Analysis of the Propagation of a Short Radio Pulse in Media with Negative Permittivity

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***Abstract*— An analysis is carried out in the time domain of the propagation of a short radio pulse through a medium with a negative dielectric constant, which simulates a plasma layer with a given frequency dispersion for a collisionless plasma without taking into account the motion of positive ions. The process of signal formation in the time domain is shown for a plasma frequency of 10 GHz with a radio pulse duration of 0.1 ns with a filling frequency of 10 GHz.**

It is shown that the plasma layer is a high-pass filter.

Examples of the passage of a given radio pulse through a plasma layer for plasma frequencies equal to 5 GHz and 15 GHz are given. For the analysis, we used the method of the impedance analog of the electromagnetic space, implemented in the Tamic Planar Rt-H Analyzer software package. .

Keywords — short radio pulse, numerical modeling, normalized spectral density, filter.

I. INTRODUCTION

At present, computational methods and algorithms for electromagnetic analysis are being developed quite intensively both in our country and abroad [1], not only in the frequency domain, but also in the time domain [1-4]. Apparently, when analyzing the propagation and scattering of ultra-wideband signals in media with frequency dispersion, it is more advantageous (from the point of view of calculations) to use temporal methods.

One of the developments for numerical electromagnetic analysis in the time domain is the Tamic Planar Rt-H Analyzer software package. This software package was created to solve problems associated with reflectometric diagnostics of plasma in the T-10 tokamak and the projected international ITER installation. In electromagnetic analysis for ITER, the following difficulties had to be overcome:

1) the size of the analyzed area is almost 100 per 100 wavelengths,

2) the permittivity at each point in space is different,

3) it is necessary within the framework of a unified approach to consider a waveguide, a radiating system, and an inhomogeneous plasma.

However, the fact that a sufficiently strong longitudinal magnetic field exists in tokamak installations makes it possible to solve the problem of electromagnetic analysis as a two-dimensional one, which is an essential factor.

After considering various approaches, the methodology of the impedance analogue of the electromagnetic space was chosen [5-7]. It should be noted that the method proposed by Boris Vasilyevich Sestroretsky, being, as it were, a transposition into a more modern language of ideas of works on physical modeling [2] opens a look at these ideas from the other side and actually represents a replacement for classical electrodynamics (Maxwell's equations in the space of smooth functions) information multipole (finite-difference (not FDTD) operator in discrete space-time with a single quantum characterizing the discretization of both time and space) [5-7]. Other methods of computational electrodynamics make the transition from a continuous uncountable set to a finite countable one usually implicitly. The continuity of ideas makes it possible to make good use of the results of physical plasma modeling applied [8-13] where a finite-difference grid was used.

As a result of this work, a technique was developed for the impedance analogue of electromagnetic space for 2D analysis of inhomogeneous plasma media in the time domain, which is described [14-17]. The developed technique has been tested on various tasks.

II. GEOMETRY OF THE PROBLEM

In this paper, we will consider the propagation of a short radio pulse with a filling frequency of 10 GHz and a duration of 0.1 ns through a plasma layer given by the permittivity ε, shown in Fig. 1 [18-20]. The geometry consists of two matched inputs (Input 1 and Input 2), between which there is a 600 mm thick plasma layer. The matched inputs are separated from the plasma by a vacuum of 100 mm on the left and 100 mm on the right. When calculating with the Tamic Planar Rt-H Analyzer software, a spatial sampling step of 0.1 mm (which corresponds to a time sampling of 0.000235865 ns) was used, the ratio of the grid step to the wavelength at a frequency of 10 GHz was 299.792458.

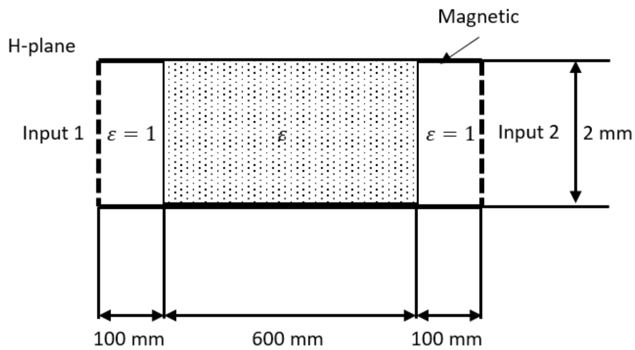

Fig. 1. Geometry of the considered problem.

III. CALCULATION OF RADIO PULSE SPREAD THROUGH PLASMA

The calculation of the problem with the specified parameters at a permittivity ε = -0.01 [21,22] was carried out using the Tamic Planar Rt-H Analyzer software package. The calculation result is shown in Fig. 1.

The process of signal formation can be traced by considering the spatial distribution of the electric field amplitude in the analyzed geometry at different points in time

(Fig. 2). In Fig. 2, the boundary separating vacuum and plasma is shown by a dashed line. At the moment of time 0.1 ns, the distribution corresponding to the incident signal is visible. At the moment of time 0.5 ns, the first period of the reflected signal is formed. By the second ns, the transmitted signal was formed, which was already quite strongly stretched in space. At 2.8 ns, the precursor passed the second plasma-vacuum interface. By 4.5 ns, beats are already visible, which is a consequence of repeated reflection from the vacuum - dielectric boundaries.

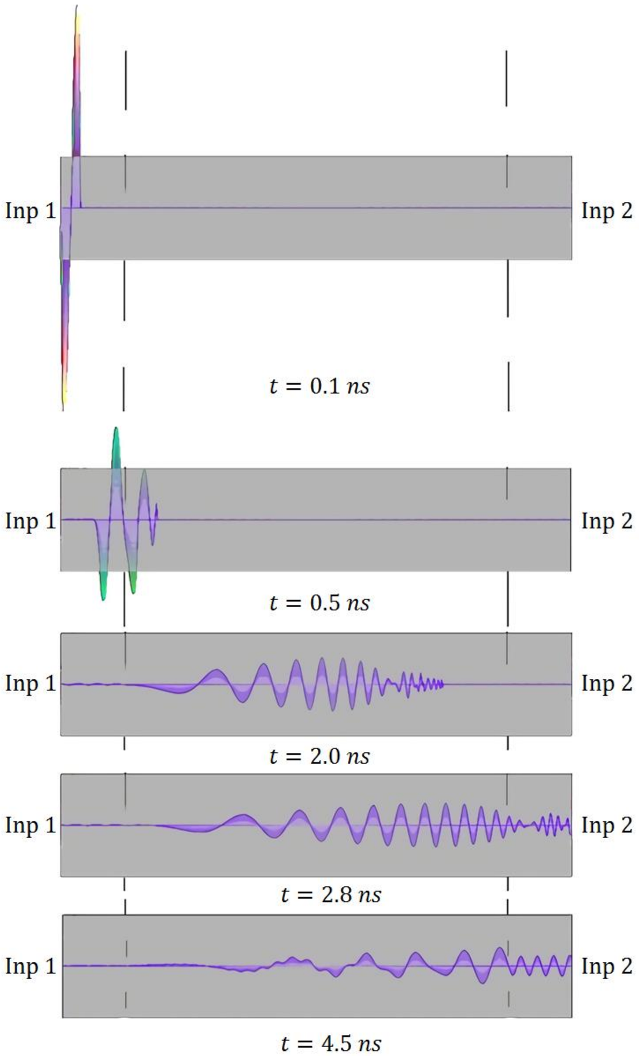

Fig. 2. Distribution of the electric field amplitude at different times.

The amplitude of the signal incident on the first input (curve 1), the result of calculating the amplitude of the reflected signal at the first input (curve 2) and the transmitted signal at the second input for the permittivity $\varepsilon = -0.01$ (curve 3), are shown in Fig. 3.

As seen from Fig. 3, due to the dispersion of the permittivity of the plasma, the reflected and transmitted signals are strongly stretched in time. The duration of the signal reflected to the first input increased 1.4 times. The amplitude of the signal reflected to the first input is 73% of the amplitude of the incident signal. The signal passes to the second input with a delay of 3.66 ns. In this case, a precursor with a duration of 0.33 ns first comes, and then the rest of the signal (starting from 3 ns). The precursor amplitude is 0.09 V, the amplitude of the remaining part is from 0.13 V to 0.016 V.

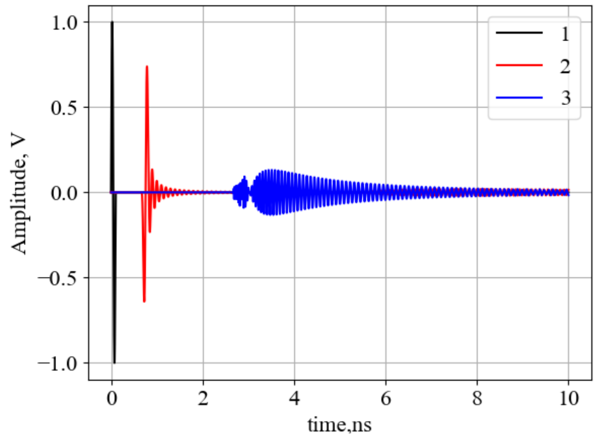

Fig. 3. Dependence of the amplitude of the incident (curve 1), reflected (curve 2) and transmitted through the plasma layer (curve 1) of signals on time at the value of the permittivity $\varepsilon = -0.01$.

69.96% of the incident power is reflected from the plasma layer back to the first input. The second input receives 27.48% percent of the power generated at the first input.

Fig. 4 show normalized spectral densities of signals of the incident (curve 1) and reflected (curve 2) signal at the Input 1, and the transmitted signal (curve 3) at the Input 2 in frequency range up to 20 GHz, obtained from the calculation results.

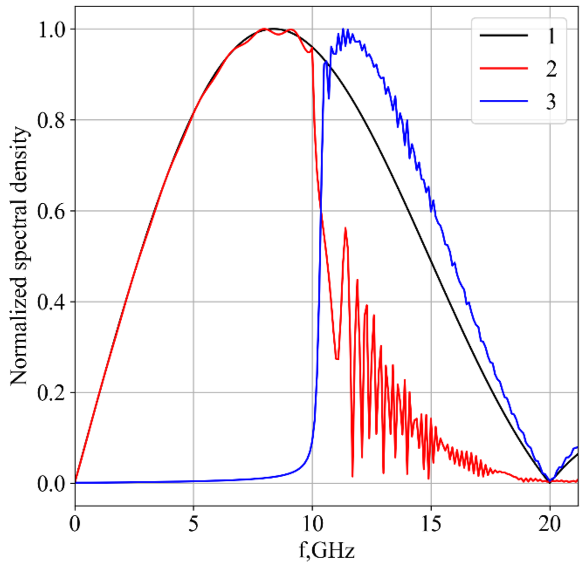

Fig. 4. Dependence of the normalized spectral densities of incident (curve 1), reflected (curve 2), and transmitted through the plasma layer (curve 1) signals on frequency at a permittivity value of $\varepsilon = -0.01$

As follows from Fig. 4, a medium with a negative permittivity, simulating a plasma layer, is a high-frequency filter: signal components with a frequency below 10 GHz are reflected from the plasma layer at the first input, and signal components with a frequency above 10 GHz passed to the second input. The presence of harmonics in the reflected signal at frequencies above 10 GHz can be explained by the presence of a gradient of permittivity at a distance of 100 mm from the first input.

The permittivity value required to adjust such a filter can be determined from the following expression [10,14]:

$$\varepsilon = 1 - \left(\frac{f_p}{f}\right)^2, \quad (1)$$

where f is the signal filling frequency, f_p is the plasma frequency, which determines the cutoff frequency of the filter.

Let's consider an example of filter tuning for frequencies f_p equal to 15 GHz and 5 GHz. For the selected parameters, the values of the permittivity, simulating the plasma layer will be equal to $\varepsilon = -1.25$ and $\varepsilon = 0.75$.

Fig. 5 show the dependences of the signal amplitude on time at inputs 1 and 2. The amplitude of the incident signal at the first input (see curve 1), the result of calculating the amplitude of the reflected signal at the first input (see curve 2) and the signal transmitted to the second input (see curve 3) for the value of the permittivity $\varepsilon = -1.25$, corresponding to f_p equal to 15 GHz.

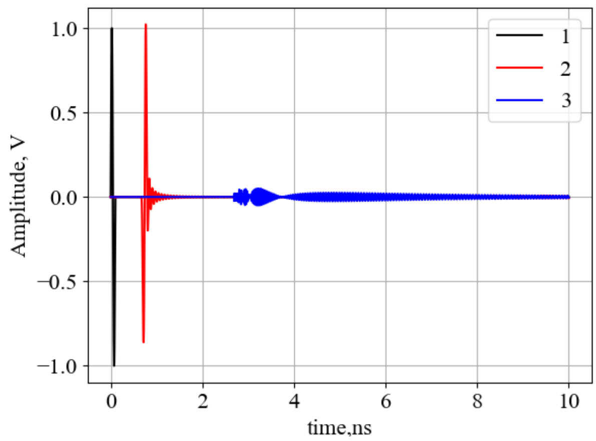

Fig. 5. Dependence of the amplitude of the incident (curve 1), reflected (curve 2) and transmitted through the plasma layer (curve 1) of signals on time at the value of the permittivity $\varepsilon = -1.25$.

Fig. 6 show the dependences of the signal amplitude on time at inputs 1 and 2. The amplitude of the incident signal at the first input (see curve 1), the result of calculating the amplitude of the reflected signal at the first input (see curve 2) and the signal transmitted to the second input (see curve 3) for the value of the permittivity ε = 0.75, corresponding to f_p equal to 5 GHz.

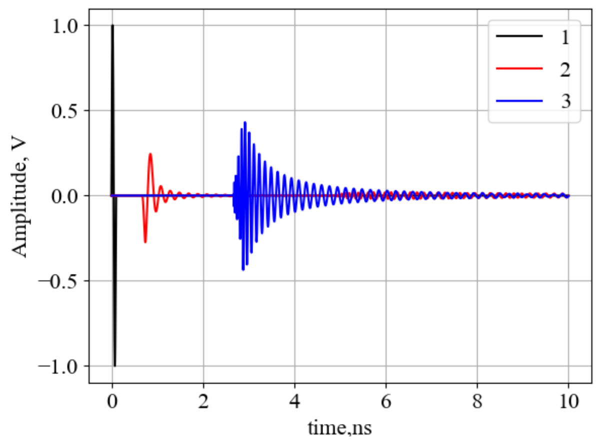

Fig. 6. Dependence of the amplitude of the incident (curve 1), reflected (curve 2) and transmitted through the plasma layer (curve 1) of signals on time at the value of the permittivity $\varepsilon = 0.75$.

As seen from Fig. 5 and 6, the amplitude of the signal reflected to the first input from the interface for a dielectric constant $\varepsilon = -1.25$ corresponding to f_p equal to 15 GHz is significantly greater than the amplitude of the signal reflected to the first input for a dielectric constant ε = 0.75 corresponding to f_p equal to 5 GHz .

Fig. 7 show the spectral densities of the reflected signals at $\varepsilon = -1.25$ (see curve 1) and $\varepsilon = 0.75$ (see curve 2). As can be seen from the figure, the frequency components of the signal below the specified f_p equal to 15 GHz and 5 GHz are reflected at the first input.

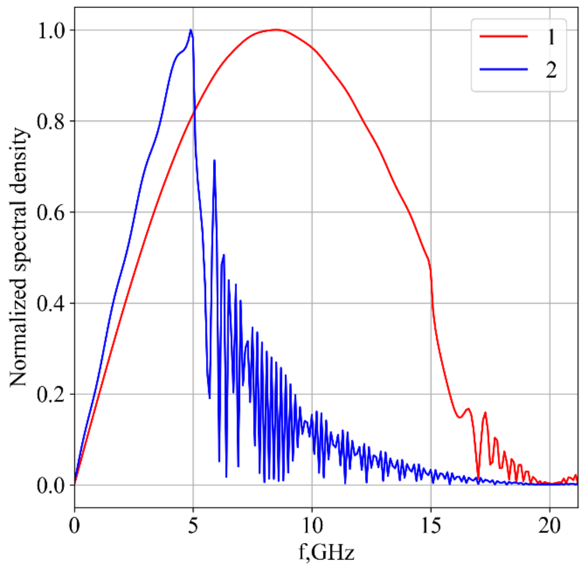

Fig. 7. Dependence of the spectral density of the reflected signals on frequency at $\varepsilon = -1.25$ (see curve 1) and $\varepsilon = 0.75$ (see curve 2).

Fig. 8 show the spectral densities of the transmitted signals at $\varepsilon = -1.25$ (see curve 1) and $\varepsilon = 0.75$ (see curve 2). As can be seen from the figure, the frequency components of the signal above the specified f_p equal to 15 GHz and 5 GHz pass to the second input.

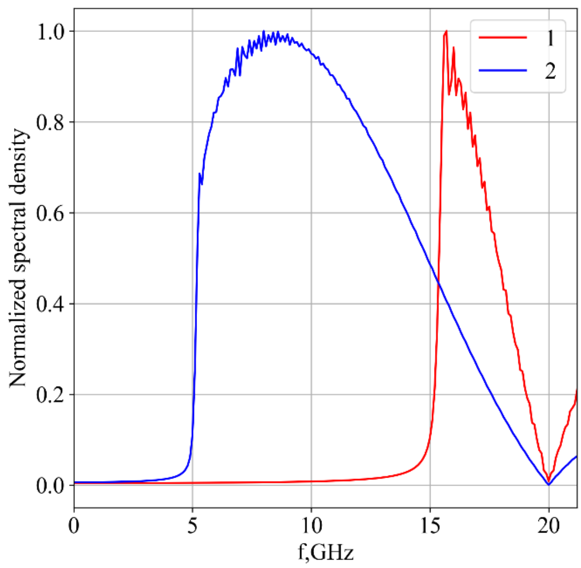

Fig. 8. Dependence of the spectral density of the transmitted signals on frequency at $\varepsilon = -1.25$ (see curve 1) and $\varepsilon = 0.75$ (see curve 2).

From the presented data, it follows that the signal reflected to the first input contains spectral components below 15 GHz (at $\varepsilon = -1.25$) and 5 GHz (at $\varepsilon = 0.75$), while in the signal transmitted to the second input there are no spectral components at frequencies below 15 GHz (at $\varepsilon = -1.25$) and 5 GHz (at $\varepsilon = 0.75$).

IV. Conclusion

Numerical electromagnetic modeling in the time domain of the propagation of a short radio pulse through the plasma is carried out. The process of changing the signal amplitude in the spatial and temporal areas is presented. The amplitude characteristics of the signal at the inputs of the system under consideration versus time are given. The influence of the plasma layer on the spectral density of the signal is considered. It is shown that the plasma layer is a high-pass filter. Examples of the passage of a given radio pulse through a plasma layer for plasma frequencies equal to 5 GHz and 15 GHz are given.

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