Microwave response of ITER vacuum windows

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HIGHLIGHTS

- Microwave response of ITER vacuum windows.
- Analytical microwave response dielectric slab.
- Simulated microwave response of dielectric slab.
- Finite element and finite integration technique.
- Comparison analytical response to simulated response.
- Microwave response of tilted or wedged vacuum windows.

ARTICLE INFO

ABSTRACT

Diagnostic systems are essential for the development of ITER discharges and to reach the ITER goals. Many of these diagnostics require a line of sight to relay signals from the plasma to the diagnostic, typically located outside the torus hall. Such diagnostics then require vacuum windows that isolate the torus vacuum and, crucially, ensure containment of hazardous substances. While such windows are routine in many fusion experiments, ITER poses new challenges. The vacuum windows are safety important components class 1 that must withstand all ITER loads. As a consequence, in many cases double disk windows are used with modified frequency response as compared to single disk windows. ITER is a long pulse machine with 20 MW microwave heating installed, giving rise to gradual heating of windows due to stray radiation. The particular microwave heating scheme at ITER may also – in case of an erroneous polarization setting – result in a refracted beam with much higher power density. This paper looks at microwave aspects of ITER windows. The microwave response as a function of frequency is calculated for proposed arrangements. From this response the impact on diagnostic performance may be assessed as well as the thermal load on the window itself.

1. Introduction

Vacuum windows provide lines of sight for optical and microwave electro-magnetic (EM) waves. At the window boundary the wave encounters an impedance mismatch causing reflection while the transmitted fraction undergoes absorption. Given a particular system an optimization of the window arrangement can be made by selecting the type of ceramic and thickness and spacing between disks. However, windows at ITER are also safety important components (SIC) – as they are barriers for hazardous substances – limiting these options. This paper reports on methods and tools to find fractions of transmitted power (T), reflected power (R) and absorbed power (A) as a function of frequency in the microwave range. With these quantities the impact of the window on the diagnostic or heating system and the load on the window can be evaluated.

Different system requirements combined with boundary conditions, such as sizes and fixtures, have led to the development of a set of windows using different dielectric materials. Clear apertures range from 25 mm to 160 mm in a double disk arrangement (with the exception of CVD-diamond windows used for gyrotrons [1]). The disk thickness is still under review given SIC concerns. In this work a thickness $d = 12$ mm is used for illustrative purposes. As disk material ITER foresees fused silica, crystalline quartz, sapphire, zinc selenide, silicon nitride, and CVD diamond. For examples in this paper properties of fused silica are used, type Infrasil301^{TM} by the company Heraeus with $\epsilon_r = 3.81$, and $\tan\delta = 2.9 \times 10^{-4}$ at 90 GHz.
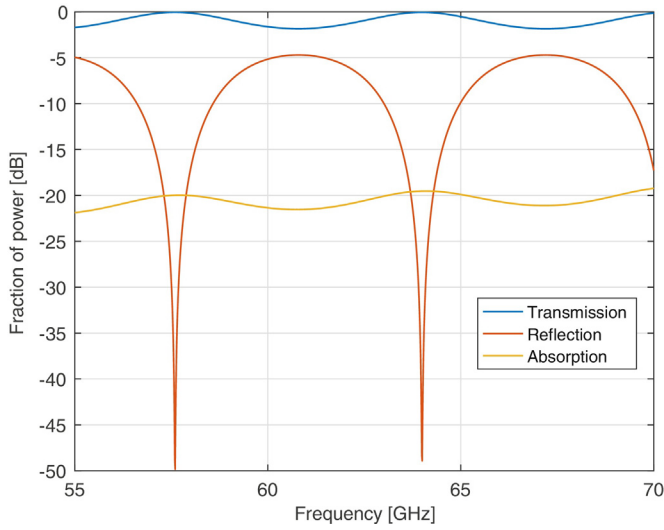
Fig. 1. Frequency response of a fused silica disk with $d = 12$ mm (radius $\gg \lambda$: TEM-mode propagation considered).

Fig. 2. Absorbed fractions of power in the disk of Fig. 1.

2. Review of microwave window response

The theory of reflection and transmission of multiple dielectric slabs is well understood [2]. Application to vacuum windows in waveguides is more specific, although good literature is available here too, e.g. [3–5]. In this section a review is given on how to analytically obtain a multilayer disk response including losses inside a waveguide. This is followed by comparison to results from a simulation code with the aim to also assess more complex structures such as double disk tilted windows.

2.1. Response of a single dielectric slab

An EM-wave perpendicularly incident on a dielectric slab of infinite thickness will be partly reflected denoted by the field reflection coefficient Γ_b on the boundary. In case of non-magnetic materials $\Gamma_b = \frac{1-n}{1+n}$ [2], with n the refractive index $n = \sqrt{\epsilon_r}$ and ϵ_r the relative permittivity. R at normal incidence is in such case Γ_b^2 and is minimized for n approaching unity. A practical disk has thickness d giving rise to multiple reflections within the disk leading to an interference pattern of T and R as function of frequency. The multiple reflections in this simple geometry can be summed and they converge to give the total reflected fraction of electric field Γ_{tot} and the total transmitted fraction of electric field t_{tot} [2] as follows:

$$\Gamma_{tot} = \frac{\Gamma_b\left(1 - e^{-j\varphi}\right)}{1 - \Gamma_b^2 e^{-j\varphi}}, \qquad t_{tot} = \frac{(1 - \Gamma_b^2)e^{-j(1/2)\varphi}}{1 - \Gamma_b^2 e^{-j\varphi}}. \tag{1}$$

φ is the electrical length of one round trip inside the dielectric: $\varphi = 2\beta d$ with β the phase constant of the propagation constant $\beta = 2\pi/\lambda$ and λ the wavelength inside the dielectric, i.e. the vacuum wavelength divided by $\sqrt{\epsilon_r}$ and d the thickness of the disk. Losses can be taken into account by redefining ϵ_r as the complex permittivity $\epsilon_r = \epsilon_r'(1 - j\tan\delta)$, in which the term $\tan\delta$ is the loss tangent and ϵ_r' is the real part of the relative permittivity. With this definition the real part of β represents the attenuation constant and the imaginary part represents the phase constant. By taking the complex conjugates of Γ_{tot} and t_{tot}, R and T are obtained and $A = 1 - T - R$. Fig. 1 shows a plot of T, R, A on a dB scale ($10 \cdot \log_{10}$ of the quantities). A modest frequency is used to allow simulation later.

Transmission is optimized in case the initial reflected wavefront is in counter phase with the wavefronts reflected by the internal reflections. This is called resonant and occurs when $\Gamma_{tot} = 0$
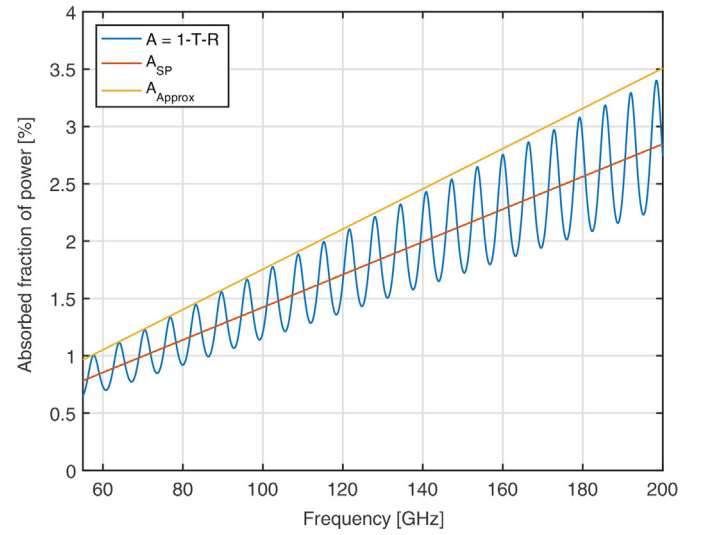
resulting in $d = m \cdot \frac{1}{2}\lambda$ with m an integer. The transmission cannot be at 0 dB (100%) due to the absorbed fraction of power. These losses are in this case at -20 dB (1%). In terms of signal loss for the system this is low, but at high power, such as caused by gyrotrons, the dielectric heating may be high. To assess the losses quickly one could also look at the single-pass loss or an approximation in case of multiple reflections. The single-pass loss follows from the attenuation constant α in the propagation constant $\gamma = \alpha + j\beta$, recalling that the variation with distance of the electric field is written as $E(z) = E_0 e^{-\gamma z}$, with z the distance in the direction of propagation. Solving the Maxwell equations accounting for losses it is shown that for low-loss materials $\alpha \approx (\pi f \sqrt{\epsilon_r'} \tan\delta)/c$ [6]. The single-pass absorbed fraction of power is $1 - e^{-2\alpha z}$, which for $\alpha z \ll 1$ can be approximated by $2\alpha z$ and single-pass A becomes:

$$A_{SP} \approx \frac{2\pi f \sqrt{\epsilon_r'} \tan\delta}{c} d. \tag{2}$$

Nickel [7] showed that in the case of multiple reflections the loss may be approximated by:

$$A_{Approx} \approx \frac{\pi f (1 + \epsilon_r') \tan\delta}{c} d, \tag{3}$$

i.e. a factor $(1 + \epsilon_r')/2\sqrt{\epsilon_r'}$ larger then the single-pass result. The three different results for the lost fraction of power in the disk are plotted in Fig. 2.

Eq. (3) gives a minor overestimate but is safe to use in all cases.

2.2. Multiple disks in waveguide

The model used in Section 2.1 uses TEM-mode propagation and a single disk. However at ITER multiple disks situated inside a waveguide will be used. Depending on the ratio of radius to wavelength, TE or TM propagation must be used opposed to TEM. In such a case dividing the window assembly in cascaded sections and applying matrix calculus may be used. Such work is covered in [3–5]. Here, an extract for circular wave-guides using the dominant TE_{11} mode is reproduced to allow assessment of ITER windows and comparison to the response obtained using simulation.

The S-matrix for a disk in waveguide is given by:

$$S = \frac{1}{1 - \Gamma_{mn}^2 e^{-2\gamma_{mn}d}} \begin{bmatrix} \Gamma_{mn}\left(1 - e^{-2\gamma_{mn}d}\right) & \left(1 - \Gamma_{mn}^2\right)e^{-\gamma_{mn}d} \\ \left(1 - \Gamma_{mn}^2\right)e^{-\gamma_{mn}d} & \Gamma_{mn}\left(1 - e^{-2\gamma_{mn}d}\right) \end{bmatrix} \tag{4}$$
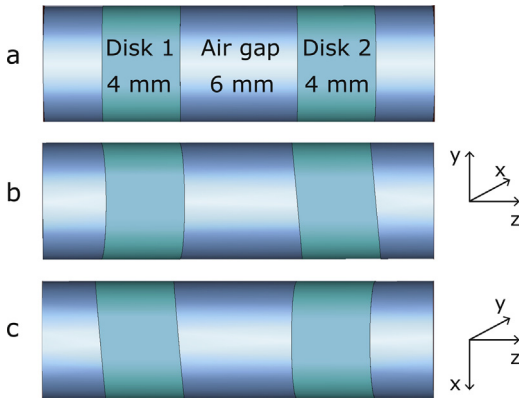
Fig. 3. Small scale double disk arrangement for modelling: (a) disks are parallel, (b–c) with tilted disks. Rotating (b) over the horizontal axis clock wise 90° (as seen from the right) gives (c). The window radius is 3 mm, *z* is the direction of propagation. The overall arrangement is enclosed in a circular waveguide.

In which the mode-dependent propagation coefficient is:

$$\gamma_{mn} = \sqrt{k_{cmn}^2 - \epsilon_r' k_0^2} \tag{5}$$

with $k_0 = 2\pi f/c$ and k_{cmn} is the quantity that modifies the propagation depending on mode and wave-guide size. For a circular waveguide with dominant TE_{11} mode $k_{cmn} = 1.841/r$ with r the radius of the waveguide [8]. The mode-dependent reflection coefficient for TE-modes Γ_{mn} is:

$$\Gamma_{mn} = \frac{\sqrt{1 - \left(k_{cmn}/k_0\right)^2} - \sqrt{\epsilon_r' - \left(k_{cmn}/k_0\right)^2}}{\sqrt{1 - \left(k_{cmn}/k_0\right)^2} + \sqrt{\epsilon_r' - \left(k_{cmn}/k_0\right)^2}} \tag{6}$$

The equations have been implemented in a MATLAB® code which reads *d*, the disk spacing and ϵ_r' of each section from a spread sheet and computes the S-matrices. While such S-matrices are convenient for lab measurements they are not well suited for matrix manipulation and thus each S-matrix is converted to a T-matrix as suggested in [5]. The T-matrices are multiplied right to left and the overall product is converted back to an S-matrix. *R* is extracted as $S_{11}S_{11}^*$ and *T* is extracted as $S_{21}S_{21}^*$. Losses are included again by replacing the relative permittivity with the complex permittivity. The code takes a few seconds to run. A result is shown in Section 2.3.

2.3. Simulation model

A fundamentally different method to obtain the microwave response is to use simulation. The frequency domain solver of CST MICROWAVE STUDIO (2016) was used which is based on finite elements. By using simulation models with physical sizes of several wavelengths this technique can be used in tandem with the analytical methods in Sections 2.1 and 2.2. A small scale double disk window was drawn up and the frequency response was obtained. Fig. 3(a) shows the simulation model.

Fig. 4 shows the frequency response obtained with simulation compared to the analytical response of Section 2.2. The model takes several minutes to run.

3. Discussion on ITER windows

3.1. Frequency response

To assess the impact of the window on system performance, and to possibly tune thickness and disk spacing, the methodology of Section 2.2 may be used. For example, the high reflection starting
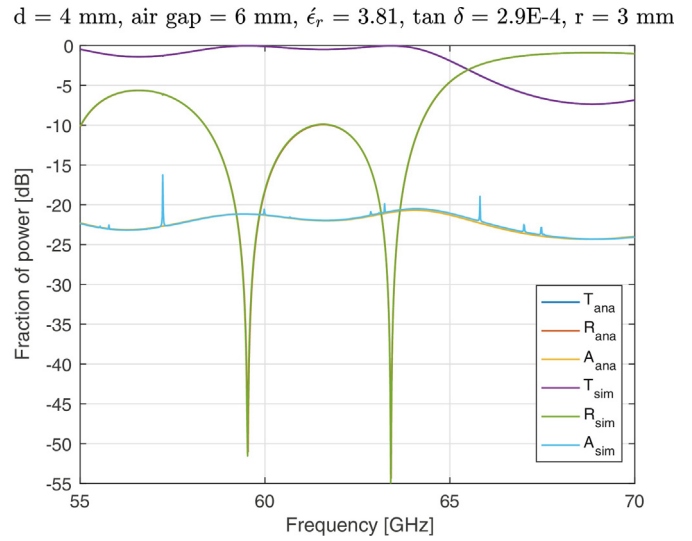
$d = 4$ mm, air gap $= 6$ mm, $\epsilon_r = 3.81$, $\tan \delta = 2.9E\text{-}4$, r $= 3$ mm

Fig. 4. Response of the window in Fig. 3a using the multiple disk model (subscript 'ana') and the simulation (subscript 'sim'). The curves of analytical response and the simulated response overlap.
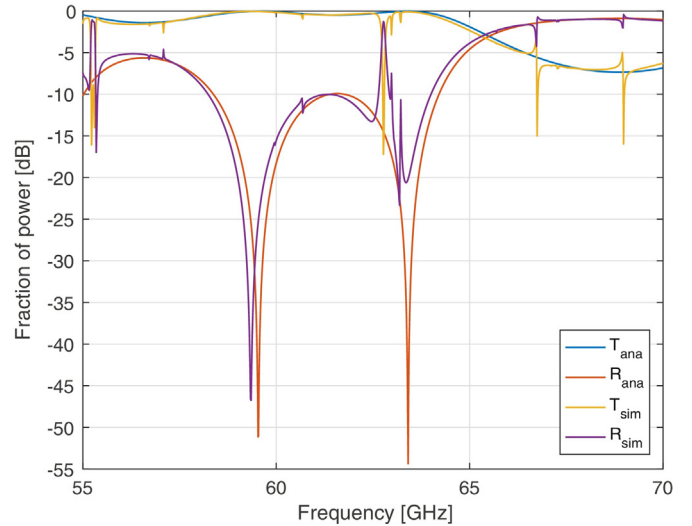

Fig. 5. Simulated response of double disk window with tilts at an angle of 5° (subscript 'sim') compared to analytical response of double disk model with no tilts (subscript 'ana').

at $f \approx 64$ GHz in Fig. 4 may be shifted. The assemblies also use various tilts of the disks to reject undesired signals. The effect of such tilts may be investigated by simulation. A configuration with the first disk tilted at an angle of 5° with respect to *y* and the second disk tilted at an angle of 5° with respect to *z* (coordinate system as in Fig. 3b and c) has been simulated. The result is plotted in Fig. 5 with respect to the result of the simulation using parallel disks (Fig. 4). There are two key observations: (i) a small overall frequency shift, and (ii) spikes appear on the signal. The small shift in frequency is likely caused by the small modification to the cavity length and can in this case be projected to the analytical model. The spikes were investigated further by using the time domain solver, which is based on finite integration technique. Computation times increased to about 15 min but again the spikes were obtained indicating that in this precise geometry and excitation they mathematically exist. Verification measurements are required such as for instance reported by Simonetto [9].

3.2. Losses

Losses are generally low with respect to signal/noise of the system but they cause a load to the window in case of high stray power. For refracted beams A should be calculated using Eq. (3) as incidence angles are mostly unknown but will shift the interference pattern. The power absorbed inside the disk is computed by multiplication of the expected stray power density p [$W\,m^{-2}$] [10–12] with the disk surface S [m^2] and absorption A: $P[W] = p \cdot S \cdot A$. As a hypothetical example, take a refracted gyrotron beam with incident power density 1.25 MW m^{-2}, disk diameter 110 mm, absorbed fraction at 170 GHz = 3%. The power in the disk is in this case $\approx$ 350 W. This is a large value but not all windows will be at risk from refracted beams [11] and mitigation measures must be developed. Isotropic stay radiation levels – incident on all components, all angles and polarizations – are expected to be at least a factor of 10 lower, although isotropic stray radiation absorption coefficients itself may be up to a factor of two higher. Measurement and analysis are under investigation.

4. Summary

Basic operation of a resonant dielectric disk has been reviewed to facilitate tuning the microwave response of vacuum windows and to assess losses. Equations for a multiple disk arrangement are reviewed and a computer model is described. Comparison is made against simulation and good agreement is found, opening the possibility to assess more complex structures such as tilted or wedged windows of small electrical length.

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