Protection Filters in ECEI Systems for Plasma Diagnostics

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For plasma diagnostic imaging systems such as the electron cyclotron emission imaging (ECEI) system, spurious rf heating power may saturate or even damage the mixer arrays. Without protection, the sensitivity of the mixers can significantly decrease or in the extreme case, the diodes can even be burnt. A metallic dichroic plate is usually used to rejection the spurious rf heating power. However, as a high pass filter, the dichroic plate can not be used when the frequency of the heating power is in the middle of the frequency range of interest. Consequently, a frequency selective surface (FSS) has been introduced as a planar filter in ECEI systems. FSSs can work as low pass, high pass, and band stop filters according to the various system requirements. Also, as a thin, light, planar filter, it is very easy to mount in imaging systems. This paper will focus on the design and fabrication of the FSS notch filter applied in TEXTOR, which is used to protect the imaging array from stray 140 GHz ECRH power. The filter is used in TEXTOR due to its deep rejection, and excellent angle insensitivity. The design procedure will be presented. More FSS applications will be talked in this paper. The new fabrication technique Electro Fine Forming (EF2) technology will also be introduced. FSS filters in the millimeter wave range also have possible applications in imaging systems in other fusion machines such as KSTAR, DIIID, and LHD.

Keywords: plasma diagnostic, frequency selective surface, electro fine forming technology, notch filter, beam splitter, dichroic plate

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1. Introduction

With recent advances in millimeter wave technologies, millimeter wave imaging is now applied for plasma diagnostics. In imaging system, optics and FSSs are now used together to lead signals to the detector arrays. FSSs in microwave engineering are the counterpart of filters in circuit. At resonant frequencies, FSSs provide total reflection or transmission. In this way, FSSs perform as various filters, high pass filter, low pass filter, band stop filter or band pass filter. They have wide applications in millimeter-wave and infrared regions such as radomes, dichroic reflectors, RFID tags, auto collision, photonic bandgap structures and EMI protection. Two types of FSS are generally employed: Capacitive FSS consists of an array of periodic metallic patches on a dielectric substrate, such as the notch filter and beam splitter presented in this paper; Inductive FSS are usually a metal screen periodically perforated with apertures such as dichroic plate [1]. As a planar, light and low cost structure, FSS is suitable to be applied among imaging optics. FSS is first designed as a band stop detector protection filter in Rijnhuizen Tokomak [2]. Now in recent millimeter wave imaging systems for plasma diagnostics, which is electron cyclotron emission imaging (ECEI) and microwave imaging reflectometry (MIR), FSS is applied as the planar protection notch filter [3, 4]. This notch filter can protect the mixer arrays from spurious ECRH power, so that the detectors won't be saturated or even burnt. This paper will focus on the design procedure and fabrication method for a 140 GHz FSS notch filter applied in Tokamak Experiment for Technology Oriented Research (TEXTOR) devices. It is fabricated in Kyushu Hitachi Maxell using Electro Fine Forming technology (EF2) [5]. With this technique, there is more flexibility when select FSS unit cell element. Other FSS applications in plasma diagnostics, such as dichroic plate, and beam splitter will also be introduced in this paper. Further applications can be found in other tokomak machines such as KSTAR, NSTX, DIIID and LHD.

2. EF2 Fabrication

Due to the small wavelength in the millimeter wave range, the unit cell structures on FSS are so small that FSS pattern are limited and it is hard to fabricate it precisely with standard PCB technique. The 140 GHz FSS square loop notch filter is fabricated with Electro Fine Forming technology (EF2) instead of stand PCB technique. EF2 is an additive microfabrication technology that combines

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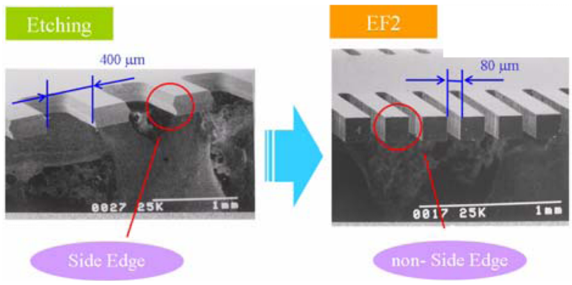

Fig. 1 side shape of etching (left) and EF2 (right).

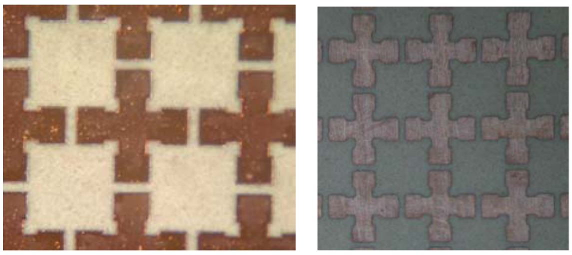

Fig. 2 Close-up photographs of the Jerusalem cross structures fabricated with EF2 (left) and standard PCB technique (right).

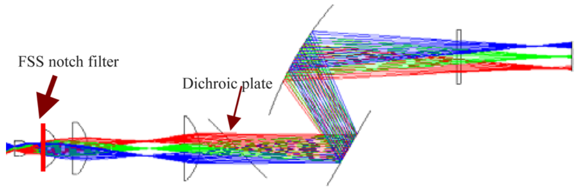

Fig. 3 2-D ECEI ray tracing figure in TEXTOR, notch filter and dichroic plate position is shown.

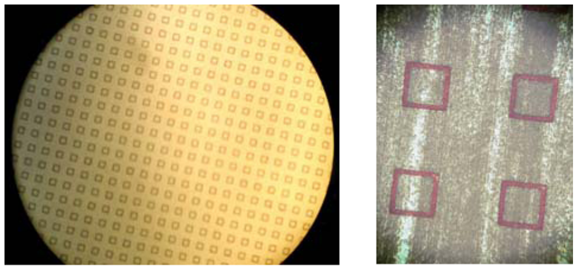

Fig. 4 Photo of final square loop FSS filter.

two advanced technologies. Parex Patterning Technology, which is a micro-lithography exposure technique, is used to enhance forming resolution and provide precise aperture patterns with micron level tolerances. Maxell's patented "Stay-Land Technology" can control the plating thickness well (10 μm to 300 μm) and make an evenly distributed metal deposition with homogeneous current density. It can provide excellent vertical cross section, smaller holes and accurately controlled hardness (Fig. 1). 15 μm line width and 6 μm gap can be realized with this technology. More details can be obtained in [5]. Jerusalem cross FSS filters fabricated with standard PCB and EF2 is compared in Fig. 2. It is obvious that EF2 provides more precise geometry.

3. 140 GHz FSS Notch Filter

The 140 GHz FSS notch filter applied in TEXTOR tokomak is modeled with periodic moment method (PMM) and fabricated with EF2 technology. FSS notch filter with Jerusalem cross structures are first employed in TEXTOR [6]. The rejection is enough to protect the detector from burning, but the sensitivity is still affected by the ECRH power. When the ECRH power increases, the detected signal on the ECEI mixer array becomes weaker or even gets burnt. This Jerusalem cross filter (Fig. 2) can provide more than 25 dB rejection at normal incidence, but when millimeter wave is obliquely incident, the rejection decreases quickly to less than 6 dB. Jerusalem cross filter still allows obliquely incident signals to pass. To provide more rejection, we can either put the filter on a lens with collimated beam, or build a filter insensitive to the angle of incidence. Fabrication limits at millimeter-wave frequencies make it difficult to fabricate a > 30 cm diameter notch filter which can be inserted into the optical system at a point where the incident range of angles is minimized. Instead, the FSS notch filter is mounted on a smaller lens (20 cm diameter) where the input waves impinge at different angles as shown in Fig. 3. The filter should reject all 140 GHz millimeter wave no matter what incident it has. From optical calculations, the notch filter should be angle insensitive over at least a range of 15 degrees with respect to normal. The 140 GHz notch filter must provide > 25 dB rejection at 140 GHz and low loss below 130 GHz while being angle insensitive over this $\pm 15^\circ$ angular range.

Different from previous work, angle insensitivity is a critical specification in this application. Five potential FSS structures are investigated, and the unit cell elements are the ring, square loop, square center, Jerusalem cross and double square [7]. FSSs with square loop and ring unit cell structures show best angle insensitivity. The square loop structure is selected as the final model because it is easier to fabricate than the ring structure [4]. Photos of the final square loop FSS filter is shown in Fig. 4.

The square loop FSS filter is composed of periodic 25 μm thick copper square loop on 254 μm RO3006 substrate. Periodic moment method (PMM) is compared with finite element method (FEM) and Finite-difference time-domain method (FDTD) in the FSS filter design. There is frequency difference between the simulated and measured results. FDTD gives more than 20 GHz frequency shift although it is fast. FEM can give similar result to PMM, but it is very time consuming. Ansoft Designer with PMM code which considers the metal thickness is selected by providing closest resonant frequency and rejection to mea-

$$S_{21} = 10 * \log\left(\frac{\frac{Vout\_f}{Vin\_f}}{\frac{Vout\_n}{Vin\_n}}\right)(dB)$$

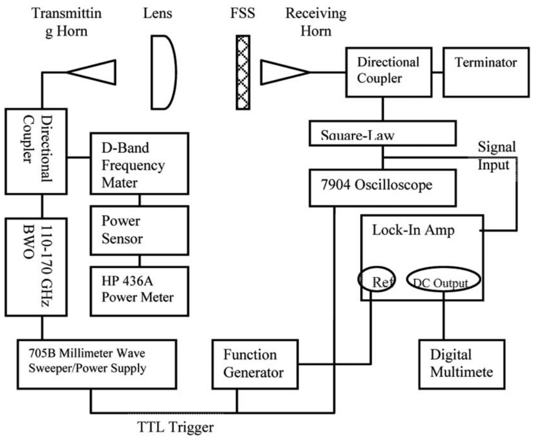

Fig. 5 Schematic of the original FSS notch filter testing setup.

sured values. There is a good match between simulation results with metal thickness considered and measurement results as shown in Fig. 6. This frequency shift is not constant, and it varies with the metal thickness. For the filters with 25 μm copper metallization, the frequency difference is 1 GHz.

The measurement setup is shown in Fig. 5. 110 GHz-170 GHz BWO (backward wave oscillator) is used as the millimeter wave source here. The power is separately transmitted and received by two horns. The lens between the two horns can transform the point radiation waves to parallel waves which can normally pass the FSS notch filter. A square law detector is used to detect the signal in the receiving system. In this measurement, the FSS notch filter is fixed on a sliding test fixture. By sliding the filter, we can measure the transmission performance with and without the FSS notch filter. Then the transmission performance of the FSS notch filter can be obtained by calculating the difference of the two transmission coefficients. The test fixture also allows us to change and read the angular position of the notch filter so that the incident angle of the plane wave can be varied. The advantage of this measurement method is that the calibration procedure before testing is simple and it eliminates concern about the loss of the test devices.

The attenuation is calculated using the formula below according to square law.

The final square loop FSS notch filter is measured to have 35 dB rejection at 140 GHz at normal incidence, and it is insensitive to angle of incidence over the range of concern, which is 15 degrees, shown in Fig. 7. It can provide at least 25 dB within 15 degrees at 140 GHz. In addition to the large rejection, high Q, and angle insensitivity, the square loop structure is also easier to fabricate than other structures. It is applied as the protection notch filter in the

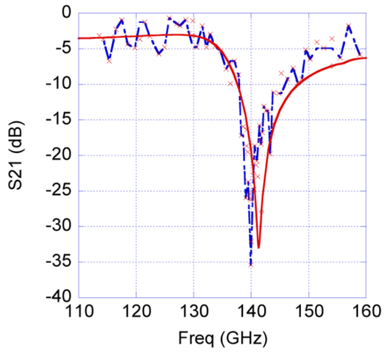

Fig. 6 Measured and simulated results for the final square loop structure.

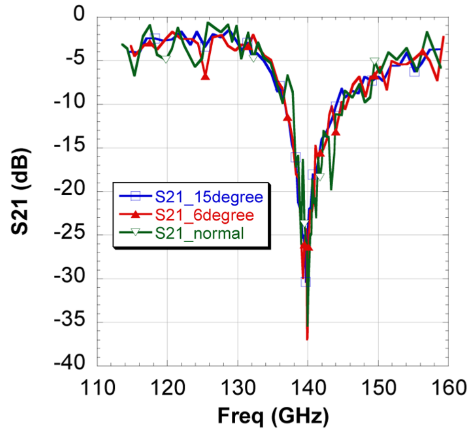

Fig. 7 Measured angular performance of a square loop FSS filter.

TEXTOR imaging system [4].

Through modeling and measurement, thick metallization is also proved to provide better performance. When metal thickness increase, the filter has larger rejection, higher resonant frequency and wider bandwidth. EF2 technology which can fabricate thicker patterns can bring better microwave performance.

4. Dichroic Plate

Dichroic plates have wide applications in antenna systems. Now dichroic plate is used in combined ECEI/MIR system to combine ECEI and MIR system. The quasi-optical dichroic plate consists of a metal plate with a tightly packed array of circular holes and acts as a high pass filter [8]. It can be fabricated by numerically controlled milling of circular waveguide slots in half-wavelength-thick metal plates and it is tilted 45° in the system. This dichroic plate is designed to reflect the incident electromagnetic radiation at frequencies below its cutoff frequency while allowing most of the radiation at higher frequencies to pass through.

In the combined system, higher frequency ECEI signal (> 100 GHz) passes the dichroic plate and reaches the ECEI imaging detector array. Lower frequency MIR signal

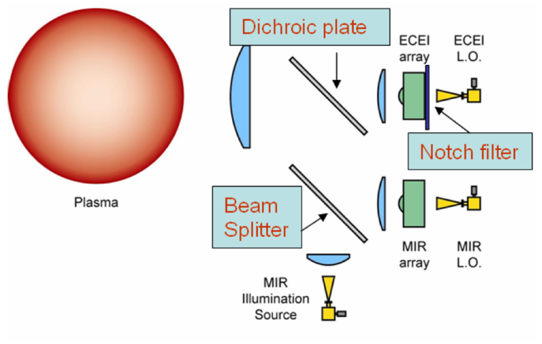

Fig. 8 Schematic of combined ECEI/MIR system.

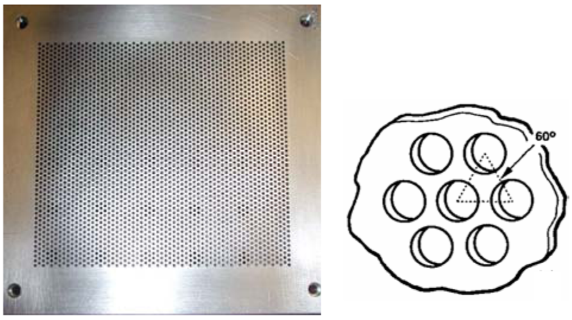

Fig. 9 Left: photo of dichroic plate with 100 GHz cutoff frequency; right: dichroic plate structure.

Table 1 Dichroic plate diameter versus Cutoff Frequency.

Diameter (inch)	0.068	0.0655	0.063	0.0606	0.058
Cutoff Freq (GHz)	102.7	106.6	110.8	115.1	120.2

(< 90 GHz) is then reflected at this dichroic plate and goes to MIR receiver system [3,9]. The cutoff frequency of the dichroic plate are just slightly greater than that of the ECEI LO source, and it thereby also functions as a high pass filter to ensure SSB operation of the mixer array. Fig. 9 shows one dichroic plate in TEXTOR.

Dichroic plate is one type of inductive FSS. Like other FSSs, The aperture shape can determine the transmission performance and the diameter of the holes determines its cutoff frequency as shown in Table 1. Dichroic plate can also work as diplexer and beam splitter too. With a more complex dichroic plate as a diplexer, the mixer array can work as harmonic or subharmonic mixer with LO source at half of the rf frequency. It has potential application on tokomak machines such as KSTAR.

5. Quasi-Optical Beam Splitter

As an inductive FSS, dichroic plate can work as a beam splitter. Capacitive meshes can be designed as beam splitter too. In NSTX scattering system, a metal grid FSS is designed as beam splitter in the Michelson diplexer.

Beam splitters are used in the Michelson diplexer to split the LO beam into 6 channels. The diplexer requires

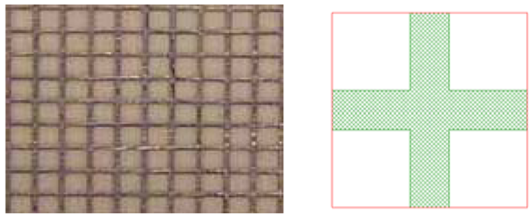

Fig. 10 Left: Close-up View of Metal Grid Patterned Beam Splitter (45 mil spacing) Right: unit cell structure for metal grid frequency selective surface [10].

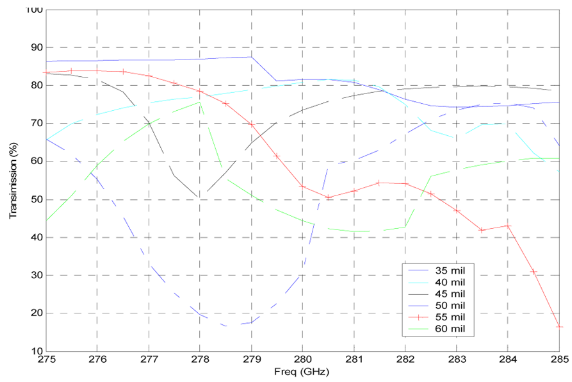

Fig. 11 Metal Grid Pattered Beam Splitter on RO4305B PCB with 20 mil Thickness and Various Grid Spacings.

a 50 % and a 78 % transmission ratio beam splitter with vertical polarization, i.e. the E field is parallel to the beam splitter. The physical dimensions of this beam splitter are 4 by 4 to cover the 2.5 diameter waveguide (Fig. 10).

The beam splitter is also designed with Ansoft Designer. They are fabricated on RO4350B with a maximum 20 mil thickness, and the printed pattern resolution is an 8 mil line on 1/2 ounce copper. Simulated results for metal grid FSSs with various spacing are shown in Fig. 11. The simulation shows beam splitters with 45 mil and 55 mil grid spacing offer 53 % and 73 % transmission ratio, respectively and are very close to design specification, i.e. 50 % and 78 %.

6. Conclusion

Several frequency selective surfaces have been applied in the combined ECEI/MIR system on TEXTOR. The 140 GHz square loop FSS filter can provide 35 dB rejection at 140 GHz and within at least 15° it has excellent angle insensitivity. It is able to protect the mixer array by rejecting most of leaked ECRH power. Other applications such as dichroic plate and beam splitter are introduced here too. Since the light, planar FSS structures are not difficult to fabricate with new advanced fabrication technologies such as EF2, more applications will be found in plasma diagnostics systems.

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