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Modernization of the filtration system for the Doppler reflectometry diagnostics of the L-2M stellarator for operation in regimes high-power ECR heating

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Abstract: The commissioning of the MIG-3 gyrotron complex at the L-2M stellarator has made it possible to reach a record power density input into plasma of 3.4 MW/m^3 during the ECR heating of the plasma. This power input, however, resulted in noisy Doppler reflectometry signals (with a high-amplitude component at the gyrotron working frequency of 75.3 GHz), which could not be processed and analyzed. We modernized the filtering system of the Doppler reflectometry diagnostics, which had consisted of two pin-type band stop waveguide filters. Another pin-type filter was added to the filter system and a new compact bandstop filter was designed based on the Fabry-Perot resonator (BFFPR) to provide high suppression at the frequency of 75.3 GHz and low attenuation at the 30–40 GHz diagnostic frequency. We optimized the cavity length of the filter and calculated the characteristics of filters with different numbers of resonators by using numerical simulations. The filter layout was designed, and its characteristics were measured. The results of experimental measurements and numerical simulations have a good match. The redesigned filters were used to suppress the noise from the MIG-3 gyrotron complex.

Keywords: Attenuators, Filters; Plasma diagnostics - interferometry, spectroscopy and imaging; Simulation methods and programs; Radiation calculations

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Contents

1 Introduction and motivation

An important problem of modern radio engineering diagnostics in the millimetric range is the expansion of their dynamic range and the suppression of noise components in diagnostic signals. This problem is relevant in systems used for research and control of plasma parameters in controlled fusion installations.

The aim of this study was to develop and produce a filter that would be compact and simple in structure and operation for suppressing the noise components of the probing signal and expanding the dynamic range of the Doppler reflectometry (DR) diagnostics of the L-2M stellarator. The DR diagnostics [1] allows one to obtain information on the plasma poloidal rotation velocity from the frequency shift of the back-scattered radiation spectrum; it is used on many tokamaks and stellarators. In installations of this type, such as T-10, TJ-II, L-2M, plasma can be heated by the microwave radiation of gyrotrons at the frequency of electron-cyclotron resonance (ECR).

The commissioning of the MIG-3 gyrotron complex on the L-2M stellarator had made it possible to bring the ECR heating power to 1 MW and the specific energy input to 4 MW/m^3. The heating is carried out at the second harmonic of gyrotron radiation with the basic frequency of 75.3 GHz. Currently, this is the maximum energy input for such a heating method among all toroidal magnetic plasma confinement installations [2].

Troubles in the operation of the DR diagnostics were found [2, 3] in experiments where the plasma was heated by a single gyrotron with a frequency of 75 GHz (gyrotron pulse duration of 14 ms, gyrotron power of 550 kW, specific microwave power of 2.1 MW/m^3, power level change in the stationary phase does not exceed 2%). The probing frequency of the reflectometer was of 37.5 GHz, the antenna tilt angle was 4° relative to the normal to the poloidal cross section of the stellarator, the digitization frequency of the analog-digital converter (ADC) was of 6.25 MHz in all channels, and the memory buffer of the ADC had 262 144 points. Figure 1 shows the example of the signal recorded in one of the DR channels and the Fourier spectra plotted over two time intervals. The spectra obtained are broadband and there are special mathematical procedures for determining the Doppler shift (described in [4]). In time-lapse 48–57 ms one gyrotron (G1) operated with power of 170 kW. At these conditions the filtration system of the DR diagnostic reduced noises which propagated through plasma from the gyrotron, and the frequency shift f_{shift} can be defined by the spectrum of the DR signal (see top left of the figure 1). In time-lapse 57–61 ms, two gyrotrons (G1+G2) were used for plasma heating in the stellarator L-2M with the total power of 370 kW. In this case, the filtration systems of the DR channel cannot reduce noises, which makes it impossible to determine the frequency shift (see top right of the figure 1) [2, 3].

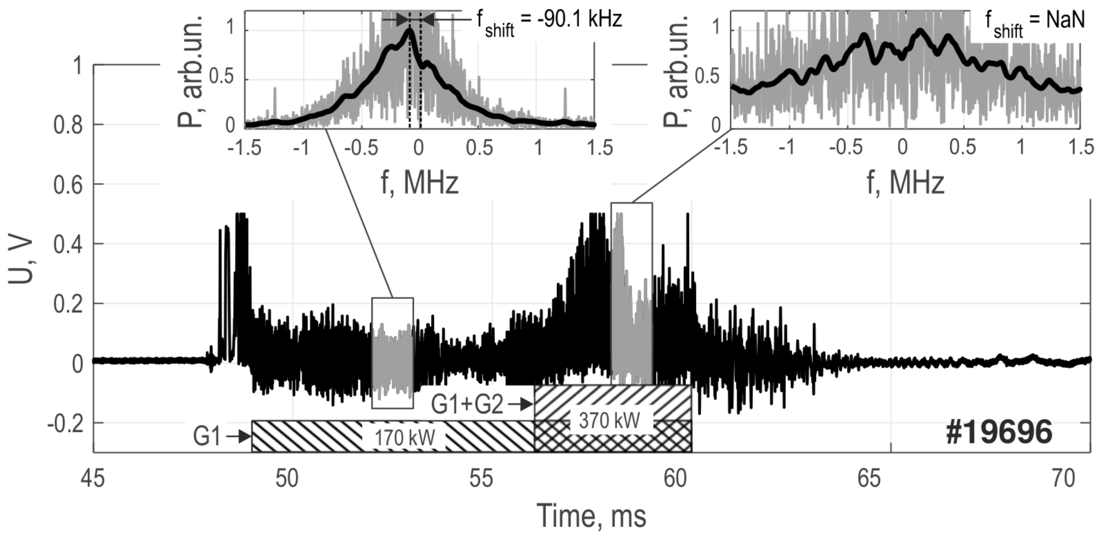

Figure 1. Noisy DR signal (stellarator pulse #19696) and spectra of its parts.

Due to the design features of the diagnostics (in particular, the limited dimensions of the waveguide), we were able to add only one more band-stop waveguide filter with lumped components (the same as in [1]) in each channel. But it was not enough for reducing noises in DR diagnostic signal. We developed and manufactured a compact band-stop filter with a center suppression frequency of 75 GHz [3], which consists of a sequence of Fabry-Perot resonators.

2 Modernization plan and filters

2.1 Modernization plan

We modernized the filtering system for the DR electromagnetic radiation (figure 2a). One band-stop Chebyshev waveguide filter with lumped components (pins) was added to each out of two DR diagnostic channels (F3 and F4 on figure 2a) as compared with previous DR diagnostic systems [1].

The waveguide filters' coefficient S21 is near -30 dB in the suppression band 65–80 GHz and their linear size is 27 cm. As mentioned above this was not enough for normal operation DR diagnostics, but the additional installation of similar size filters into the tract was no longer possible. In the measuring system, there was only space left between the diagnostic window of the stellarator chamber (on the left side of figure 2a) and the LS lens system. It was decided to create a new compact band-stop filter that was developed based on the Fabry-Perot resonator (BFBFPR) and install it on the glass of the diagnostic window to provide a high suppression of the frequency of 75.3 GHz and low attenuation at the 30–40 GHz diagnostics frequency band.

2.2 Filter based on Fabry-Perot resonator

Millimeter filters based on Fabry-Perot resonators are actively used in various diagnostics [5–7]. We used Fabry-Perot resonators with flat round mica plates with diameter $D = 80$-mm and thickness $S = 0.12$ mm (the relative dielectric permittivity of mica $\varepsilon = 6$, refraction index $n = 1.5$ and reflection coefficient $R \approx 0.03$ at the frequency of 75 GHz). The operation of the proposed filter is based on the Fabry-Perot resonator-interferometer with two parallel mica plates (used as reflectors) (figure 2b) without applying metal grids to them, unlike [5, 6]. This solution made it possible to provide the required characteristics, temperature stability, and simplicity in the manufacture of the filter.

The resonant properties of the Fabry-Perot resonator-interferometer are determined by the interference minima and maxima associated with its cavity length d. For the band-stop filter, we need to obtain an interference minimum at a frequency of 75 GHz ($\lambda_0 = 4$ mm), which is found from the expression:

$$2d_0 = m\lambda_0\,, \tag{2.1}$$

where d_0 is the resonator length (including plates), m is an integer, and λ_0 is the electromagnetic wavelength in free space. The length of the resonator is determined as

$$d_0 = \frac{m\lambda_0}{2}\,. \tag{2.2}$$

It equals $d_0 = 2$ mm for $m = 1$ and $\lambda_0 = 4$ mm. In our case, however, it is also necessary to take into account that the resonator was made of mica with the relative dielectric permittivity $\varepsilon_r = 6$, the magnetic relative permittivity $\mu = 1$ and the thickness $S = 0.12$ mm. The electromagnetic wavelength in mica is

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon\mu}}\,. \tag{2.3}$$

The length of the resonator d should be calculated taking into account the length of the electromagnetic wave in mica (2.3):

$$d = d_0 - \Delta d\,, \tag{2.4}$$

where Δd is

$$\Delta d = m\frac{kS(\lambda_0 - \lambda)}{2}\,. \tag{2.5}$$

In our case, $m = 1$, k is the number of mica plates in the resonator ($k = 2$), and $S = 0.12$ mm is the mica plate thickness. We get $\Delta d \approx 0.3$ mm, $d = 1.7$ mm and the distance between the plates $l = 1.46$ mm.

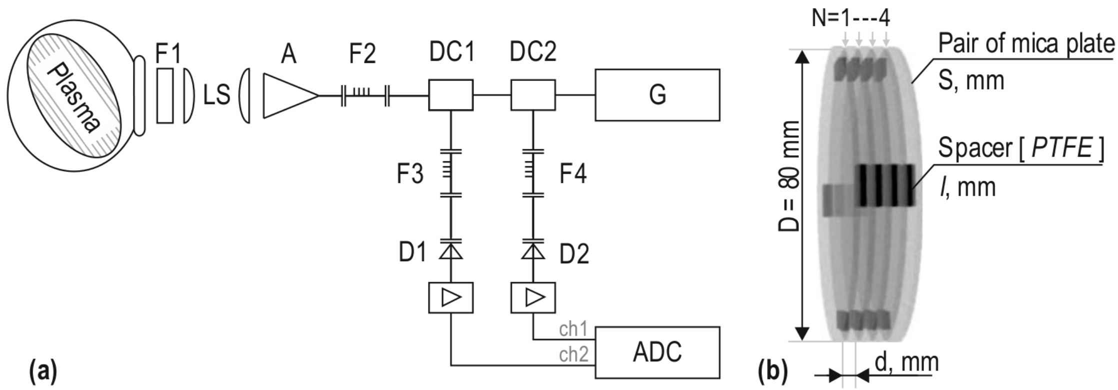

Figure 2. Scheme of experimental setup of *R* diagnostic (a) and new filter with Fabry-Perot resonators (BFBFPR).

3 Numerical simulations

3.1 Description of the numerical model

A filter model based on the Fabry-Perot resonator using mica plates as reflectors was developed in the EMPro computer-aided design system (CAD) from Keysight Technologies. The model was built in three-dimensional geometry. The simulations were carried out by the finite element method (FEM) in the Agilent FEM Simulator block [8]. In the model, the plates were placed in a coaxial system with open walls to ensure the propagation of the TEM wave. The boundary conditions at the edges of the countable domain (external walls of the coaxial system) were given by the Perfect Matching Layer (PML) model. Waveguide ports were installed on both sides of the filter.

3.2 Numerical simulation results

Using numerical simulations, the distance between mica plates in the resonator was optimized and the optimal number of resonators was selected. The distance between the plates $l = 1.46$ mm obtained in the preliminary simulations was accepted, taking into account the possible manufacturing accuracy of 0.1 mm, and simulations were performed for the distance between the plates of 1.2, 1.4, 1.5, 1.6 and 1.8 mm with four resonators in the filter. The simulation results in the form of S-parameters (S11 and S21) are presented in figure 3. For the parameter S11, the curves for the cavity lengths of 1.6 and 1.8 mm were removed for better readability of graphs for the cavity lengths of 1.5 and 1.4 mm.

Figure 3 shows that the optimal distances between the resonator plates are 1.4 and 1.5 mm. For these distances between mica plates, the S-parameters of the filters were calculated for different numbers of resonators in the filter. It is seen in figure 4 that filters consisting of 7 and 8 resonators have the largest S21, and the difference between them is not very significant. Note that in some cases, a smaller number of resonators can provide optimal results, because they are more compact. For the experimental measurements of S-parameters and installation in the measuring path, we chose a filter consisting of 4 resonators with the same distances between the plates $l = 1.5$ mm.

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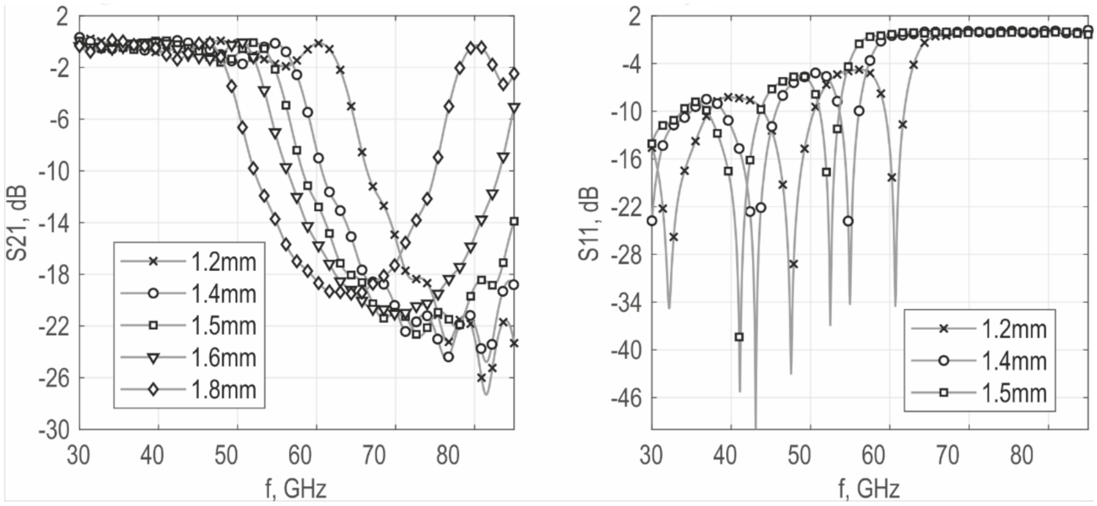

Figure 3. The results of modeling the parameters (a) S21 and (b) S11 of the band-stop filter based on the Fabry-Perot resonator with four resonators with different distances between the plates.

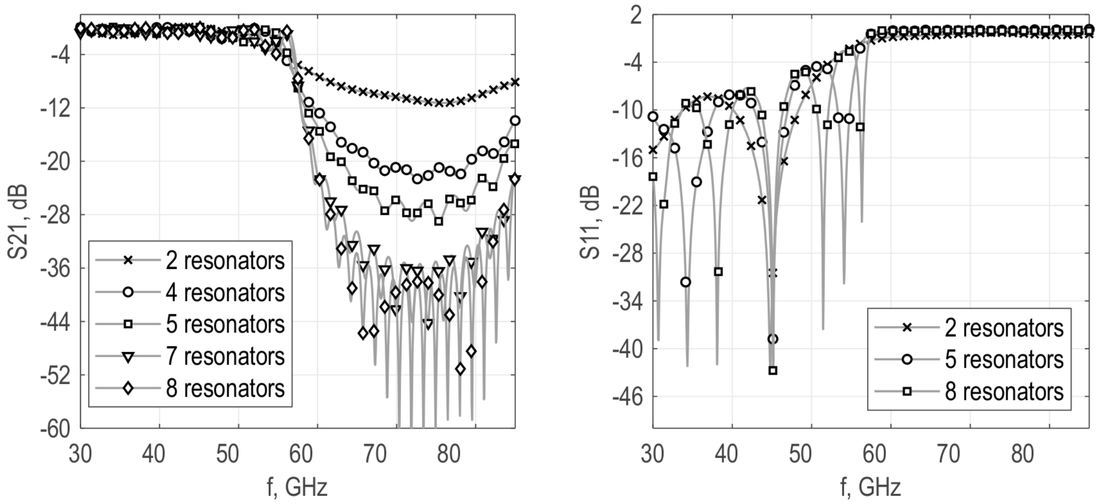

Figure 4. The simulation results of the parameter (a) S21 and (b) S11 of a band-stop filter based on the Fabry-Perot resonator with a different number of resonators with the distance of 1.5 mm between the plates.

4 Experimental studies

4.1 Description of the measuring setup and installation location of the filter in the reflectometer

Measurements of the S-parameters of the manufactured BFBFPR were carried out using the MVNA-8-350 Vector Network Analyzer.

4.2 Measurement results

Figure 5 shows the results of measuring the parameter S21 of a filter with 4 Fabry-Perot resonators with a plate separation $l = 1.5$ mm. The experimental result coincides well with the simulation

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result in the suppression band. The grey curve shows S21 in the measuring path and open space between the ports of network analyser without filter, the length of open space and filter length are the same). The differences between modelling and experimental results of S21 parameter in the passband (frequencies 40 . . . 55 GHz) appeared due to reflection and radiation losses of the electromagnetic wave at the point of contact between the equipment of the vector network analyzer (cable connectors) and the filter under study.

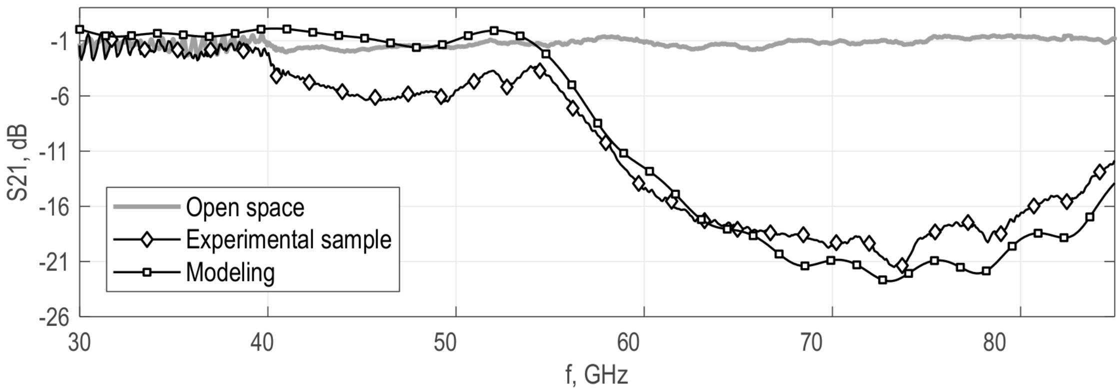

Figure 5. Comparison between the experimental and simulation results.

After measuring the S-parameters, the BFBFPR was installed on the diagnostic window of the L-2M stellarator chamber between the window and the fluoroplastic lens, which is located opposite to the receiving horn antenna of the Doppler reflectometer [3]. The new filter was installed in the DR system, after which an experimental session was conducted with ECR heating of the plasma by gyrotron. The recorded DR signal is shown in figure 6. This signal differs from the signal in figure 1 by the absence of noise at the gyrotron frequency 75.3 GHz, which makes it possible to obtain the DR spectra (figure 6) and the frequency shift f_{shift} can be defined by the spectra of the DR signal (see top of the figure 6).

5 Conclusions

In the course of optimization of the Doppler reflectometry system of the L-2M stellarator, we modeled, designed and created a band-suppressive filter based on the Fabry-Perot resonator made of dual mica plates for the frequency range of 70–80 GHz. Several options for the distance between the plates of the resonator were considered, of which the optimal one was chosen, showing a greater attenuation at the main frequency of 75 GHz (for suppression) and the smallest attenuation in the working frequency range 30–40 GHz of the reflectometer. In addition, different numbers of resonators in the filter were considered and the minimum number of resonators, four, was chosen for the design, which allowed us to successfully measure the DR signal.

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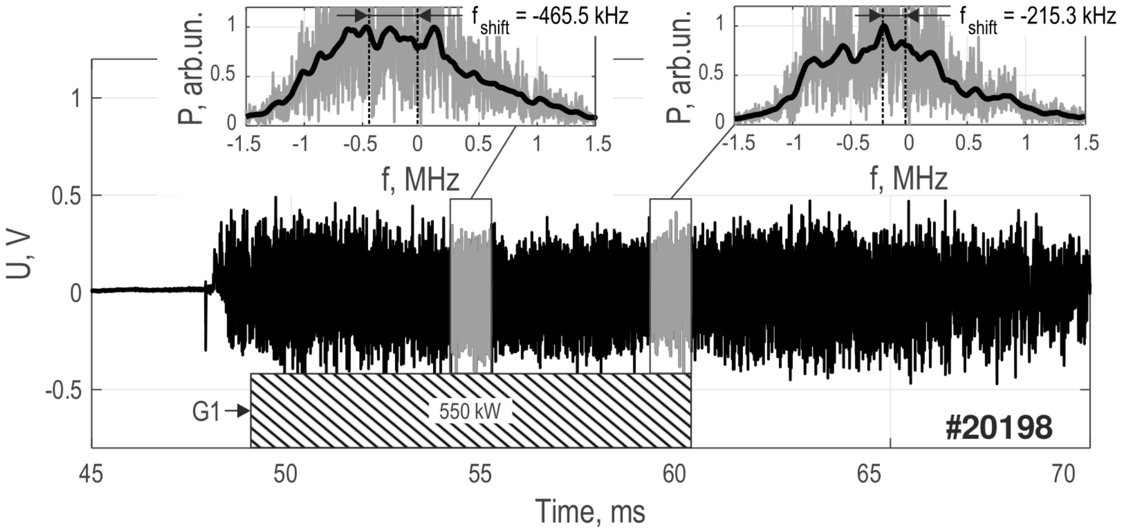

Figure 6. The clear DR signal (stellarator pulse #20198.) and spectra of its parts after modernization of the filtration system.

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