Frequency Selective Surface Applications in Millimeter Wave Imaging Diagnostics for Fusion Plasmas

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***Abstract*— Both capacitive and inductive frequency selective surface (FSS) filters have been applied in millimeter wave imaging plasma diagnostic systems to protect the imaging arrays from stray ECRH power as well as ensure working bandwidth control. Several FSS filters with improved performance have been designed and tested.**

I. INTRODUCTION

As microwave technology advances, imaging diagnostic systems have been developed to visualize process in magnetic fusion plasmas. For example, Electron Cyclotron Emission Imaging (ECEI) passive radiometric systems have been developed to measure electron temperature fluctuations in fusion plasmas and Microwave Imaging Reflectometer (MIR) radar imaging systems to measure electron density fluctuations [1].

Both ECEI and MIR systems employ heterodyne detection, in which a sub-THz beam is guided to a Schottky diode imaging antenna array through a set of quasi-optical substrate lenses. In a tokamak environment, stray Electron Cyclotron Resonance Heating (ECRH) power with frequency near or even within the measured signal bandwidth with much higher power poses a significant problem. For example, this stray heating power can saturate the diode mixer, in which case, the sensitivity of the mixer significantly decreases; or in the extreme case, the diodes can be destroyed. Consequently, to protect the imaging system, a band-stop filter with high rejection at the resonant frequency is required. To be better integrated into the imaging system, a planar FSS is utilized. In addition, this ensures single side-band mixing at the diode mixer by cutting off the high frequency signals. Right after the notch filter, a perforated metal plate dichroic filter serves as a high pass filter to ensure single-sideband mixing by cutting off lower frequency signals.

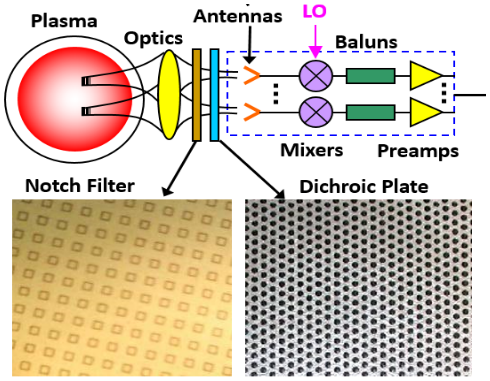

Fig. 1. Simplified ECEI schematic showing how the notch filter and dichroic plates are incorporated.

II. DESIGN OF THE NOTCH FILTER

As an important protection filter, various unit cell structures as well as simulation tools have been investigated. The square loop structure was finally chosen because of its angle insensitivity and relative ease of fabrication [2]. In this square loop based notch filter, there are three major parameters that affect the resonant frequency: a) the outer square side length; b) the inner square side length; and c) spacing between two adjacent unit cells.

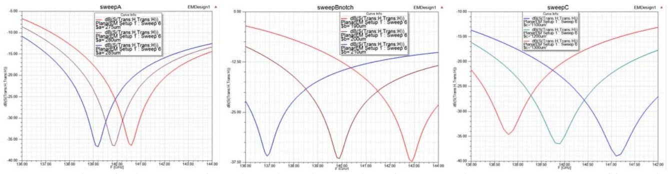

Fig. 2. Simulation results showing how the three major parameters affect the resonant frequency.

Typically, a single sheet of notch filter can provide 25 to 30 dB rejection at the resonant frequency. As the imaging optics have improved, such as the use of mini-lenses [3], it is now possible to stack 2 to 3 notch filters to provide very high rejection [4]. However, stacking filters together can introduce extra loss to the passband signal, which will decrease the signal to noise ratio (SNR). In order to maintain high rejection without affecting the system SNR, different substrate materials as well as different substrate thicknesses have been investigated to provide the best performance.

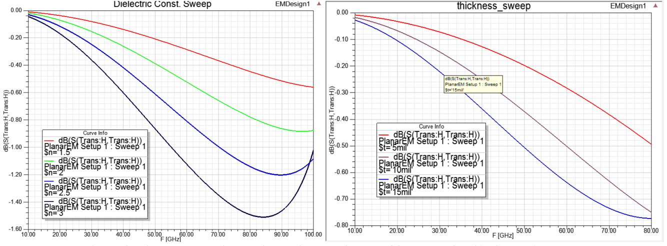

Fig. 3. Simulation results showing the effect of dielectric constant and thickness on the insertion loss. Results indicate that pass-band insertion loss decreases as the dielectric constant and thickness decrease.

After investigating commercially available laminate materials, Rogers RO5880LZ with 10 mil thickness and relative dielectric constant of 1.96 was finally chosen. Several notch filters have been designed and tested using RO5008LZ: these include the 105 GHz notch filter for the ECEI system on the HL-2A tokamak (Sichuan, China); 110 GHz for both ECEI and MIR systems on the DIII-D tokamak (San Diego, California, USA); 140 GHz for the ECE radiometer, ECEI and MIR systems on EAST (Hefei, China). They all have insertion loss of less than 1 dB in the passband and by stacking 3 of them together will increase the passband signal by 3 dB compared to using previous designs.

III. LABORATORY TESTING OF NOTCH FILTER

Laboratory testing of the transmission performance of the filters is a necessary step before final fabrication and application in the real system. In the previous testing, a complete transceiver system needed to be manually set up. Because of the high frequency involved, Backward Wave Oscillators (BWOs) are used to generate 110 to 170 GHz signals and frequency multipliers are used to achieve frequencies higher than 170 GHz. The system setup was complicated and it took considerable time just to make measurement at some discrete frequency points.

With the introduction of the Agilent (now Keysight) PNA-X, the test setup has become much more compact and easier. Also, by using frequency extender units, it's now possible to rapidly make precise frequency sweeping measurements.

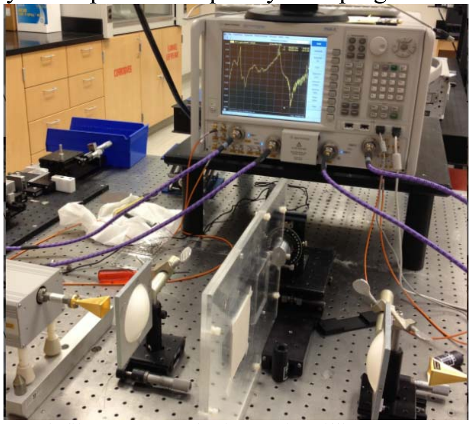

Fig. 4. Notch filter test setup in the Davis Millimeter-wave Research Center (DMRC) using the Agilent PNA-X. The notch filter is attached to the transparent plastic board in the center.

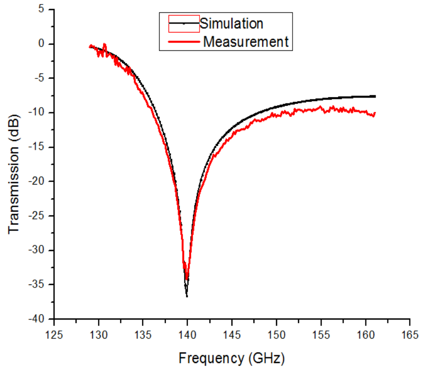

Fig. 5. Testing result (red) and simulation result (black) of a 140 GHz notch filter near the resonant frequency.

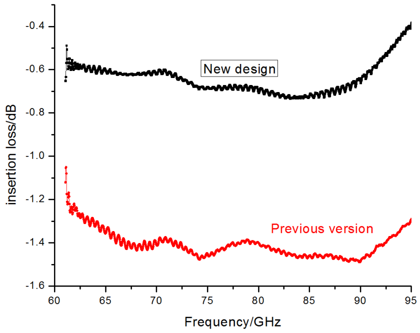

Fig. 6. Measured pass-band insertion loss of the new design versus the previous generation design.

IV. USE OF DICHROIC PLATE

The dichroic plate integrated into the optical path serves as a high pass filter to ensure single side-band mixing and also to block any unwanted low frequency signal. A dichroic plate is essentially a perforated metal plate with an equilateral array of hexagonally closed-packed circular waveguides [5]. The cutoff frequency is determined by the size of the circular waveguide, the spacing between the waveguides, and the thickness of the metal plate itself. In our passive imaging system, the received signal has a frequency range determined by the fusion plasma scenario, so several dichroic plates with different cutoff frequencies are needed. In our active imaging system, the received signal has a fixed frequency range and is the same as the transmitted beam. Consequently, only one dichroic plate is needed. For example, the MIR system for the EAST tokamak will be operate in W band, so a dichroic plate with 3 dB cut off frequency at around 72 GHz is desired.

When designing dichroic plates rough sizes can be calculated from equations with desired cutoff frequency [5] and further 3-D EM simulation is performed to finalize the dimensions.

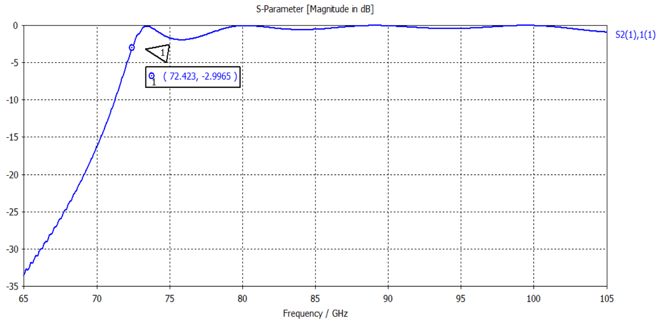

Fig. 7. Simulation result of dichroic plate for EAST MIR system**.**

This 72 GHz dichroic plate is expected to be fabricated and installed on the EAST MIR system in October, 2015.

ACKNOWLEDMENTS

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