Notch Filter in 70 GHz Range for Microwave Plasma Diagnostics[*)]

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A notch filter for the rejection of stray light from gigahertz range heating sources was developed to protect a vulnerable microwave plasma diagnostic system. As one of the applications, we consider the installation of the notch filter into the receiver of a collective Thomson scattering diagnostic in the Large Helical Device. Experimental observations indicate that two types of notch filters are required for main and spurious mode rejection; they have very narrow, steep shapes to avoid disturbing the diagnostic signal. On the basis of numerically simulated results, notch filters were fabricated, and their performance was evaluated. An attenuation level of 35 dB at 74.746 GHz with a 3 dB bandwidth of 0.49 GHz is achieved by two pairs of resonator cavities. This attenuation is acceptable in our study.

1. Introduction

Fusion plasma diagnostics are essential for understanding plasma physics, controlling burning plasmas, and protecting vacuum vessels from disruptions or fast ion losses in fusion devices. One possible method of plasma heating and controlling is to use millimeter waves from megawatt power gyrotrons in electron cyclotron (EC) heating and current drive. However, microwave diagnostic devices, in particular those using electron cyclotron emission (ECE), microwave reflectometry, and collective Thomson scattering (CTS), suffer from stray light originating in the main mode radiation of a gyrotron inside the vacuum vessel, even if it becomes a small fraction. To protect microwave components from the stray light, a notch filter with a sharp, deep stop bandwidth can usually be applied.

These millimeter-wave diagnostics are typically used during EC heating to understand the underlying plasma transport. The noise radiation in the gyrotron radiation is mixed into the main mode radiation of the gyrotron. This spurious mode radiation from the gyrotron lies outside the frequency of a notch filter for the main mode radiation. For the CTS diagnostic, for example, the mixed spurious mode radiation in a probing beam should be excluded to protect the microwave components and reduce the interference signals. Some approaches have been considered to fix these problems. One approach is to optimize the gyrotron

operation to suppress the spurious mode output [1]. This decreases the gyrotron power; however, the power degradation is not suitable for plasma heating and the probing beam used in CTS diagnostics. Therefore, as another approach, we consider using a notch filter to protect a receiver from spurious mode radiation and reduce the superimposed noise.

In addition to these reasons, we have a possibility to develop a CTS diagnostic system with two sightlines. Thus, we need a notch filter for a new CTS receiver. The pass bandwidth of the present notch filter is limited to + 3 GHz (80 GHz in RF signal) from the nominal probing beam frequency of 76.95 GHz. It is desirable to extend this to + 5 GHz (82 GHz) for a fast ion diagnostic.

A new gyrotron for plasma heating is recently operated in the Large Helical Device (LHD) experiment. It has a frequency of 154 GHz. We would like to use a notch filter for CTS or to protect the millimeter-wave receivers from the stray radiation. Our final goal is to fabricate a notch filter with a steep and very narrow rejection area, which is less than 200 MHz around 77 GHz or in the 154 GHz range for main mode rejection with a total attenuation level of 120 dB. We also need a notch filter for spurious mode rejection with an attenuation level of 30 dB. In both cases, high manufacturing precision is required for these notch filters. We started by developing notch filters for spurious rejection to solve the present problems and to achieve relatively easy development because of the attenuation level. It

is also advantageous because the area of the CTS spectrum removed by the notch filter is very narrow.

In this paper, we describe a design study using computer simulation software and the fabrication and characterization of notch filters for the reduction of spurious mode radiation with a narrow bandwidth from 74 to 80 GHz.

2. Design Model for a Notch Filter

Former studies showed that the spurious mode frequency between 74 and 80 GHz is about 74.7 GHz at the on and off timings of a 77 GHz megawatt gyrotron during normal operation. As one example, the spectrogram measured by the CTS receiver for shot #113377 is shown in Fig. 1. The spectrogram in three frequency regions is shown, and the raw signal before signal processing is plotted at the bottom. The probing beam power of the 77 GHz gyrotron (L#7) used for the CTS diagnostic is modulated at a frequency of 50 Hz. The PIN switch, which can pass or intercept a signal within a few tens of nanoseconds, is driven at the rising and trailing edges to mask the strong spurious mode radiation. The spurious $TE_{17,6}$ mode radiation can be masked at the rising edge but cannot be perfectly masked at the trailing edge. It is necessary to adjust the PIN switch timing and duration of a few milliseconds. The frequency of the $TE_{17,6}$ mode radiation chirps down at the trailing edges. The chirping frequency should be covered by the notch filter's bandwidth. In addition, a spurious $TE_{m,n}$ mode, whose mode number has not been identified, appears at a frequency region of 79.33–79.34 GHz. Although it does not significantly affect the raw signal of the
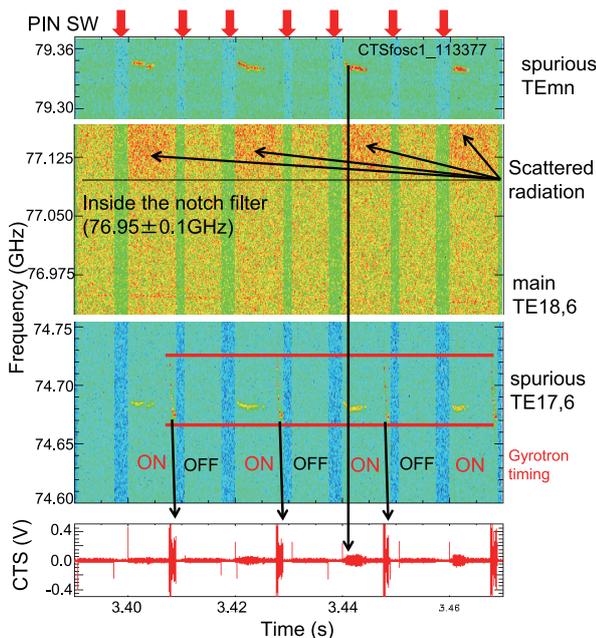
fast digitizer, a notch filter must be used for a certain channel in the filter bank receiver.

A notch filter with a central frequency of 74.7 GHz has been designed using the commercial software ANSYS HFSS. We simulated a waveguide-type notch filter that satisfied our specifications. For the narrow 3 dB bandwidth, mode control in resonator cavities is effective [2–5]. The main design parameters are listed in Table 1. The TE_{11} mode is excited in the resonator cavities. The parameters determined here are noted. The distance between cavities Δl is given by

$$\Delta l = \frac{l_g}{4}(1 + 2N). \tag{1}$$

Here N is an integer, and λ_g is the guide wavelength, which is introduced from the dispersion relation with the RF wavelength λ_0 as

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - (\lambda_0/\lambda_c)^2}}. \tag{2}$$

The condition $\lambda_c > \lambda_0$ is enforced. The cavity length l is determined by

$$l = \xi \frac{\lambda_g}{2}, \tag{3}$$

where ξ is an integer. The cut-off wavelength for the $TE_{m,n}$ mode becomes

$$\lambda_{c,mn} = \frac{\pi D}{v'_{mn}}, \tag{4}$$

where v'_{mn} is the nth root of the derivative of the Bessel function $J'_m(x) = 0$. The notch filter modeled here according to the determined parameters is shown in Fig. 2. Only two coupled cavities are shown in the model for simplicity. The design parameters, which mainly consist of the slit shape and cavity length, are adjusted to obtain the desired characteristics. The final design parameters are listed in Table 2. A bandwidth of 200 MHz was ultimately achieved at the 3 dB rejection bandwidth by the simulation. The

Fig. 1 Spectrogram of the gyrotron (L#7) frequency measured by a high resolution CTS receiver during CTS experiments.

Table 1 Design parameters of a notch filter for spurious rejection in [mm].

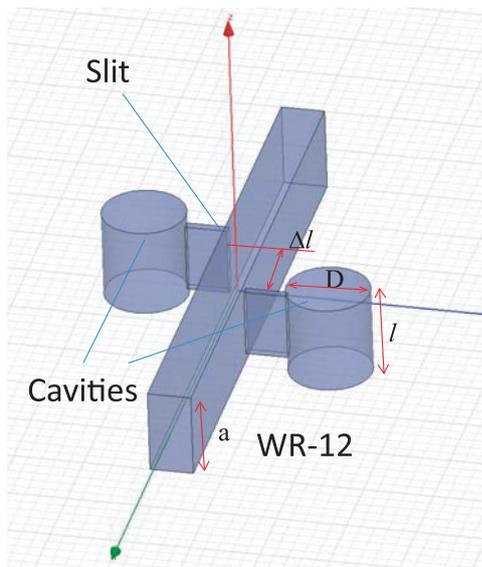| broad side of waveguide	a	3.099
RF wavelength	λ_0	4.013
cavity diameter	D	3.000
cut-off wavelength	λ_χ	6.198
cut-off wavelength for TE_{mn}	$\lambda_{c,11}$	5.120
guide wavelength	$\lambda_{g,11}$	6.465
cavity length	l	3.232
	$2l$	6.465
	$3l$	9.697
guide wavelength for main waveguide	λ_g	5.267
Length between subsequent cavities	Δl	3.950

Fig. 2   3D model of a notch filter used in the study.

Table 2   Adjusted parameters and filter specifications obtained by simulation.

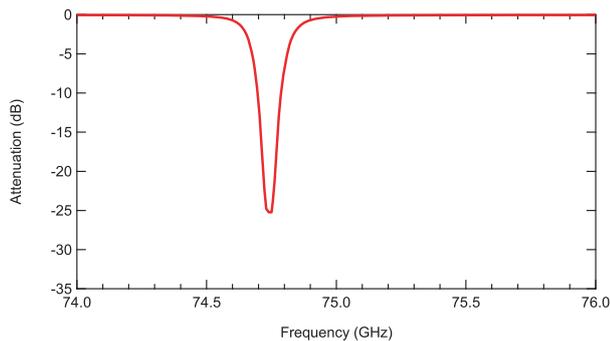|	[mm]
Cavity length	3.33
Slit width	0.1
Slit length	2.5
Slit depth	0.6
f	74.75 GHz
$\delta f_{3\,\mathrm{dB}}$	0.2 GHz
Attenuation	25 dB

Fig. 3   Simulated characteristics of a notch filter for spurious rejection.

attenuation in the notch region was 25 dB with two resonant cavities, as shown in Fig. 3. We found that the cavity length changes the central frequency of the notch filter by around 0.01 mm/150 MHz. To adjust the cavity length using screws, a smaller pitch is easier. A pitch of 0.34 mm is adopted.
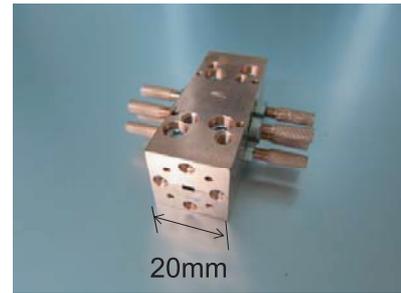

Fig. 4   Fabricated notch filter for spurious rejection. The cylindrical cavity lengths are adjusted from both ends by the screws visible in the photograph.
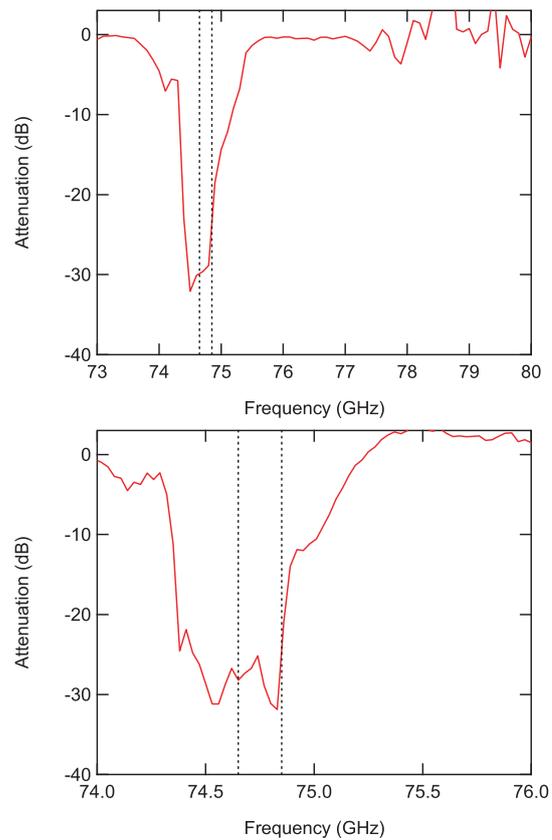

Fig. 5   Measured characteristics of the first trial notch filter. (a) Wide range and (b) near notch region.

3. Notch Filter Fabrication

After the design parameters were determined, the first trial piece was fabricated. The main body is a cuboid ($20 \times 20 \times 40 \, \mathrm{mm}^3$), as shown in Fig. 4. A total of four cavities are arranged along the main waveguide, WR-12. Twice as many cavities as in the design model were adopted to obtain an attenuation of more than 40 dB. The main material is oxide-free copper. Figure 5 shows the measured characteristics. The bandwidth of 200 MHz is shown as broken lines in the graph. The measured 3 dB bandwidth is around 500 MHz, which is wider than the designed one. The difference was attributed to fabrication errors in the slit width
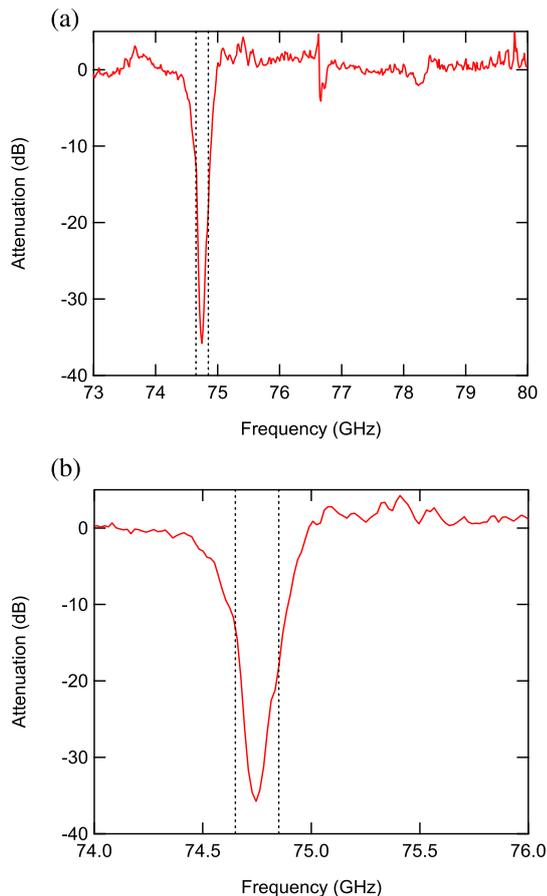
(a)

(b)

Fig. 6 Measured characteristics of the second trial notch filter. (a) Wide range and (b) near notch region.

and shape.

The second trial piece was carefully fabricated to realize a structure as close to the simulated one as possible. The measured filter characteristics are shown in Fig. 6. A 3 dB bandwidth of 0.49 GHz and an attenuation of 35 dB were obtained at a central frequency of 74.746 GHz. The 3 dB bandwidth of the second trial piece is still wider than the design value. To examine this, the fabricated slit width and shape were measured by a digital microscope. The slit width was found to be 0.12 mm, but the design value was 0.10 mm. We simulated it again including a practical fabrication error of ~ 0.02 mm. The result shows an increase in the 3 dB bandwidth from 0.2 to 0.4 GHz. The measured bandwidth of 0.49 GHz is still wider than this simulated value of 0.4 GHz.

Unexpected notches related to spurious modes were observed at 76.65 and 78.22 GHz. We believe that other $TE_{m,n}$ modes are excited in the gap between the tuning plungers and the cylindrical cavity walls. As recommended in ref. [2], the insertion of attenuation rings in the cavities to absorb the spurious waves would be a good solution for the next trial.

4. Summary

We designed, fabricated, and characterized a 70-GHz-range notch filter for microwave plasma diagnostics. An attenuation level of 35 dB at 74.746 GHz is achieved by two pairs of resonator cavities. This attenuation is acceptable in our study. The 3 dB bandwidth is 0.49 GHz, which is twice the design value. This is attributed to an increase in the slit width of ~ 0.02 mm compared to the design value in fabrication. The unexpected spurious notches are expected to be reduced by improving the plunger structure, producing a flat passband and low insertion loss.

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