

# Dual-Polarization Jerusalem-Cross Slot Type FSS for a Submillimeter-Wave Band

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**Abstract**—A dual-polarization Jerusalem-cross slot array (JCSA) type frequency selective surface (FSS) is designed for separating the submillimeter-wave band around 650 GHz in view of future application to spaceborne submillimeter-wave spectrometric radiometer. Based on this design, the FSS is fabricated by applying a photolithographic process and gold-plating to SiC substrate. The transmission and reflection characteristics measured for the fabricated JCSA agree well with those simulated by the method-of-moment calculation.

## I. INTRODUCTION

In recent years, several future planetary exploration missions to observe planetary atmosphere or surface with submillimeter-wave heterodyne spectrometric radiometers are proposed [1][2]. In these missions, there is an increasing demand for dual-polarization diplexer to separate submillimeter wave received by single antenna dish into two or more frequency bands in each of which orthogonal polarizations are simultaneously observed. For this purpose, we are now considering the use of a frequency selective surface [3][4][5] of the Jerusalem-cross slot array type.

The Jerusalem-cross slot array (JCSA) type frequency selective surface (FSS) [6] is an array of Jerusalem-cross slots formed on a conductive substrate, and is complementary to the Jerusalem-cross patch array [7][8]. Fig. 1 shows a unit cell of Jerusalem cross slot consisting of crossed slots inductively loaded at each end of the crossed slots. This inductive loading allows us to closely pack the array elements with a period less than half wavelength keeping grating lobes away from interfering the resonant frequency band of the FSS even for large angles of incidence. In addition to this, the JCSA has a freestanding structure without supporting dielectric substrate that may cause additional loss in the submillimeter-wave region.

In this paper, we describe a single-layer JCSA designed for a dual-polarization FSS separating a submillimeter-wave band around 650 GHz as the first step in view of future multi-layerization for actual use in submillimeter-wave radiometers. In Section II, a design of dual-polarization JCSA and its simulation results of transmission and reflection characteristics are described. In Section III, the measurement method of the transmission and reflection characteristics is described, and the measurement results are compared with the simulation results.

## II. DESIGN AND SIMULATION OF DUAL-POLARIZATION FSS

For a diplexer separating the submillimeter-wave band around 650 GHz and the lower frequency band around 500 GHz, at an angle of incidence of  $45^\circ$  for both polarizations, a Jerusalem-cross slot array (JCSA) type frequency selective surface (FSS) is investigated from the point of view of dual polarization characteristics. The JCSA type FSS is a periodical two-dimensional array of Jerusalem-cross slot formed on a thin conducting substrate.

Fig. 1 depicts the geometry of the unit cell of the Jerusalem-cross slot where  $p_x$  and  $p_y$  are the period along the  $x$  and  $y$  directions, respectively. In what follows, a plane wave is assumed to be incident at an angle of incidence of  $45^\circ$  along the  $y-z$  plane of incidence. The polarization state of incident wave is decomposed into TE and TM components according to the orientation of the electric field parallel and perpendicular, respectively, to the plane of incidence. The transmission and reflection characteristics of the JCSA were analyzed as a function of frequency by using the method of moment (MoM) based electromagnetic simulation software, FEKO [9]. The thickness of the substrate was assumed to be  $2 \mu\text{m}$ .

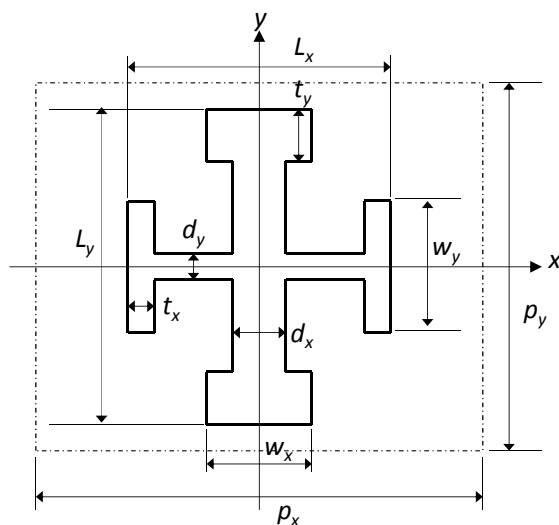


Fig. 1. Geometry of the unit cell of the Jerusalem-cross slot.

After some trial and error to make the resonant frequencies

for TE and TM polarizations coincide, we determined the geometrical parameters of Jerusalem-cross slot as follows:

$$\begin{aligned}
 L_x &= 150 \text{ } \mu\text{m}, & L_y &= 189 \text{ } \mu\text{m}, \\
 W_x &= 60 \text{ } \mu\text{m}, & W_y &= 78.75 \text{ } \mu\text{m}, \\
 d_x &= 30 \text{ } \mu\text{m}, & d_y &= 15.75 \text{ } \mu\text{m}, \\
 t_x &= 15 \text{ } \mu\text{m}, & t_y &= 31.5 \text{ } \mu\text{m}, \\
 p_x &= 255 \text{ } \mu\text{m}, & p_y &= 220.5 \text{ } \mu\text{m}.
 \end{aligned} \tag{1}$$

The transmission and reflection coefficients for TE and TM polarizations calculated by assuming that the material of the FSS is perfect conductor are shown in Fig. 2. It is found that the resonant frequencies for TE and TM polarizations coincides with each other, and that the frequency characteristics agree well with each other except for the frequency region around 714 GHz. A sharp resonance found around 714 GHz for TE polarization is attributable to so-called crooked or bent mode resonance [3].

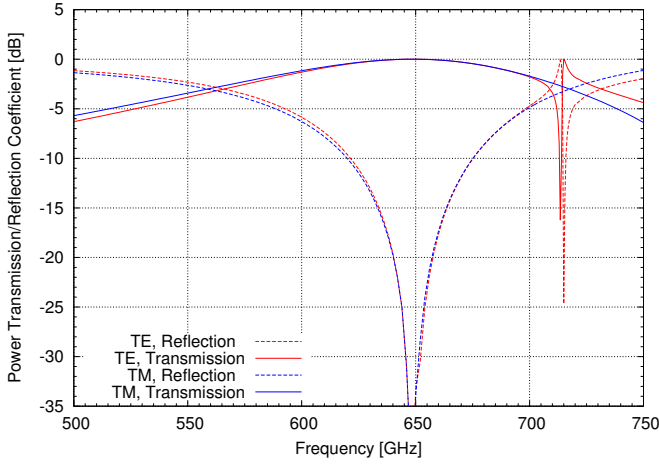


Fig. 2. Transmission and reflection coefficients of JCSA made of perfectly conducting material calculated for an angle of incidence of  $45^\circ$ .

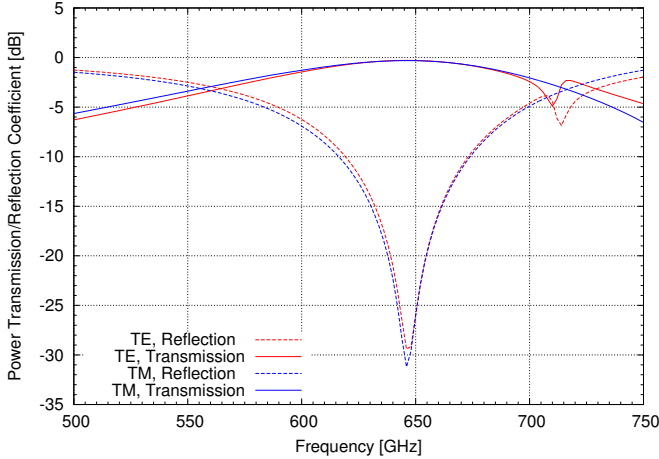


Fig. 3. Transmission and reflection coefficients of JCSA made of material with a finite conductivity of  $4.35 \times 10^7$  S/m calculated for an angle of incidence of  $45^\circ$ .

In order to see the effect of the finite conductivity of the FSS material, we calculated the transmission and reflection

coefficients by assuming the FSS is made of gold with a finite conductivity of  $4.35 \times 10^7$  S/m [10] for the same geometrical configuration of JCSA as in Fig. 2. Fig. 3 shows the transmission and reflection coefficients calculated for this case. The transmission loss due to the ohmic loss is found to be about 0.4 dB at the resonant frequency. It is also clearly found in Fig. 3 that the crooked or bent mode resonance found around 714 GHz becomes much less prominent as compared with the case of the FSS made of perfect conductor shown in Fig. 2.

### III. FABRICATION AND MEASUREMENT OF JCSA

#### A. Fabrication of JCSA

The Jerusalem-cross slot array pattern was formed by photolithographic process on a  $1.8\text{-}\mu\text{m}$ -thick membrane of silicon carbide (SiC) formed on a silicon wafer. After the silicon wafer was removed and 5-nm thick chrome was coated on the surface, the FSS was gold plated. The thickness of gold plating was about  $0.5 \text{ } \mu\text{m}$  and was thick enough as compared with the skin depth of about  $0.1 \text{ } \mu\text{m}$  of gold at frequencies around 600 GHz. The effective aperture of the JCSA was  $30 \text{ mm} \times 30 \text{ mm}$  in which  $136 \times 127$  Jerusalem-cross slots were arrayed.

#### B. Measurement Method

The complex transmission and reflection coefficients of the JCSA for an angle of incidence of  $45^\circ$  were measured by using a vector network analyzer (Agilent E8361C+N5260A) with VDI Vector Network Analyzer Extenders equipped with WR1.5 diagonal feedhorns. Configurations of measurement optics for transmission and reflection measurements are shown in Fig. 4 and 5, respectively. The measurement optics was a focused Gaussian beam transmission system consisting of two hyperboloidal mirrors (Mp1, Mp2), ellipsoidal mirrors (Mtk1, Mtk2), and wire-grid polarizers (WG1, WG2).

The JCSA under test was inserted at an angle of incidence of  $45^\circ$  at the beam waist. The beam diameter  $2w_0$  at which the field strength of the fundamental Gaussian beam mode falls to  $1/e$  relative to its on-axis value was  $5.27 \text{ mm}\phi$  at the beam waist ensuring a beam clearance of four beam-waist radii ( $-35$  dB). For the transmission measurements, the complex transmission coefficient was derived by comparing the complex  $S_{21}$  measured with and without JCSA under test. On the other hand for the reflection measurements, the complex transmission coefficient was derived by comparing the complex  $S_{21}$  measured with JCSA with those measured by replacing the JCSA with a flat aluminum mirror whose reflection coefficient is known.

#### C. Measurement Results

In Fig. 6, measured transmission and reflection coefficients for both polarizations are compared with those calculated by the method of moment (MoM) for JCSA made of a material with a finite conductivity of  $4.35 \times 10^7$  S/m. Although small differences of about 7 GHz in resonant frequencies are found, the measured and calculated frequency characteristics of these coefficients are in very good agreement in general. This indicates that the measured JCSA was fabricated with a mechanical accuracy better than 1 %. The transmission

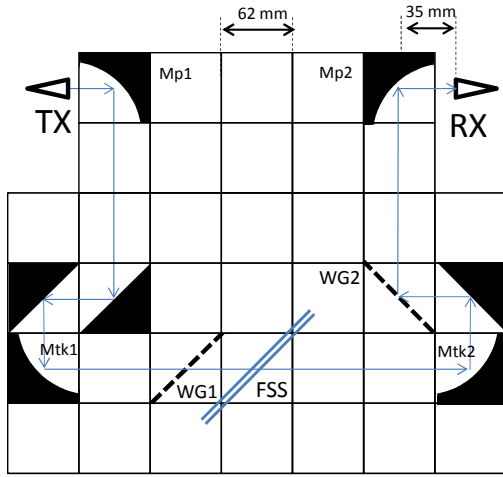


Fig. 4. Measurement configuration for transmission coefficient.

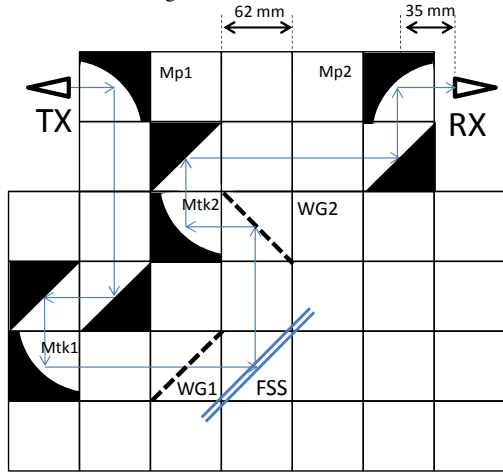


Fig. 5. Measurement configuration for reflection coefficient.

coefficients measured at the resonant frequency are around  $-0.45$  dB for both TE and TM incidence, which agree well with the theoretically predicted value of  $-0.4$  dB for JCSA made of gold.

#### IV. CONCLUSION

A dual-polarization Jerusalem-cross slot array type frequency selective surface was designed for separating the submillimeter-wave band around 650 GHz at  $45^\circ$  angle of incidence. Based on this design, the FSS is fabricated by applying a photolithographic process and gold-plating to SiC substrate. The transmission and reflection characteristics measured for the fabricated JCSA agree well with those simulated by the method-of-moment calculation. Wider transmission bandwidth and faster roll-off characteristics could be achieved by stacking two or more JCSAs with appropriate spacings to form a multi-layer FSS.

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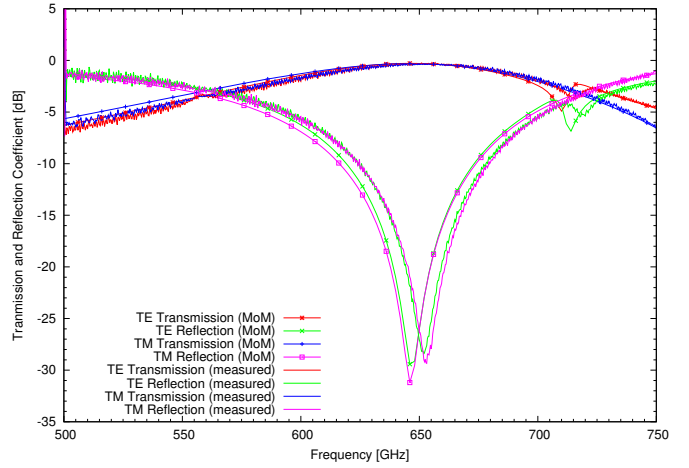


Fig. 6. Transmission and reflection coefficients of JCSA for angle of incidence of  $45^\circ$ . Measured: solid curves with symbols, calculated by MoM: solid curves, TE transmission: red, TE reflection: green, TM transmission: blue, TM reflection: pink.

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