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Q-band high-performance notch filters at 56 and 77 GHz notches for versatile fusion plasma diagnostics

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A 6-pole Q-band waveguide filter with a notch frequency above the Q-band has been developed for plasma diagnostics. The previous paper [M. Nishiura, et al., Journal of Instrumentation, Vol. 10, C12014 (2015)] reports that the notch frequency exists within the standard band. In this study, the newly required notch filter extends the function, which prevents a thorny wave from being mixed into an instrument beyond the standard bandwidth of the waveguide. The mode control technique for cavities realizes a deep and sharp filter shape for Q-band notch filters with 56 and 77 GHz notches, respectively. The former filter has the attenuation more than 50 dB at 56.05 GHz and the bandwidth of 1.1 GHz at -3 dB. The latter filter has the attenuation more than 55 dB at 76.95 GHz and the bandwidth of 1.6 GHz at -3 dB. The electron cyclotron emission imaging (ECEI) and the ECE diagnostics for the Q-band implemented a pair of the fabricated filters, and demonstrated the ECE measurement successfully in the intense stray radiation from a 56 GHz gyrotron.

I. INTRODUCTION

In fusion plasma experiments, intense millimeter waves for plasma production and heating are injected into a vacuum vessel from a mega-watt class-gyrotron. The power of the electromagnetic waves is not completely absorbed by plasmas. Then, the stray radiation of the intense beams interferes with signals of measurement systems, for example, electron cyclotron emission (ECE) [1], reflectometer and collective Thomson scattering (CTS) diagnostics [2, 3]. In most serious cases, intense millimeter wave radiation can damage a mixer in receivers. To avoid such situations, we have started developing a notch filter with a narrow stop band and the wide pass band in the frequency range from 74 to 80 GHz [4, 5]. The notch filter is tuned for a mode which is excited at the cavity resonators. In our case, the purpose was the reduction of main stray radiation as well as spurious radiations from the gyrotron associated with the on – off modulation timing.

The electron cyclotron resonance heating (ECH) system of the LHD has implemented two gyrotrons for 77 GHz, and three for 154 GHz. The new frequency of 56 GHz has recently been prepared for plasma experiments at low magnetic field of ~ 1 T. The ECE imaging (ECEI) system has arrayed antennas [6]. Each antenna is connected to a mixer by Q-band waveguides. The stray radiation of 56 GHz gyrotron above the Q-band range reaches the mixers, and is converted down to the intermediate frequency (IF) from 1 GHz to 10 GHz. The mixture of ECE signals and the stray radiation saturates and/or overloads the low noise amplifiers. In some cases, the intense stray radiation can damage the down conversion mixer. Therefore, the reduction of more than 20 dB in the stop band and the low insertion loss are required to measure the clean ECE signals. The reduction level is estimated from the noise signals of the ECEI at the injection timing of the 56 GHz ECH.

We have designed a notch filter composed of an E-band waveguide with mode-controlled cavities. Those designs are reported in the references [4, 5]. A notch filter with a different concept is also reported in the reference [7]. However, a notch filter for the unwanted stray radiation, which exists above the standard band of a waveguide, requires a new concept. After the design of the basic structure, the detail is determined by a numerical simulation software Ansys HFSS. The fabricated filter is characterized by a vector network analyzer (VNA). Finally, the ECEI system implements the filters, which solved the previous problem.

II. DESIGN MODEL, SIMULATION, AND FABRICATION OF NOTCH FILTER

A notch filter is designed to attenuate intense gyrotron stray radiation in the RF line of the ECE receiver with the rectangular waveguide of WR-22 for Q-band (33-50 GHz). The center frequency of the stop band corresponds to the nominal gyrotron frequency of 56.05 GHz within the bandwidth of 1 GHz. We used E plane tee junction as the mode-coupling technique for the individual cylindrical cavities that control the attenuation and the stopband width of a notch filter [2-4]. The detail to determine the basic parameters is described in the reference [4]. When an

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electromagnetic wave with a specific frequency passes through the main waveguide, it is reduced at the exit port by a specific mode of $TE_{mn\xi}$ excited in cylindrical cavities. Here, m, n, and ξ indicate integers, respectively. From possible modes in a cylindrical cavity, the lowest TE_{111} is selected to prevent unnecessary notches from appearing in the Q band. For controlling a cavity mode, the cavity length *l* is determined by

$$l = \xi \frac{\lambda_g}{2} \qquad (1)$$

The guide wavelength λ_g is given by

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

where λ_0 is the RF wavelength, λ_c is the cutoff wavelength of the waveguide and we assume that $\lambda_0 < \lambda_c$. From the above equations and the cut-off wavelength in the cylindrical cavity $\lambda_{cmn} = \pi D/\nu'_{mn}$, the estimated cavity length becomes l = 3.089 mm at $\xi = 1$ for the center frequency of the notch filter at 56.05 GHz. Here, ν'_{mn} is the root of the derivative of the Bessel function $J'_m(x) = 0$. The cavity spacing Δl is calculated by the following equation,

$$\Delta l = \frac{\lambda_g}{4}(1+2N) \qquad (3)$$

Here an integer *N* is set to one for compactness.

As noted above, the cavity modes are used to reject undesired frequencies. The procedure of the design of the cavity mode, the numerical simulation, and the fabrication is the same as the previous procedure. The main difference in the previous filters and the new notch filters is summarized in TABLE 1. The difference is caused by the application of plasma diagnostic systems. A Q-band waveguide notch filter with a notch frequency outside the Q-band demonstrates efficient protection from a stray radiation of intense millimeter waves, although the solution for the designed notch is sensitive to the coupling structure of slits and other structures.

TABLE 1. Features of old filters[4, 5] and new filters (this paper)

	Old filters	New filters	
Purpose	Rejection and protection of main and spurious gyrotron radiations for CTS diagnostics	Rejection and protection from the main gyrotron radiation for ECE and ECEI diagnostics	
Frequency ranges	E band	Q band	Q band
Notch frequency	E band	V band	V band
Notch bandwidth	~ 0.2 GHz	~ 1.0 GHz	
Cavity length	Adjustable by screw	Fixed by fabrication	

For the coupling between the main waveguide and the cavity, the filter characteristics depend on rectangular slits. The coupling slits and the number of cavities are optimized by the Ansys HFSS to obtain the required specification. The parameters are summarized in TABLE 2. The cavity length was adjusted to set the center frequency of 56.0 GHz in the simulation. Finally, the simulated cavity length resulted in 2.95 mm for 56.0 GHz. The value was used for the filter fabrication. The distribution of the E-field in the notch filter for 56 GHz is shown in Fig. 1. The six cavities are arranged on both sides of the main waveguide. The mode is excited at some cavities during the wave propagation in the main waveguide.

TABLE 2. Design parameters for the Q-band 56 GHz notch filter (unit is in mm)

Center frequency of the notch filter	f_{center}	56.0 GHz
Cavity diameter	D	6.30
Cavity length	*l*	3.089 by Eq. (1) 2.950 by the simulation
Cavity gap length distance between two resonators	Δl	4.554
Slit width		1.0
Slit length		2.2
Slit depth		0.2

The designed notch filter is fabricated using the optimized parameters from the simulation. The outer dimensions of the filter are 20 mm × 20 mm × 50 mm (see Fig. 2). The filter is made of free cutting copper. The entrance face and the exit face need adaptors to connect the WR-22 waveguide. In the previous paper [4, 5], we used a plunger to vary a cavity length, which requires the precise adjustment for the notch frequency. We were able to eliminate the tuning procedure of each individual cavity by letting the cavity lengths be fixed. We made the first version with the cavity length designed by the Ansys HFSS. After the notch frequency of the first version was measured, the cavities in length were drilled additively to fill the frequency gap between the measurement and the design. The Q-band 77 GHz notch filter requires the procedure, and the Q-band 56 GHz does not require it.

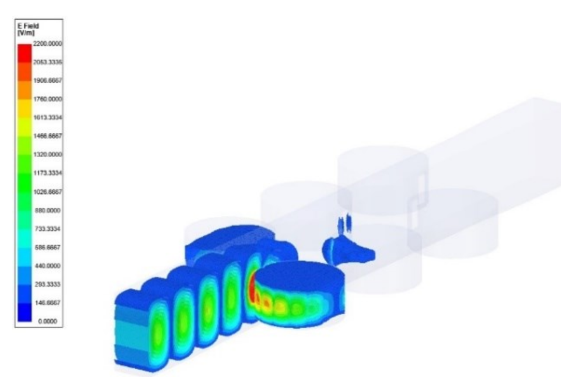

FIG. 1. The wave electric field in Q-band notch filter.

The characteristic of S parameters S_{21} is measured by a VNA in Fig. 3. The designed TE_{111} mode appeared at the center frequency of 55.85 GHz. The bandwidth at -3 dB is

1.1 GHz. The attenuation at 56.05 GHz achieved more than 50 dB. The measured insertion loss was less than 1.5 dB around 41 GHz. In the simulation, the insertion losses are 0.8 dB for 2 pairs of cavities and 1.6 dB for 3 pairs of cavities. The surface condition of the free cutting copper walls would not cause the linear increase. Therefore, the insertion loss around 40 GHz would be caused by the slit or resonator structure. The numerical result reproduces two unknown notches. The closest cavity modes correspond to TE_{112} at 65.7 GHz and TE_{311} at 79.2 GHz. The reason for the large frequency gaps is not clearly understood. Because the redundant extra notches exist out of the Q-band, the present performance satisfies our specification.

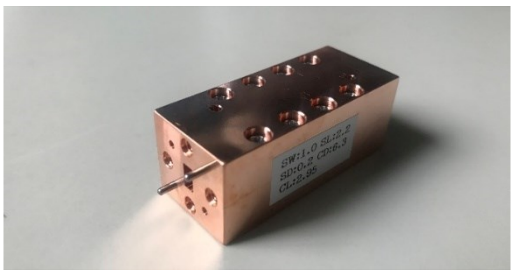

FIG. 2. The fabricated notch filter for the Q-band.

TABLE 3. Specification of the Q-band notch filter

f@center	55.85 GHz
f@3dB	55.3, 56.4 GHz
S_{21}@min	> 60 dB
S_{21}@56.05GHz	50 dB
Insertion loss	< 2 dB (in Q-band)

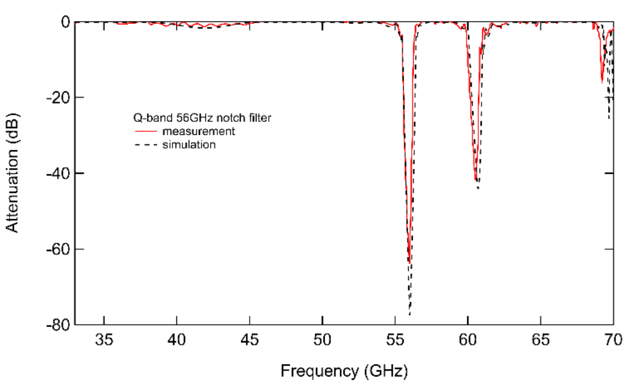

FIG. 3. Characteristic of the Q-band notch filter (see TABLE 3). The gyrotron frequency of 56.05 GHz, which should be rejected, is located inside the notch. The solid and broken curves are measurement and simulation results, respectively.

III. ECEI SYSTEM WITH Q-BAND NOTCH FILTERS

The ECH in the LHD uses the 77 GHz gyrotrons. For the same reason, Q-band 77 GHz notch filters are also prepared for the ECEI system. The design concept is the same as that described above. The outer dimensions of the cuboid shape are 20 mm × 20 mm × 42 mm. The maximum attenuation is more than 55 dB at 76.95 GHz, and the bandwidth at -3 dB is 1.6 GHz.

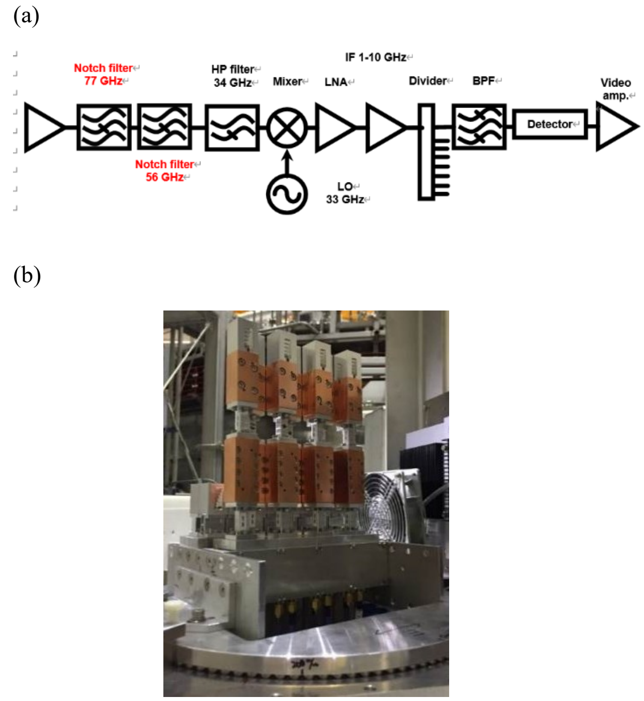

FIG. 4. ECEI system in the LHD. (a) The schematic diagram of the ECEI system. The heterodyne technique is used to down convert the RF signal. The notch filters are inserted in the RF line. (b) A pair of notch filters with notch frequencies of 56 and 77 GHz is mounted on the antenna array.

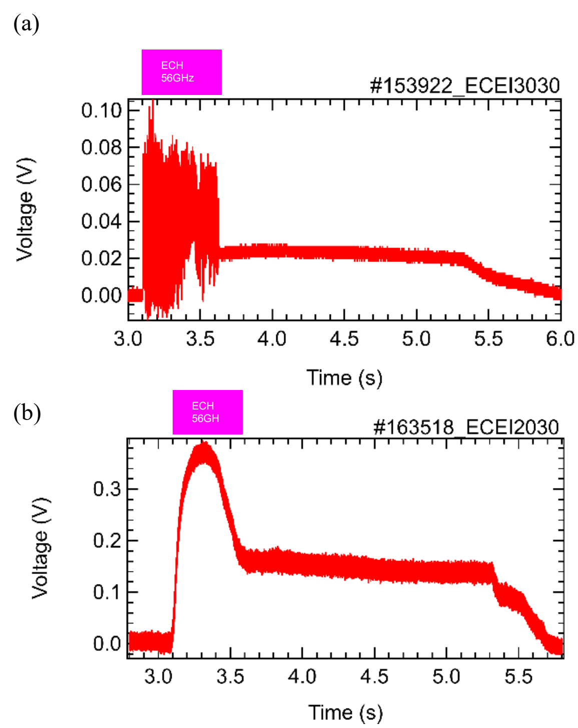

FIG. 5. ECE signals in the ECEI diagnostic (a) before and (b) after the insertion of the Q-band waveguide notch filter with 56 GHz notch.

The diagram of the ECEI system is shown in Fig. 4 (a). A pair of Q-band 56 GHz notch filter and Q-band 77 GHz notch filter is mounted in a series on the RF part of the ECEI diagnostic. The apparent system mounted on the LHD is shown in Fig. 4 (b). The time evolution of the ECE signals before and after the insertion of the notch filters are plotted in Figs. 5 (a) and (b), respectively. In Fig. 5 (a), the ECE signal does not behave correctly at t = 3.1-3.6 s due to the intense stray radiation inside the vacuum vessel caused by 56 GHz ECH. On the other hand, in Fig. 5 (b) we found that the Q-band notch filter suppresses the unexpected signal accordingly at t = 3.1-3.6 s. The diagnostics are operated successfully in this experimental campaign.

IV. SUMMARY

The Q-band waveguide notch filters with 55 and 77 GHz notches have been developed for versatile millimeter wave-diagnostics (ECE, ECEI, CTS, etc.). For signal conditioning and component protection of plasma diagnostics, the notch filters require a low insertion loss in Q-band (33-50 GHz) and a narrow stopband width at V-band (50-75 GHz) or E-band (60-90 GHz). The fabricated notch filters work well for the intended purpose of monitoring the ECE signals. The fabricated filters are implemented in the arrayed ECEI system and the ECE system of the LHD. The ECE diagnostics are available for research on heating efficiency, MHD instability, and energetic particle physics in plasmas.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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