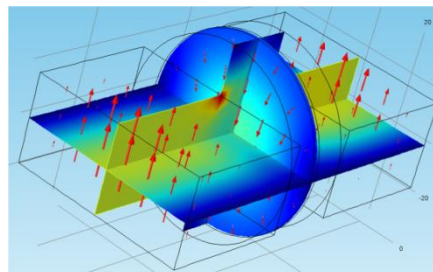


Fig. 2. Geometry and Fundamental modes Electric Field Distributions in a Pill-box DW connected to two RWg sections. The circular slice represents the medium surface of the alumina ceramic dielectric disk.

1.1 Analytical Approach

The pill-box window consists of a CWg section of length L , at which centre a dielectric disk is inserted and at which ends CWg to RWg transitions are placed. One RWg face is connected to the HPM power tube and the other is connected to the Load. The CWg subsection on the power tube side is in an UHV atmosphere and the subsection on the load side is filled by dry air or high dielectric strength gas, such as for example SF6.

Also in this case, due to the similarity of the dielectric constants of vacuum, air and SF6, for simplicity we can approximate the two CWg sectors as filled by the same dielectric. Since the CWg is partially filled with alumina ceramic, this may be treated as equivalent to the CWg filled uniformly with a dielectric having effective relative permittivity ϵ_r' . 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' [1]. Magnetic permeability of these mediums has been considered as 1.

Since the power transport system is based on RWg, we can consider λ_{gR} as a known value. As shown in [1], the CWg radius which ensures the local transparency of the discontinuity can be found by the (1)

$$r = \frac{\lambda_0 p'_{11}}{2\pi \sqrt{1 - \frac{\lambda_0^2}{\epsilon_r' \lambda_{gR}^2}}} \quad (1)$$

where λ_0 is the wavelength on free space, ϵ_r' is the dielectric constant of the medium which fills the waveguides, a is the long side of the RWg and r is the radius of the CWg. p'_{11} is the first zero of the one order Bessel function derivative ($p'_{11} = 1.841$), f the NM resonant frequency of the power tube and c_0 is the speed of the light in the vacuum.

In order to have high EM transmission, high purity alumina can be employed as the dielectric medium for the disk interposed between the two CWg subsections. Such 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 F_n , avoiding breakdowns or significant deformations. This direct stress corresponds to

the pressure P which the dielectric cylindrical disk experiences on its area in contact to the UHV [1].

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

Thickness t of the dielectric plate is to be optimized by using computer-aided design tool in order to maximize the microwave transmission efficiency of the window. Due to the waveguide pressurization adopted, the maximum pressure on the plate can be assumed to be less than 2 Bar. As high transparency medium for the dielectric plate, we have chosen an Al₂O₃ 97.6%. In order to employ a plate radius of about 30-40 mm, a good thickness in the above condition, should be around 1 mm [1].

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 [1], the total length of the CWg section can be calculated by applying the (3)

$$L = \lambda_{gR} \frac{\sqrt{\epsilon_r'} b}{2 a} \quad (3)$$

in which a and b are respectively the long and the short side of the RWg cross section.

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 $\epsilon_r = 1$ we obtain $\lambda_{gR} = 49$ mm and $\lambda_0 = 33$ mm. The DW can be dimensioned as follows: By applying the (1) with $\epsilon_r' = 1.5$ we obtain a radius of $r = 12$ mm. From the (2) results that the total length of the CWg is $L = 13$ mm.

1.2 Multiphysics Approach and Motivations

The power dissipation due to the Joule effects related to the high power in transit inside the DW produces a considerable temperature increase. Such temperature receives an additional contribution to the connected Microwave device at which is connected, principally by thermal conduction through the connection faces. The temperature increase induces a thermal

expansion of the whole structure. If the DW temperature reaches an excessive value, significant surface losses may occur.

The thermal expansion of the materials may also induce significant stresses and strains with consequent displacement of the DW structure, which alter the desired EM behavior of the device. These multiple unwanted effects make the EM performances decrease. In order to perform the complete characterization of the DW, Joule effects induced by the transported power and thermal effects due to the heating of the device connected to the DW must be considered.

A Frequency Domain (FD) study has been performed to compute the electric field inside the DW when the microwave power is applied to its input port, considering the output interface closed on matched impedance.

Such electric field is related to surface currents which are employed as input feature to the computation of the joule heating.

JHTE module with a stationary analysis computes the global temperature and deformations when the heat generated by these two contribution has been diffused on all the reachable DW components and the system has become thermally stable; since the external temperature is by then steady over all the DW outer boundaries, which are exposed to the external environment.

2. Use of COMSOL Multiphysics

The main EM optimization of the analytical model has been performed by using the EMW Module of COMSOL. Once the DW is designed, a Virtual Prototype has been developed in order to consider the multiple effects related to the Joule heating and Thermal Expansion described above. The model has been developed by employing the version 4.4 gently conceded in evaluation copy by COMSOL Italy.

In the proposed analysis the vacuum can be considered effectively as the real medium which fills the UHW side of the DW, because we can set such region composed by a non ideal vacuum that is air at the pressure of 10^{-7} mbar. The normal atmosphere side is air at the pressure of 2 bars. We show how is possible to mitigate the degradation of the performances induced by the thermal losses by choosing a device shape and

material which, when deformed by its temperature, modify constructively the EM fields re-increasing performances.

2.1 Electromagnetic Model Optimization

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, 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 has been optimized by an EM simulation.

The aim of the simulation is to search the optimum values of L and t which provide the minimum reflection parameter S_{11} and the maximum transmission parameter S_{21} at the two ports of the Pill-box Window. EM simulation has been performed setting two vacuum circular sections of radius r and variable length L , which enclose the dielectric plate, as previously defined and 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 considers the field penetration inside the conductor, according to its skin depth. At the RWg's external faces, TE ports are placed.

The wave equation in the frequency domain (4) has been computed by employing the EMW module [17].

$$\nabla \times \mu_r^{-1}(\nabla \times \bar{E}) - k_0^2(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0})\bar{E} = 0 \quad (4)$$

where μ_r is the permeability, ϵ_r the permittivity and σ the electric conductivity of the material; ϵ_0 is the permittivity of the vacuum, k_0 the wave number in free space, ω the wave angular frequency and \bar{E} the electric field. Fields are computed in the dielectric (Non ideal Vacuum, Air and Alumina) and guided by the copper surfaces shared with the DW carrier walls.

The solution is computed by a Stationary solver at the operative frequency f , by sweeping the length L and the thickness t and calculating the scattering parameters at two ports.

Simulation has been set with the DW values analytically calculated above, $L = 13$ mm and $r = 12$ mm, and an Al_2O_3 97.6% plate of thickness $t = 1$ mm. This Alumina presents a dielectric constant of $\epsilon_r = 9.0$ in S band, which in the simplified analytical dimensioning has not been considered properly. By introducing this value in a numeric computation, we obtained an accurate dimensioning of the structure. Optimization has shown an optimum length of the circular sections $L = 14$ mm and optimal dielectric plate thickness $t = 0.7$ mm, as reported in Fig. 3.

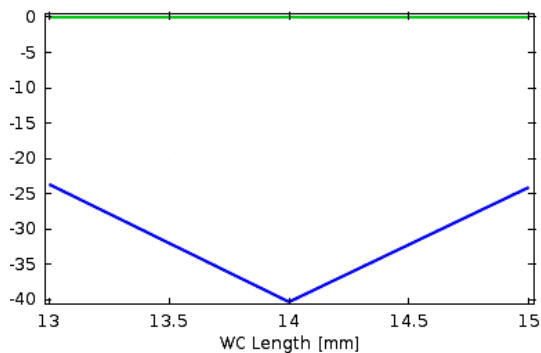


Fig. 3. Simulated S_{11} (blue trace) and S_{21} (green trace) in dB @ 9 GHz versus the CWg length L (mm), $S_{11} = -40$ dB for $L = 14$ mm and $t = 0.7$ mm.

2.2 Virtual Prototype

The Virtual Prototype consists of an accurate Multiphysics model which considers concurrently the EM aspects with the surface losses and related Joule effects and the thermo mechanical aspects at the same time. In order to save computational costs while maintaining a high grade of reliability, several strategies have been adopted: The Thermo mechanical with joule effect computation and EM analysis have been independently performed in the effective spaces in which respectively structural stresses and EM waves must be computed; then, by considering the thermo structural alteration, a mesh modification has been applied to the whole space, including the region of the EM computation.

The solver is organized in performing the following steps:

First, a frequency domain analysis to compute the Electric Field by receiving the power at the input port. This study is applied only to the dielectrics.

Subsequently, a stationary analysis to compute the joule effects by receiving the surface currents related to the electric field previously computed. Joule effects have been computed 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. 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 LINAC's are thermostated at this value. The dielectrics are modeled only to consider the heat transfer through them.

Displacements are received in input by the MM calculation in order to move the meshes of the whole system, including the vacuum volume, in which the thermo mechanical analysis has not been performed.

Then a stationary analysis to calculate the electric fields in the frequency domain and the scattering parameters.

The DW EM behavior, altered by the thermo mechanical and EM heating factors has been evaluated by a linking the JHTE analysis results on the whole DW to an EM simulation. Computed displacements have been used by the MM calculation to produce new meshes.

The ultimate EM analysis has been performed on these moved meshes, considering the temperatures computed by JHTE study. The wave equation in the frequency domain (4) has been solved again in this step. Such analysis is obviously applied only to the dielectrics; copper and steel volumes are excluded.

Due to the simplicity of the geometry, default settings have been adopted, by choosing Physic controlled mesh with finer element size. Complete mesh consists of 28806 elements. Minimum element size is 10.1 mm, which corresponds to 4.8λ , where λ is the wavelength at 9 GHz.

2.3 Electromagnetic Waves Module Features

EM FD analysis has been performed between 8.9 and 9.1 GHz. In order to consider the computed temperature resulted from the JHTE analysis, the information has been inserted as the default temperature in all the features in the EMW module settings, where required. Such temperature information allows for the

computation of the losses in the different heating situations.

The wave equation in the frequency domain (4) has been computed by the EMW module, considering the surfaces losses, by employing the following features [2]:

- Impedance boundary condition: The DW surfaces, shared between dielectrics and carrier walls, are modeled in order to consider the losses due to the partial penetration of the electric field in the lossy material which constitutes such walls. This condition allows to exclude the anode and cathode domain to the EMW calculation, avoiding the meshing and saving computational cost. The specified thickness of the wall boundaries is fixed to 3 mm.
- Rectangular port: In order to allow EM energy enters or exits the waveguide, a rectangular port has been used to modeling the Waveguide port. This port is set to launch and absorb the TE10 mode of a RWg.

2.4 Joule Heating and Thermal Expansion Module Features

The accurate Thermo-mechanical with Joule effect analysis has been performed in order to estimate the mechanical modification and temperature alteration when the DW operates at full power. This study has been modeled in the JHTE module.

In this model, DW the external side of the walls is intended as cooled by the external environment. Solid model is isotropic and the structural transient behavior is quasi-static. For this analysis we have considered the temperatures dependent of the displacements and a coupled computation has been adopted. The JHTE module is employed to solve the system of steady state equations (5-9) [3]:

$$-\nabla \cdot \sigma_s = \bar{F}_v \quad (5)$$

$$\nabla \cdot \bar{J} = \bar{Q}_j \quad (6)$$

$$\bar{J} = \sigma \bar{E} + \bar{J}_E \quad (7)$$

$$\bar{E} = -\nabla V \quad (8)$$

$$\rho C_p \bar{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \quad (9)$$

where σ_s is the stress and \bar{F}_v is the force per unit volume; J is the current density, \bar{Q}_j the

current source, \bar{J}_E the external current density, V the electric potential, ρ is the density of the material, C_p the heat capacity at constant pressure and k the thermal conductivity of the material. Q is the heat source, \bar{u} is the spatial displacement vector, T is the temperature, k the thermal conductivity of the material and Q is the heat source.

The JHTE module describes the model by employing the following features [3]:

- Heat transfer in Fluids: The non ideal vacuum and the air atmospheres inside the DW volume are modeled only to describe the heat transfer and excluded from moment computations.
- Fixed constraints: 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.
- Temperature: The same external surfaces of the DW input port is connected to the vacuum tube, which is typically cooled by high efficiency fluid cooling systems. The temperature of tube outer boundaries is constant and equals the cooling fluid temperature. This temperature has been fixed to 35°C, consistently with many typical Magnetrons, Klystrons and LINAC's cooling systems.
- Convective cooling: The outer surface of the DW carrier walls are intended as exposed to the external atmosphere filled with air. In order to not include an external volume with air flux modeling, the convective cooling boundary condition has been introduced. In order to consider the transfer by the DW surface in contact with the air, a Heat Transfer coefficient of $h=5 \text{ Wm}^{-2}\text{K}^{-1}$ has been assumed.
- Ground: The input and output port surfaces, to be shared with the power tube and the load are referred to ground potential.
- Normal Current Density: The surfaces shared between carrier walls and dielectrics are the surface in which flows the current related to the electric field produced by the power input of the DW. For this reason, these boundaries are modeled by introducing this feature, in which the values of the surface currents computed by the EMW analysis have been linked as $J_0 = \text{emw.Jx, emw.Jy, emw.Jz}$.

2.5 Moving Mesh Module Features

The MM module is employed to give the rules on how to move the mesh in function of the displacement computed by the JHTE analysis. In order to perform the EM analysis on the deformed geometry, the MM module uses the following features [4]:

- Prescribed deformation: The carrier wall structure of the DW and the alumina represent the volumes subjected to deformation. The displacement vectors (u , v , w) computed by the JHTE module are employed to specify this volumetric deformation. Its prescribed mesh displacement is set to $d_x=u$, $d_y=v$, $d_z=w$. Free deformation: The non ideal vacuum and air volumes (which are not subjected to any structural elastic formulation by the JHTE analysis) are free to move. Initial deformation is set to $dx_0=0$, $dy_0=0$ and $dz_0=0$.
- Prescribed Mesh Displacement: This condition specifies that the boundary is to be deformed by the JHTE computation, though is attached to the free deformation air and non ideal vacuum boundaries. Such surfaces are subjected to deformation. This superficial displacement has been specified by setting the prescribed mesh displacement to $d_x=u$, $d_y=v$, $d_z=w$.
- After this 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 tree. 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 in the “Mesh Selection” box.

3. Results

3.1 Surface Current

The proposed DW may operate connected with a Magnetron at a maximum power input of $P_{\text{peak}}=3\text{MW}$ pulsed with a duty Cycle of $\delta=0.004\%$. By imposing a Power input of average power $P_{\text{ave}} = \delta \cdot P_{\text{peak}} = 120\text{W}$, the EM FD stationary analysis has shown a maximum surface current density of $I_s=58.3\text{ A}$. The current density in frequency trend is reported in Fig.4

and the surface current density distribution on the DW walls is depicted in Fig. 5.

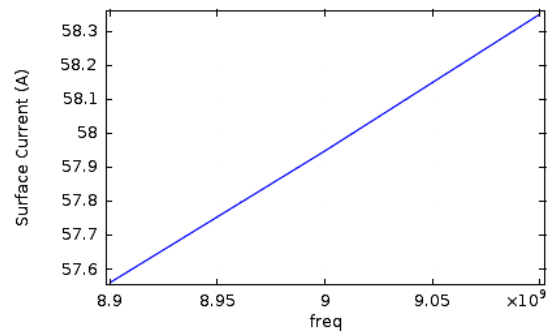


Figure 4. Surface Current (A) versus Frequency (Hz).

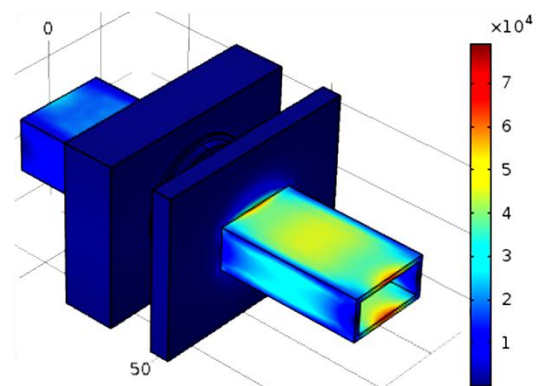


Figure 5. Surface Current Density (A/m^2).

3.2 Temperature

By receiving the current density shown above, at the maximum frequency, the JHTE analysis have given a maximum temperature of $T = 35^\circ\text{C}$. This result is shown in Figure 6.

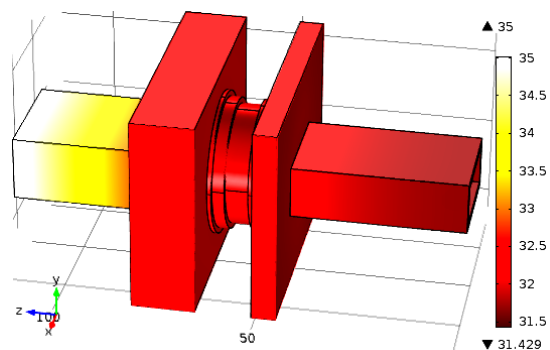


Figure 6. Temperature ($^\circ\text{C}$).

3.3 Stress and Displacement

In order to underline the deformation, stress and displacement are been plotted with a

magnified scale, so that the deformation scale has been increased. In the following figures, black outlines represent the original conformation, and the stained volume represents the deformed structure.

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 $0.14 \text{ [GNm}^{-2}\text{]}$ as shown in Figure 7.

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 $10 \text{ }\mu\text{m}$ and is shown in Figure 8.

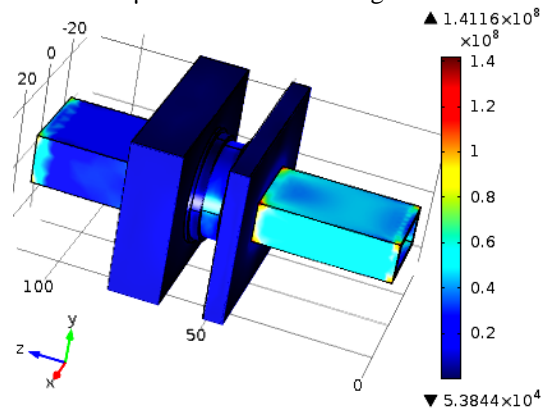


Figure 7. Stress (Nm^{-2}) – Magnified.

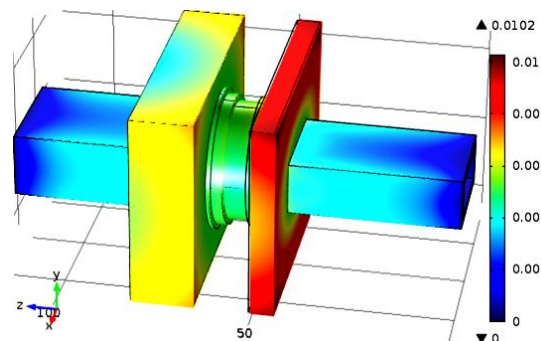


Figure 8. Displacement (mm) – Magnified.

3.4 Electric fields

In Fig. 9 we report the 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.

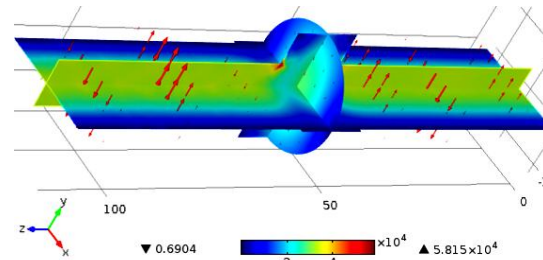


Figure 9. E field (Vm^{-1}) - cross section – working conditions.

3.5 Scattering Parameters

Scattering parameters at the DW ports are described in Fig. 10 and 11. Note that, by adopting the multiphysics modeling based design of the DW, we have ensured the mitigation of the power losses due to the surface currents. This result is evident by observing the improvement of the scattering parameters when the deformation is considered i.e. the EMW analysis is performed on the deformed meshes.

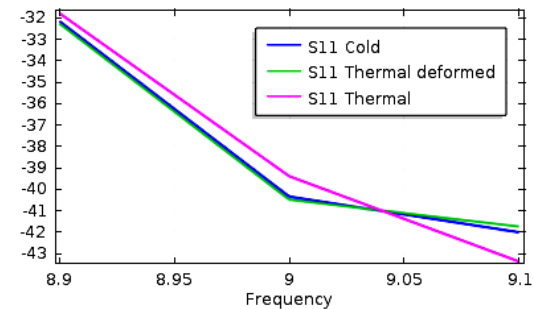


Figure 10. Scattering Reflection Parameters (dB) versus Frequency (GHz) in cold condition, in operating condition by considering all the thermo mechanical conditions (Thermal Deformed) and by considering only the heating (Thermal).

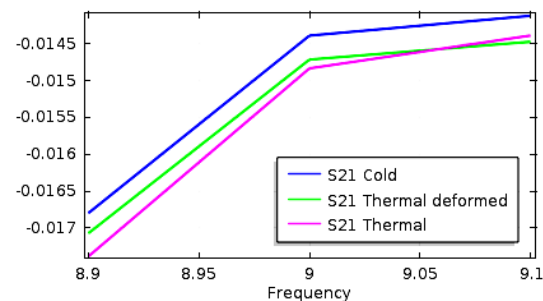


Figure 11. Scattering Transmission Parameters (dB) versus Frequency (GHz) in cold condition, in operating condition by considering all the thermo mechanical conditions (Thermal Deformed) and by considering only the heating (Thermal).

4. 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 EM 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 EM heating due to the joule effects induced by the power dissipation of the signal carried through the DW.

This design technique have allowed for the correct dimensioning of the DW which ensures the compensation of the power losses due to the alterations in operative conditions with a better matching of the deformed structure.

We have shown how to mitigate the degradation of the performances, induced by the thermal losses, by choosing a device shape which, when deformed by its temperature, modify 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 a maximum Insertion Loss $IL=0.017$ dB when it is carrying a pulsed power of $P_{peak}=3$ MW with a Duty Cycle of $\delta=0.004\%$ provided by an X-Band Magnetron or Klystron. It operates at the center frequency $f=9$ GHz with 200 MHz of Bandwidth.

8. References

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