

Scattering singularities of a resonant cavity containing plasma

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The influence of plasma on the evolution of scattering singularities in microwave cavities remains largely unexplored, despite its importance for controlling reflectionless plasma excitation. In this work, we investigate the evolution of scattering singularities in a plasma-loaded microwave cavity. To analyze this complex interaction, a numerical model describing an experimental cavity containing a plasma tube is developed. This model enables the tracking of singularity evolution across various plasma configurations and explains the underlying physical mechanisms. Our results demonstrate that significant changes in the imaginary frequency of these singularities occur under two specific conditions: high collision frequency associated with optimal electron densities or high electron densities associated with optimal collision frequency. Furthermore, in the collisionless regime, we show that the variation of the real frequency increases due to the excitation of a transverse plasmonic resonance inside the plasma tube.

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I. INTRODUCTION

Controlling wave scattering is a fundamental issue in physics, with significant consequences for the design of either microwave or optic devices. In this context, considerable efforts have been devoted to the development of structures capable of achieving tailored scattering properties. On the one hand, the advent of metamaterials over the past decades has enabled the realization of increasingly sophisticated devices exhibiting unusual scattering behavior. The artificial nature of these materials, together with the growing demand for multifunctional and reconfigurable technologies, has stimulated strong interest in electromagnetically reconfigurable metamaterials [1]. Plasmas are particularly attractive in this context, as their effective complex permittivity can be tuned in real time through external control of the electron density and pressure [2–8]. On the other hand, recent progress in the coherent control of wave scattering has led to the theory of reflectionless scattering modes [9], which enables zero reflection back into the input channels at specific frequencies. These reflectionless states are referred to as reflection zeros (*R*-zeros) when

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they occur off the real-frequency axis, and as reflectionless scattering modes (RSMs) when they occur on, or are tuned to, the real-frequency axis. More recent work has focused on extending this concept to simultaneously control the output channels without backscattering (at real frequencies) [10]. Beyond these reflectionless states, a variety of more exotic phenomena have been reported, including bound states in the continuum and exceptional points [11]. All these phenomena can be traced back to the properties of *scattering singularities*, specifically the poles and zeros of the corresponding scattering matrix.

Gaining control over these singularities provides a powerful framework for predicting novel physical phenomena and engineering electromagnetic scattering responses, both with and without metamaterials. Accordingly, recent work has focused on the control of such scattering singularities using a reconfigurable element embedded in a multiport resonant cavity. This element consists of a tunable metasurface composed of resonant meta-atoms [12–19], even though more recent work exploited mechanically programmable all-metallic elements [20] or a tunable set of rotating ellipsoidal scatterers [10]. By modifying the boundary conditions of the cavity, the tunable element enables precise control of the complex scattering environment, allowing it to be harnessed for specific tasks. Such capabilities have already been demonstrated, for example, for signal routing [13], signal filtering and routing [20], and analog differentiation [19]. In all these cases, the zeros of the scattering matrix or submatrix are tuned to the real axis by scanning a large parameter space of random element configurations, thereby suppressing backscattering under harmonic excitation.

Tuning of the zeros on the real axis is also particularly important and has been used for a long time in the context of plasma sources [21–24]. Indeed, usual microwave resonance plasma sources rely on the concept of “critical coupling,” a one-port case of RSMs. The cavity is initially specifically designed in order to get this RSM at the desired real frequency, so that the reflected power is zero. The high-power microwave signal transmitted at this frequency to the cavity produces the breakdown of the gas inside the cavity, and thus a plasma appears. The presence of this plasma changes the behavior of the waves and the frequency associated with the RSM is shifted off the real axis to become an R zero. Hence, a tunable element enabling to change the boundary conditions of the cavity is tuned so that this R zero is tuned back to real axis, to an RSM. As for the previous examples with tunable elements in cavities, the zero of the reflection coefficient is tuned to the real axis, thereby suppressing backscattering with plasma under harmonic excitation.

The development of plasma sources relying on nonharmonic excitation has also recently been proposed in the literature and named “space-time plasma steering source” [25]. The idea is to dynamically control the plasma by changing the temporal waveform of the transmitted signal to a large, overmoded cavity [25]. For example, plasmas have been experimentally ignited in cavities using time reversal [26,27] or the linear combination of configuration fields [28]. The transient nature of these plasmas makes the analysis of their influence on the electromagnetic behavior of the cavity quite complex. This makes it difficult to study the evolution of the poles and zeros in this context, given that these have a meaning in a dynamical system. Hence, zero reflection has not yet been achieved with this plasma source. However, a step in that direction has recently been done with the ignition of plasma in a undermoded cavity using an R -zero state, namely, virtual perfect absorption (VPA) [29]. The complex frequency excitation (an exponentially growing microwave signal) has been shown to ignite a plasma in a tube with no reflection as long as its electron density remains low. When the electron density increases to a point where it significantly affects the electromagnetic behavior of the cavity, the R -zero is shifted in the complex domain and reflection appears. Maintaining zero reflection during the whole high-density plasma ignition requires the knowledge of the influence of the plasma on the scattering singularities of the resonant cavity.

This has not yet been addressed directly and this paper intends to fill this gap. We focus on the evolution of the scattering singularities of a cavity containing plasma. In particular, the cavity is the one used during the reflectionless plasma ignition using VPA [29]. A plasma tube is inserted inside of this cavity and externally driven by a dc voltage source. The interaction between the waves and the plasma inside of the cavity gives rise to rich complex phenomena. For example, localized surface plasmons resonance can be excited for certain conditions, as shown recently with a plasma-based

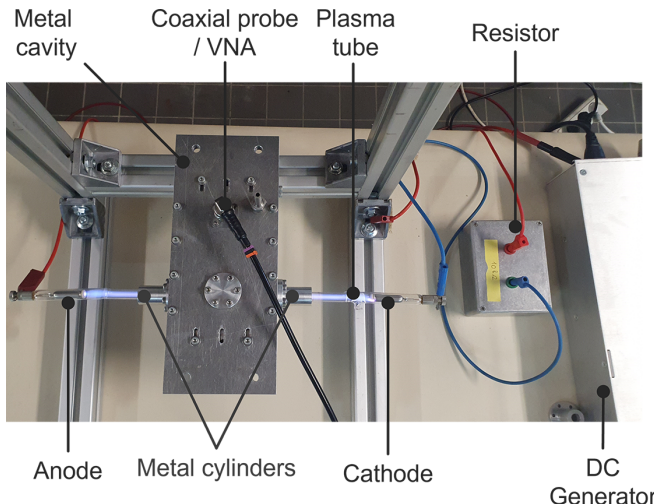


FIG. 1. Picture of the experimental setup: a metal cavity into which a glass tube containing an argon plasma is inserted.

microwave sink [30]. A numerical model describing this experimental setup is developed to grasp the rich physics. This model is exploited to follow the evolution of the scattering singularities of the cavity for different plasma configurations.

The remainder of this article is organized as follows. In Sec. II, we present the numerical model and validate it through comparison with an experimental setup. In Sec. III, we examine, using this model, the evolution of the poles and zeros of a cavity resonance mode as functions of the plasma collision frequency and electron density. Finally, conclusions are drawn in Sec. IV.

II. NUMERICAL MODELING

The resonator is here a rectangular parallelepiped cavity in aluminum (AU4G 2017A), measuring $136 \times 86 \times 43 \text{ mm}^3$, designed and manufactured by Fragne *et al.* [31], as shown in Fig. 1. It is a versatile cavity, with one port consisting in a copper coaxial probe (N-type connector receptacle, female socket, 50Ω , panel mount) with a length of 17 mm inside the cavity, partially surrounded by polytetrafluoroethylene (PTFE), and connected to a vector network analyzer (VNA). A glass tube (of inner and outer radii of 4.25 and 5.5 mm, respectively) is inserted into the cavity through two metal cylinders shown in Fig. 1. These metal cylinders act as circular waveguides under cutoff to prevent from leakage and ensure electromagnetic field confinement within the resonator.

The plasma is ignited with a dc generator (Technix SR2.5kV-300W) connected to the cathode and anode within the glass tube. It produces a homogeneous discharge in the sealed glass tube filled with argon at a pressure of 14 Torr, manufactured by Néon Aquitaine. It is sustained at a voltage of 896 V and a current of 23.4 mA. A resistor of $10 \text{ k}\Omega$ is placed between the generator and the cathode to prevent arcing.

The reflection coefficient, or S_{11} parameter, of this single-port cavity is measured without and with plasma from 1.8 to 5.8 GHz. This parameter is shown in Fig. 2 for the case without plasma.

This frequency band allows us to observe the first resonant modes of the cavity. The transverse electric TE_{012} mode resonating at 2.76 GHz is of particular interest for this study because, as shown in Fig. 3(b), the glass tube in which the plasma is ignited is located at a maximum of the electric field magnitude, making this mode sensitive to the plasma [32]. Moreover, unlike higher-order modes, it is less sensitive to geometrical inaccuracies, which makes it the best mode for studying the influence of the plasma only. In addition, this mode is sufficiently separated from neighboring resonant modes

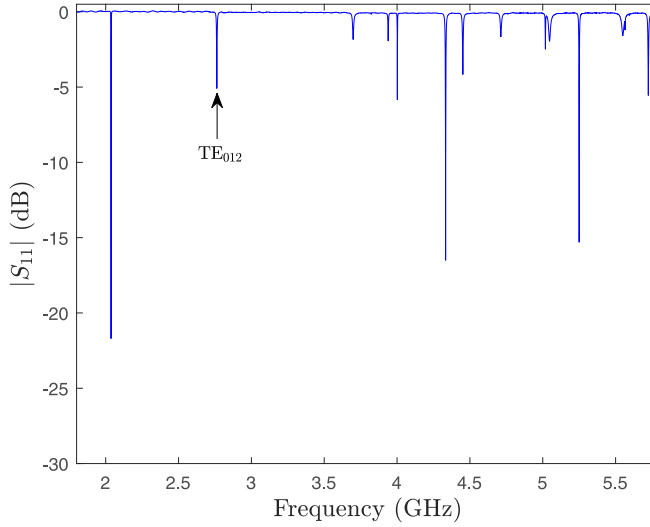


FIG. 2. Measured magnitude of the reflection coefficient of the cavity without plasma as a function of the frequency.

to allow the evolution of its scattering singularities to be tracked without overlap with other modes frequencies.

In order to study its evolution, the S_{11} parameter is required for different plasma configurations. To obtain such results, the experimental setup is modeled using the electromagnetic software Ansys HFSS, illustrated in Fig. 3(a) (see the Supplemental Material [33] for detailed cavity geometry). To build this model, we proceed step by step by comparing the numerical reflection coefficient with the experimental one.

A. Cavity model

The cavity and its feeding port are modeled by reproducing their dimensions with submillimeter precision. In addition to the dimensions, it is important to consider the material electromagnetic properties. The aluminum internal walls of the cavity are characterized in Ansys HFSS by a finite conductivity boundary, denoted as σ_{surf} , while the glass tube is defined by its relative permittivity ϵ_{r_g} and dielectric loss tangent $\tan(\delta_g)$.

We first varied this wall's conductivity to investigate its influence on the resonance frequency and on the magnitude of the reflection coefficient. This analysis showed that the conductivity affects mainly the magnitude of the reflection coefficient. Based on the similarity between the experimental and numerical reflection coefficients, we find that the conductivity must be $\sigma_{\text{surf}} = 4.3 \times 10^6 \text{ S/m}$, which is plausible given the wear inside the cavity [34,35].

For the glass tube, two parameters are required: the relative permittivity ϵ_{r_g} and the dielectric loss tangent $\tan(\delta_g)$ of the glass. It is therefore essential to study separately the influence of these two parameters on the reflection coefficient. The relative permittivity of the glass only modifies the resonance frequency, while the dielectric loss tangent affects its magnitude. This is consistent with the perturbation theory [36], for which the real part of the complex permittivity of the medium affects the resonance frequency, while the imaginary part, represented by the dielectric loss tangent, influences the quality factor and therefore the magnitude of the reflection coefficient. We find that the glass's relative permittivity is 5.6 (close to the permittivity commonly used in commercial simulation software of 5.5), while the dielectric loss tangent is 0.006 (between 10^{-3} and 10^{-4} on manufacturers' websites).

Thanks to this study based on comparisons between experimentally and numerically obtained S_{11} parameters, we were able to accurately reproduce the electromagnetic behavior of the experimental

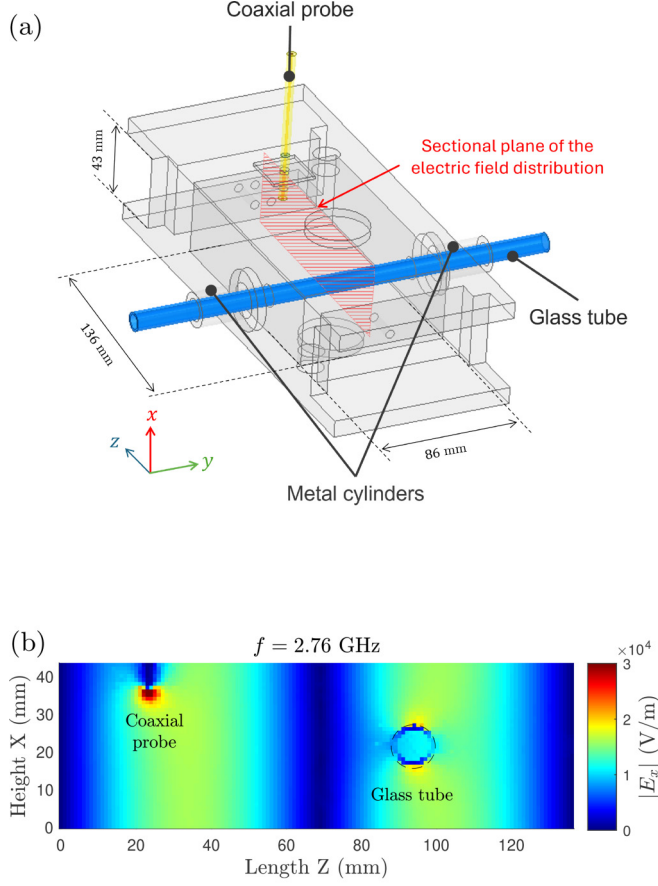


FIG. 3. Numerical model on Ansys High Frequency Structure Simulator (HFSS) of the cavity with the glass tube [panel (a)]. Distribution of the electric field main component E_z , magnitude for the TE_{012} mode of the cavity obtained at 2.76 GHz on Ansys HFSS, side view, center cut plane [panel (b)].

cavity without plasma for the TE_{012} mode, using the parameters listed in Table I, as illustrated in Fig. 4(a).

B. Plasma model

The dc plasma can be considered as a stationary and homogeneous positive plasma column along the axis of the cylindrical tube inside the cavity [37–39]. For simplicity, we also consider radial

TABLE I. Final model parameters.

Parameter	Value
σ_{surf}	4.3×10^6 S/m
ϵ_{rg}	5.6
$\tan \delta_g$	0.006
p	14 Torr
n_e	5×10^{11} cm $^{-3}$

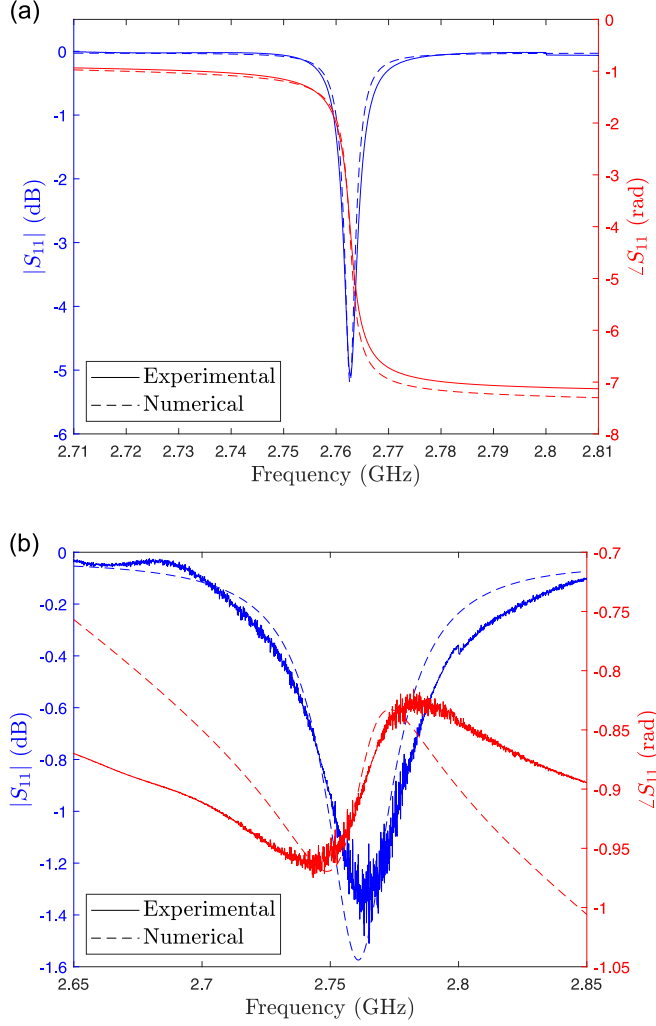


FIG. 4. Magnitude and phase of the reflection coefficient, for the TE₀₁₂ mode, of the experimental (solid line) and numerical cavities (dashed line) without [panel (a)] and with [panel (b)] plasma as described in Table I.

homogeneity of the plasma. This assumption is justified by the small internal diameter $\phi_{g_{\text{int}}}$ of the glass tube compared to the wavelength for the target frequency bandwidth, namely, $\phi_{g_{\text{int}}} \approx \frac{\lambda_0}{12}$ at 2.76 GHz.

The electromagnetic behavior of the plasma can be found using the Drude model, which gives us the complex relative permittivity of the plasma as a function of the plasma parameters, i.e., the plasma electron density n_e and collision frequency ν_m , and the wave angular frequency ω [40]:

$$\tilde{\epsilon}_{r_p}(n_e, \nu_m, \omega) = 1 - \underbrace{\frac{\omega_{pe}^2}{\omega^2 + \nu_m^2}}_{\epsilon'_{rp}} - j \underbrace{\frac{\nu_m}{\omega} \frac{\omega_{pe}^2}{\omega^2 + \nu_m^2}}_{\epsilon''_{rp}}, \quad (1)$$

with the plasma angular frequency defined as $\omega_{pe}^2 = \frac{e^2 n_e}{\epsilon_0 m_e}$, where e is the elementary charge, m_e the electron mass, and ϵ_0 the vacuum permittivity. The collision frequency ν_m can be roughly expressed

as a function of the gas pressure p expressed in Torr. For argon, Raizer *et al.* [37] gives

$$\nu_m = 5.3 \times 10^9 p. \quad (2)$$

At the end, the numerical model of the plasma depends on the electron density n_e of the plasma, the gas pressure p , and the wave angular frequency ω . The pressure in the numerical model is taken to be equal to that of the sealed glass tube, i.e., $p = 14$ Torr and $\nu_m = 7.42 \times 10^{10} \text{ s}^{-1}$.

Several diagnostics (optical, electric, electromagnetic, etc.) exist to determine the electron densities of a dc plasma. Unfortunately, these methods cannot be easily implemented for our experimental conditions (high pressure, small tube diameter, and complex sheath configuration [3,41]). The simplest approach is to determine the electron density using a fitting between the experimental and numerical reflection coefficients of the cavity with plasma [42]. This parametric study gives us an electron density value of $n_e = 5 \times 10^{11} \text{ cm}^{-3}$, similar to the densities obtained in the literature for a comparable configuration [43].

C. Experimental validation

The experimentally measured S_{11} and the one obtained numerically from this parametric study lead to the curves shown in Figs. 4(a) (without plasma) and 4(b) (with plasma). Despite minor discrepancies, the numerical model captures the overall behavior of the system. The observed changes in the amplitude, phase, and resonant frequency can be interpreted as resulting from a change in the impedance seen by the VNA due to the presence of the plasma in the cavity.

We now have a complete numerical model that provides the reflection coefficient for various plasma configurations [44]. This allows us to investigate numerically the influence of the plasma on the cavity's electromagnetic behavior, especially through the study of its scattering singularities.

III. STUDY OF SINGULARITIES

The electromagnetic behavior of a cavity is contained in its scattering matrix, which can fully be described only by the positions of poles and zeros [11]. Within the framework of the temporal coupled-mode theory, the complex angular frequencies of scattering singularities (poles and zeros) can be expressed as a function of the resonance angular frequency ω_0 and the external γ_{ext} and internal γ_{int} decay rates [45,46], according to the time convention $e^{-j\omega t}$:

$$\tilde{\omega}_{\text{pole}} = \omega_0 - j(\gamma_{\text{ext}} + \gamma_{\text{int}}), \quad (3)$$

$$\tilde{\omega}_{\text{zero}} = \omega_0 + j(\gamma_{\text{ext}} - \gamma_{\text{int}}). \quad (4)$$

The complex angular frequencies of these scattering singularities are determined from the numerical reflection coefficients obtained for various plasma configurations, using the method introduced in Ref. [47]. The corresponding poles and zeros obtained from the numerical and experimental results, both with and without plasma, are represented in Fig. 5.

Without plasma, the internal decay rate γ_{int} is lower than the external decay rate γ_{ext} , indicating that the system is overcoupled (i.e., the imaginary part of ω_{zero} is positive). The introduction of plasma into the cavity leads to an increase in the internal decay rate, which then exceeds the external decay rate, thereby switching the system from the overcoupled to the undercoupled regime (the imaginary part of ω_{zero} becomes negative). In this case, the presence of plasma induces only a slight shift in the complex pole and zero frequencies along the real axis.

The slight deviations previously observed in the S_{11} parameters are consistently associated with corresponding shifts in the positions of the singularities in the complex plane. Overall, the numerical model captures the underlying physics with sufficient accuracy to evaluate the sensitivity of scattering singularities to plasma parameters.

To describe how plasma affects the scattering singularities, the two plasma parameters (ν_m/ω and n_e) are investigated.

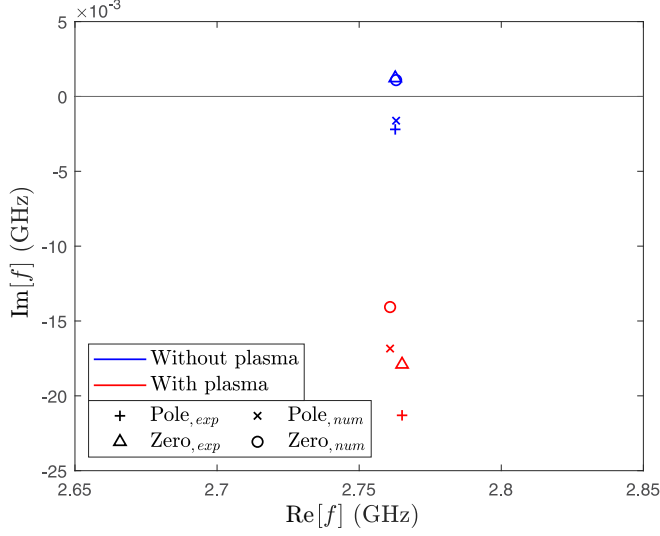


FIG. 5. Measured and simulated scattering singularities obtained without (blue marker) and with (red marker) plasma for the TE_{012} resonance mode.

A. Influence of the collision frequency

We consider three different plasma collisional regimes, defined by the ratio between the plasma collision frequency ν_m and the wave angular frequency ω : a weak collisional regime ($\nu_m \ll \omega$), a balanced collisional regime ($\nu_m \approx \omega$), and a strongly collisional regime ($\nu_m \gg \omega$).

In order to study the influence of these different regimes on scattering singularities, we fix the electron density of the plasma and vary the ratio ν_m/ω by adjusting the gas pressure [48]. Two configurations are studied: a first configuration named “low electron density,” with an electron density of 10^{11} cm^{-3} , and a second configuration close to experimental conditions named “high electron density,” with $n_e = 5 \times 10^{11} \text{ cm}^{-3}$. The electron density values chosen for both cases are close, but they lead to different electromagnetic behaviors [49].

1. Low electron density

The evolution of the pole and zero in this case is shown in Fig. 6(a). For very low values of the ratio ν_m/ω , the pole and zero are positively shifted along the real axis compared to the case without plasma [50]. The imaginary frequencies remain unchanged because the plasma does not introduce additional losses into the system (the internal and external decay rates do not change).

As the gas pressure increases, the density of neutral atoms in the tube increases, gradually bringing the plasma into a collisional regime. As long as the collision frequency remains lower than the angular frequency of the wave ($\nu_m < \omega$), the electrons oscillate, gaining energy until they collide a neutral atom. Part of this energy is then transferred to the gas, increasing the internal decay rate. This results in an increase in the absolute value of the imaginary frequency of the pole and zero.

The transfer efficiency of energy from the electrons to the gas is maximal when the wave angular frequency becomes equal to the collision frequency ($\nu_m \approx \omega$). This balanced condition corresponds to an optimal compromise between the energy absorbed by the electrons from the electric field of the wave and their ability to transfer it efficiently to the gas through collisions.

When the collision frequency exceeds the wave angular frequency ($\nu_m > \omega$), electrons have less time to gain energy before colliding with a neutral atom. Energy transfer becomes less efficient, leading to a decrease in energy dissipation in the plasma, which leads to a decrease in the internal decay rate. As a result, the absolute value of the imaginary frequency of the pole and zero decreases.

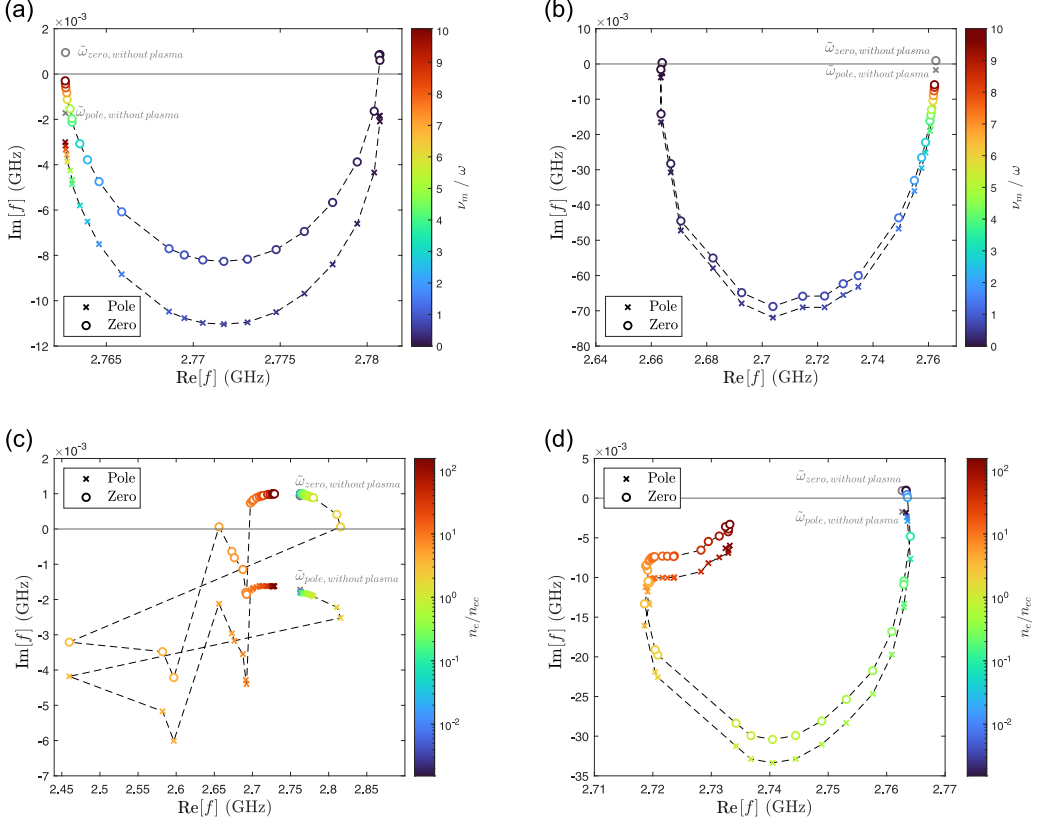


FIG. 6. Evolution of the simulated scattering singularities (pole and zero) in the complex frequency plane as a function of ν_m/ω for $n_e = 10^{11}$ [panel (a)] and $n_e = 5 \times 10^{11} \text{ cm}^{-3}$ [panel (b)], and as a function of n_e/n_{ec} for $\nu_m/\omega = 10^{-3}$ [panel (c)] and $\nu_m/\omega = 4.27$ ($p = 14 \text{ Torr}$) [panel (d)].

As the pressure increases, the electrons no longer have time to oscillate with sufficient amplitude to be perceived by the electromagnetic wave. In this high-pressure regime, the pole and zero of the plasma-filled cavity tend to converge toward that of the plasma-free cavity.

2. High electron density

The evolution of the pole and zero is shown in Fig. 6(b) for $n_e = 5 \times 10^{11} \text{ cm}^{-3}$. In this case, for very low values of the ratio ν_m/ω , the pole and zero are negatively shifted along the real axis compared to the case without plasma [50]. As the pressure increases, the real frequency increases until it approaches the real frequency in the absence of plasma. Besides, there is greater variation of the real frequency than in the previous case.

The evolution of the imaginary frequency of the pole and zero behaves similarly to that of the first case. However, this behavior is amplified by the high electron density, which improves the efficiency of energy transfer to the gas. Losses increase, leading to an increase in the internal decay rate and, consequently, a more pronounced increase in the absolute value of the imaginary frequency of the pole and zero.

B. Influence of the electron density

The plasma exhibits two different behaviors depending on the relative values of the plasma angular frequency ω_{pe} , which depends on the electron density n_e , and the wave angular frequency

ω . The transition between the two behaviors occurs when the plasma angular frequency matches the wave angular frequency. The electron density at this condition is known as the critical electron density, expressed as

$$n_{ec} = \frac{\varepsilon_0 m_e}{e^2} \times (\omega^2 + \nu_m^2). \quad (5)$$

The critical electron density was calculated at the resonance frequency of the cavity without plasma, i.e., $f = 2.76$ GHz (in this study, the wave frequency remains close to this value [51]). Two configurations were studied: a first one named “collisionless case” ($\nu_m/\omega = 10^{-3}$) and a second one named “collisional case” ($\nu_m/\omega = 4.27$), closer to experimental conditions, namely, a pressure $p = 14$ Torr.

1. Collisionless case

The evolution of the pole and zero in this case is shown in Fig. 6(c). At first glance, the evolution seems more complex than the previously studied cases. The frequency shift switches from positive to negative. This kind of complex and diverse behavior has been observed in close configurations [52,53]. In this collisionless regime, no internal cavity losses are added by the presence of the plasma [54]. However, a small change of the imaginary part of the pole and zero is observed. This can be due to a change in the external decay rate due to a reorganization of the distribution of the electric field in the cavity.

As long as $n_e < n_{ec}$, the electrons oscillate freely under the influence of the electric field, causing an increase of the real frequency of the pole and zero.

For $n_e > n_{ec}$, as the electron density increases, the interaction between the wave and the plasma is gradually limited. When $n_e \gg n_{ec}$, the complex frequencies associated with the poles and zeros tend toward those obtained with a metallic cylinder inside the cavity.

When $n_e \approx n_{ec}$, the wave-plasma interaction becomes particularly complex and gives rise to specific phenomena described in Sec. III C.

2. Collisional case

The evolution of the pole and zero in this case is shown in Fig. 6(d). In the case of a lossy plasma, electrons can no longer oscillate freely in the plasma due to the presence of numerous neutral atoms within the glass tube. The real frequency variation of the pole and zero is reduced compared to the case without collision.

Conversely, the imaginary frequency variation of the pole and zero is greater than in the first case. The imaginary frequency follows the same trend described in Sec. III A, depending on the collision frequency. However, this time we are dealing with the electron density rather than the neutral density.

As long as $n_e < n_{ec}$, as the electron density increases, the collision probability between neutral atoms and electrons increases: The energy transfer to the gas becomes more efficient.

As in the previous case, when $n_e > n_{ec}$, the interaction between the wave and the plasma is gradually limited as the electron density increases, making the energy transfer to the gas less efficient.

C. Overview

Figure 7 compiles the evolution of the scattering singularities analyzed in the previous sections. There are two cases in which the electron density is fixed and the collision frequency varies, and two cases in which the collision frequency is fixed and the electron density varies. Comparing these four configurations enables us to assess the influence of the plasma parameters on the variation of the scattering singularities in the complex plane.

The maximum variation of the imaginary frequency occurs when there is either a high collision frequency associated with a specific electron density, or a high electron density combined with a

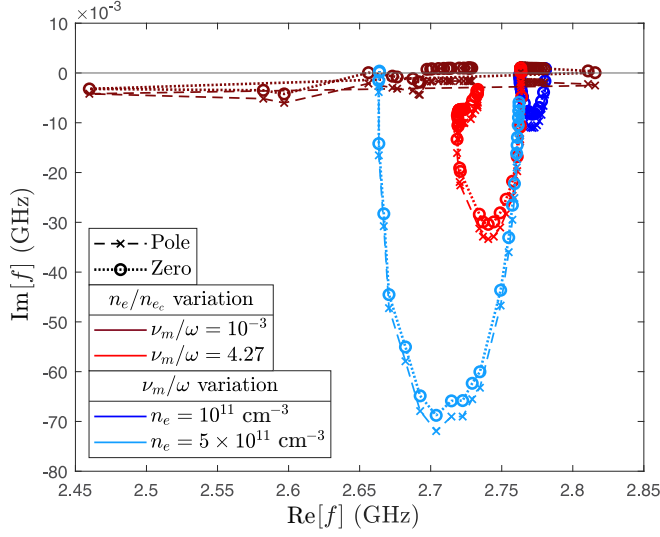


FIG. 7. Overview of the evolution of the scattering singularities in the complex frequency plane as a function of plasma parameters.

specific collision frequency. This spreading is due to the varying efficiency of energy transfer from electrons to the gas.

On the other hand, the most pronounced variation of the real frequency is obtained in collisionless plasma when the electron density changes. This behavior suggests that the plasma tube approaches the surface plasmon resonance condition when the ratio n_e/n_{ec} is close to 3 [55], as illustrated in Fig. 8(a) [56]. The complex behavior of the scattering singularities observed in Fig. 6(c) when

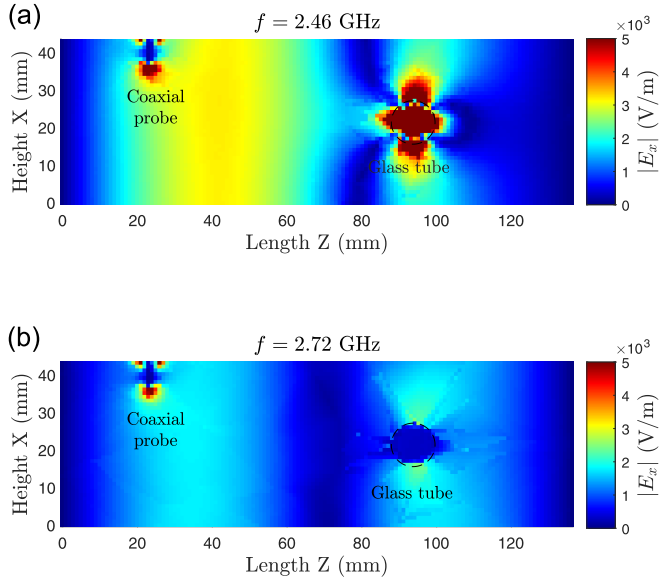


FIG. 8. Simulated magnitude of the electric field component $|E_z|$ for the TE_{012} resonance mode of the cavity, side view, center cut plane for $\nu_m/\omega = 10^{-3}$ [panel (a)] and $\nu_m/\omega = 4.27$ [panel (b)], with $n_e/n_{ec} = 3$.

$n_e/n_{ec} \approx 3$ originates from the interaction between the plasmon and cavity resonances. As a result, even a slight variation in the plasma density modifies this interaction and, consequently, the overall scattering response of the system [57]. When the collision frequency increases, this resonance attenuates, as illustrated in Fig. 8(b). This results in a reduction in the variation of the scattering singularities along the real axis.

Finally, in all cases, the R -zeros can theoretically be tuned to the real axis, i.e., to an RSM, highlighting the potential of plasma as a reconfigurable element for achieving CPA in microwave systems.

IV. CONCLUSION

The influence of a plasma on the scattering properties of a resonant cavity has been investigated. To that end, the reflection coefficient of a cavity containing a sealed plasma tube has been measured with the plasma “off” and “on.” A numerical electromagnetic model of this system has been developed and validated by fitting the numerical reflection coefficient with the experimental one for the TE_{012} mode.

This numerical model has then been used to investigate the influence of the plasma parameters on the scattering singularities of the cavity. Four configurations were studied: two cases in which the electron density is fixed and the collision frequency varies, and two cases in which the collision frequency is fixed and the electron density varies. The results show that a high collision frequency combined with a specific electron density, or a high electron density combined with a specific collision frequency, leads to a wide variation of the imaginary frequency of the scattering singularities. In the case of collisionless plasma, the variation in real frequency is increased by the appearance of a transverse surface plasmon resonance in the plasma tube. These variations of the scattering singularities in the complex plane demonstrate the potential of plasma tubes as promising candidates for implementing tunable elements within a cavity, in line with recent studies investigating plasma tubes for reconfigurable and programmable metasurfaces [3].

This work represents a first step toward understanding how plasma influences the scattering singularities of a microwave cavity. The trajectories of these singularities in the complex plane are governed by variations in the balance between competing loss mechanisms, including cavity wall losses, port leakage, glass tube losses, and plasma absorption. Future investigations will leverage this numerical model to quantify individual loss contributions and provide deeper insight into the underlying physical mechanisms. Additional resonant modes and various orientations of the plasma tube relative to the electric field polarization will also be explored, thereby providing a more comprehensive understanding of the influence of plasmas.

The knowledge of the influence of plasma on the internal and external decay rates of the cavity is also essential for plasmas ignited by virtual absorption. This could enable the reflectionless ignition of high-density plasmas via VPA by appropriately tailoring the injected temporal waveform. This paves the way toward a fully reflectionless space-time plasma steering source, enabling spatiotemporal control of plasmas in large cavities through the injection of properly designed waveforms.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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