Design of a 170 GHz Notch Filter for the KSTAR ECE Imaging Sensor Application

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Abstract

A planar, light-weight, and low-cost notch filter structure is required for the KSTAR ECEI (Electron Cyclotron Emission Imaging) system to protect the mixer arrays from spurious plasma heating power. Without protection, this heating power can significantly degrade or damage the performance of the mixer array. To protect mixer arrays, a frequency selective surface (FSS) structure is the suitable choice as a notch filter to reject the spurious heating power. The FSS notch filter should be located between the lenses of the ECEI system. This paper presents a 170 GHz FSS notch filter for the KSTAR ECEI sensor application. The design of such an FSS notch filter is based on the single-sided square loop geometry, because that makes it relatively insensitive to the incident angle of incoming wave. The FSS notch filter exhibits high notch rejection with low pass-band insertion loss over a wide range of incident angles. This paper also reviews the simulated and measured results. The proposed FSS notch filter might be implemented in other millimeter-wave plasma devices.

Keywords: Frequency selective surface, notch filter, millimeter-wave imaging, angle independency, plasma diagnostic

1. INTRODUCTION

Generally, frequency selective surfaces (FSSs), consisting of periodically arranged metallic patches, are widely used as band-stop and band-pass filters [1]. For many decades, numerous applications in microwave, millimeter-wave, and optical filters have used FSSs. However, 1999 saw the first utilization of the frequency selective surface as a band-stop filter ranging from 30 GHz to 200 GHz, in oversized microwave systems. The Rijnhuizen Tokamak project applied this filter for the protection of microwave diagnostic from high input microwave power [2]. Recent studies have used the frequency selective surface as protection notch filters in millimeter-wave imaging sensor systems for plasma diagnostics, i.e., electron cyclotron emission imaging (ECEI) and microwave imaging reflectometry (MIR) [3-5].

The ECEI is a passive millimeter wave imaging and visualization technique used for fusion plasma diagnostics. Detection of electron temperature profiles and of fluctuations inside the plasma utilizes this technique with frequencies ranging from around 50 GHz to 200 GHz. The ECEI system uses a mixer array to collect electron cyclotron emission (ECE) from the plasma to form two-dimensional fluctuating images of the electron temperature. However, the ECEI system needs to protect its receiver from spurious plasma heating power, which may saturate or damage the diodes of the mixer array. A filter is necessary for rejecting the spurious plasma heating power, thereby protecting the mixer array from saturation, or burning out [6]. Since the protection filter should be present between the optical lenses in the imaging system, a planar FSS is appropriate, because it is thin, lightweight, and easy to implement.

The KSTAR (Korea Superconducting Tokamak Advanced Research) has been recently developed and it operates the ECEI system for imaging electron temperature and MIR for detecting electron density fluctuations. In the KSTAR tokamak, the development of a combined ECEI and MIR system has been possible because of the non-overlapping frequency ranges of ECEI and MIR [3].

Fig. 1 shows a planar, low-cost, and lightweight FSS notch (band-stop) filter, suitable for protecting the imaging mixer arrays from the spurious Electron Cyclotron Resonant Heating (ECRH) power. However, designing the FSS notch filters present numerous challenges. The most critical design specification is to provide high notch rejection with low pass-band insertion loss over a wide range of incident wave angles.
This paper presents the design of a single-sided FSS notch filter for the KSTAR ECEI sensor application. The filter operates at 170 GHz with a low insertion loss of less than 3 dB over the pass-band of 70 GHz to 110 GHz. It offers a suppression of about 40 dB at 170 GHz with a frequency range of 140 GHz to 200 GHz. The FSS consists of periodic structure of square loops, and Fig. 1 shows the periodic structure of the FSS notch filter.

### 2. Design of the FSS Notch Filter

This paper presents the implementation of the 170-GHz frequency selective surface notch filter. A desirable characteristic of the FSS notch filter is its insensitivity to or independence from the incident angle of the incoming waves in the ECE imaging sensor application. The square loop structure, selected for the design of the single-sided FSS notch filter, is the most suitable for the purpose.

Fig. 2 shows the unit cell of the proposed square loop FSS notch filter and its equivalent circuit. The equivalent circuit is represented by an inductive component in series with a capacitive component. Splitting the vertical and horizontal parts of the square loop structure completes the modeling of the FSS notch filter. In the equivalent circuit, the inductor (L) represents the vertical strip of the square loop, whereas the capacitor (C) represents the horizontal strip of the square loop. Eq. (1) and Eq. (2) can compute the values of L and C respectively [7].

\[
\frac{X_L}{Z_0} = \frac{\omega L}{Z_0} = \frac{d}{p} \cos \theta F(p, 2s, \lambda, \theta)
\]

\[
\frac{B_c}{Z_0} = \frac{\omega C}{Z_0} = \frac{4d}{p} \sec \theta F(p, g, \lambda, \theta) \varepsilon_{eff}
\]

where,

\[
F(p, w, \lambda, \theta) = \ln \left( \frac{\cos \frac{\pi w}{2p}}{\lambda} \right) + G(p, w, \lambda, \theta)
\]

\[
G(p, w, \lambda, \theta) = \frac{1 - \beta^2}{2} \left( 1 - \frac{E}{4} \right) (A_+ + A_-) + 4\beta A_+ A_-
\]

\[
(1 - \frac{E}{4}) + \beta \left( 1 + \frac{E}{2} \right) (A_+ + A_-) + 2\beta A_+ A_-
\]

with,

\[
A_\pm = \frac{1}{\sqrt{\left[ 1 \pm \frac{2p\sin \theta}{\lambda} \left( \frac{\varepsilon}{\lambda} \right) \sin \theta \right]^2}}
\]

\[
\beta = \sin \left( \frac{\pi w}{2p} \right)
\]

\[\varepsilon_{eff}\] which is equal to 0.5(\varepsilon + 1), is the effective dielectric permittivity, \(\lambda\) is the wavelength in air at the resonant frequency, and \(\theta\) is the angle of incidence wave perpendicular to the FSS.
Refer [7] for the development of Eqns. (1) to (4).

In this paper, the FSS notch filter was designed using Computer Simulation Technology Microwave Studio (CST MWS). As the FSS notch filter consists of a periodic structure, the CST MWS uses the CST’s FSS – Unit Cell (FD) solver to design a single unit cell of the FSS notch filter. The simulation uses a tetrahedral mesh in the frequency domain. Fig. 3 shows the CST model and its final mesh, where two Floquet ports (Zmax and Zmin) excite the plane waves. Parameterization of the geometry of the square loop FSS helps in optimizing the filter.

Changing three parameters of the square loop FSS notch filter, i.e., length of the loop, width of the loop, and unit cell period, also help in the optimization. They maximize the rejection at the resonant frequency and the low insertion loss at the lower frequency band.

3. RESULTS AND DISCUSSIONS

3.1 Fabrication

For the fabrication of the proposed FSS notch filter, the Rogers RO4003 substrate of 12 mil material thickness is used. The small size of the resonant structure made it difficult to fabricate millimeter-wave FSS filters using the normal etching process. As a result, the measured results show a frequency shift, and the following sections mention this. However, since the etching process is very cost-effective, it helped in reducing the fabrication cost. Fig. 4 shows the fabricated FSS notch filter for the ECE imaging sensor application.

3.2 Simulation

Design optimization resulted from studying the various simulation results of the 170-GHz single-sided FSS notch filter and the effects of various substrates. As mentioned earlier, all the simulations were conducted in CST MWS by using CST’s FSS – Unit Cell (Frequency Domain) solver. Fig. 5 shows the simulated results of the single-sided FSS notch filter. At normal incidence, the filter exhibits a rejection of 42.17 dB with 3.5 dB average pass-band losses. It also shows the performance of the proposed single-sided notch filter for angular incidences. It is clear that the performance of the FSS notch filter remains the same even when the angle of the incident wave changes by 14 degrees. Small variations of around 5 GHz in resonant frequency are present, but these are acceptable.

3.3 Measurements

Fig. 6 shows the measurement setup for testing the fabricated single-sided FSS notch filter. Mounting the FSS notch filter on a rotatable stand helped in measuring the performance of angular
incident waves using a Vector network analyzer (VNA) with an extender mixer from 140 to 220 GHz. Source and receiving antennas used with the VNA extenders generated the plane waves.

Fig. 7 shows the measured results of the single-sided FSS notch filter. At the resonant frequency, the proposed FSS notch filter exhibits rejection of 33.86 dB with a normal incident plane wave. With a plane wave at an incident angle of 6 degrees, the filter exhibits rejection of 33.23 dB at the resonant frequency. Similarly, with a plane wave at an incident angle of 14 degrees, the filter exhibits rejection of 32.12 dB at the resonant frequency. Maximum 7 GHz shift in the resonant frequency of the fabricated notch filter can be observed from Fig. 7, when the incident plane waves were applied with different angles. Table 1 summarizes the comparison between the simulated (Fig. 5) and measured (Fig. 7) results of the FSS notch filter at the resonant frequency. The major advantage of using square loop structure can be observed, which is relatively insensitive angular dependence of the designed (Fig. 5) and the fabricated (Fig. 7) FSS notch filter. The small disagreement between the simulated and measured results has been caused due to the fabrication tolerance.

Table 1. Comparison between the simulated and the measured results of the FSS notch filter at resonant frequency

| Incidence Angle | Rejection at 170 GHz (simulated) | Rejection at 184 GHz (measured) |
|-----------------|---------------------------------|---------------------------------|
| Normal          | 42.17 dB                        | 33.86 dB                        |
| 6 degree        | 35.90 dB                        | 27.13 dB                        |
| 14 degree       | 23.22 dB                        | 14.02 dB                        |

Fig. 8 compares the simulated results with the measured results for a normal incidence wave. Although the measured results exhibit the same rejection effect as that of the simulated results, there is a frequency shift of 14 GHz. This is a result of the fabrication tolerances. The resonant frequency shift, because of the fabrication accuracies of the square loop structures, is very prominent at high frequencies.

Fig. 9 shows the comparison between the simulated and
measured results, after removing the frequency shift of 14 GHz from the measured results. In terms of Q-factor and insertion loss, the shifted measured results agree with the simulated results.

In future, a more accurately fabricated FSS notch filter will achieve the desirable results and will remove this frequency shift problem.

4. CONCLUSIONS

This paper presents a 170 GHz single-sided frequency selective surface notch filter for the KSTAR ECE imaging sensor application. Design of the FSS notch filter follows a square loop structure. CST, using FSS Unit Cell boundary conditions helps perform the simulations and the simulated FSS filter exhibits the rejection of 42.17 dB at the resonant frequency of 170 GHz with average insertion loss of about 3.5 dB. The measured performance shows a 14 GHz shift in the resonant frequency because of fabrication inaccuracy. In future, a reduction in this shift at the resonant frequency will achieve desirable filter performance.

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