51-33
146831

February 15, 1993

P-7

N93-24660

Feasibility Study of a Ka-/Ka-Band Dichroic Plate With Stepped Rectangular Apertures

J. C. Chen
Ground Antennas and Facilities Engineering Section

For the Cassini spacecraft mission, a dichroic plate is needed to pass Ka-band uplink (34.2 to 34.7 GHz) and to reflect Ka-band downlink (31.8 to 32.3 GHz) for dual-frequency operation in the Deep Space Network. The special characteristic of the Ka-/Ka-band dichroic plate is that the passband and the reflective band are only 1.9 GHz (5.7 percent) apart. A thick dichroic plate with stepped rectangular apertures that function as resonator filters was chosen for the Ka-/Ka-band dichroic plate design. The results of the feasibility study are presented in this article.

I. Introduction

For the existing dichroic plates in the Deep Space Network (DSN), the passband frequency is approximately four times higher than the reflecting-band frequency. For example, the S-/X-band (2.2-GHz/8.45-GHz) dichroic plate reflects 2.2 GHz and passes 8.45 GHz, and the X-/Ka-band (8.45-GHz/32.0-GHz) dichroic plate reflects 8.45 GHz and passes 32.0 GHz. In these cases the sizes of the apertures are large enough to pass the higher frequency band, yet small relative to the wavelength of the reflective frequency, resulting in efficient reflection. However, if the passband and reflective band are close [as they are in the Ka-/Ka-band (31.8- to 32.3-GHz/34.2- to 34.7-GHz) dichroic plate], the apertures on the dichroic plate may be large enough to pass the higher frequency passband, but may not be small enough to cut off the lower frequency adequately. A dichroic plate with straight rectangular apertures may not satisfy this requirement. Therefore, a dichroic plate with stepped rectangular apertures, which act as filters, was chosen for the Ka-/Ka-band dichroic plate feasibility study.

II. Analysis

It is assumed that the dichroic plate is illuminated by linearly polarized plane waves with oblique incidence, in this case 30 deg from normal. The analysis of the dichroic plate with stepped rectangular apertures is based on a modal matching method. The electromagnetic field in the free-space region is represented by Floquet modes and the field in the waveguide region is represented by rectangular waveguide modes. By applying the boundary condition at the junctions and using the modal matching method, the scattering matrix of the dichroic plate is then achieved [1]. Two computer programs, the Thick Frequency Selective Surface With Rectangular Apertures program[1] and the Rectangular Waveguide program,[2] were integrated in order to analyze the dichroic plate with stepped rectangular apertures. The Thick Frequency Selective Surface With Rectangular Aperture program calculates the scattering matrix of the free space and waveguide junction, and the rectangular waveguide program computes the scattering matrix of the stepped waveguide region. These matrices are then combined to form the scattering matrix of the dichroic plate with stepped rectangular apertures. The computer code, the Thick Frequency Selective Surface With Stepped Rectangular Apertures program, was used to design a Ka-/Ka-band dichroic plate. Because multiple design parameters were involved, an optimization program was utilized to speed up the design process.

The number of modes representing the electromagnetic fields on either side of the junction has to be sufficient to ensure the convergence in the modal matching method [2]. There is an equation in the program in which the number of Floquet modes used increases as the number of waveguide modes increases. The speed of the convergence versus the number of waveguide modes may vary depending on the structure of the stepped waveguide. For a straight rectangular aperture, a total of 40 rectangular waveguide modes is sufficient [3], but in this particular design, a total of 180 rectangular waveguide modes was necessary. Figure 1 shows how the transmission coefficient at 34.7 GHz fluctuates as the number of waveguide modes varies. The highest waveguide number indicates that the waveguide numbers M and N are not greater than that number. For example, if the highest waveguide number is equal to one, the TE_{01}, TE_{10}, TE_{11}, and TM_{11} rectangular waveguide modes are used to expand the electromagnetic field in the waveguide region. Figure 1 indicates that the convergence is achieved when the highest waveguide numbers reach nine (180 waveguide modes) or higher.

III. Design and Theoretical Performance

The Ka-/Ka-band dichroic plate design is an array of stepped rectangular apertures on a 5.6388-mm grid with a 60-deg skew angle. Each stepped aperture consists of five steps (Fig. 2). The stepped aperture is a length of rectangular waveguide ($A_1 \times B_1 = 4.6126$ mm $\times$ 4.6228 mm) with two thin irises ($A_2 \times B_2 = 3.81$ mm $\times$ 3.9268 mm, thickness $I = 0.508$ mm) inside. The irises divide the waveguide into three sections with lengths of 9.8044 mm (L_1), 9.144 mm (L_2), and 9.8044 mm. The first and the last sections act as resonators with low quality factor Q, while the center section acts as a resonator with high Q. The size of the main waveguide aperture is smaller than the cutoff size of the highest frequency at the downlink and larger than the cutoff size of the lowest frequency of the uplink. The stepped aperture is basically a resonator filter to pass the uplink and reflect the downlink. The advantage of having only two different waveguide sizes is to reduce the fabrication costs. Since multiple metal sheets can be stacked together to be wire-electrical-discharge machined for an identical pattern, only two sets of sheets need to be run through the machine.

Theoretical performance of the Ka-/Ka-band dichroic plate design was calculated and is shown in Table 1. The transmission of the Ka-band downlink is about −36 to −48 dB over the bandwidth. The downlink is almost totally reflected, but there is a relative phase shift of 7.26 ±0.77 deg over the bandwidth between two orthogonal linear polarizations (TE and TM polarizations). The phase shift between two polarizations can be compensated for by the polarizer, which is connected to the horn in the microwave system. The transmission of the passband (uplink) is better than −0.19 dB over the bandwidth for both TE polarization and TM polarization. The relative phase shift of the passband is 9.45 ±1.00 deg over the Ka-band uplink. The curve of the magnitude of the transmission coefficients for TE and TM polarizations from 31 to 36 GHz shows nice roll-off from reflective band to passband (Fig. 3). The transmission coefficient over the passband is shown in more detail in Fig. 4. The relative phase shift between TE and TM polarizations varies less than ±1.00 deg in both downlink and uplink (Fig. 5). Since the incident wave in the Deep Space Network is circularly polarized (CP), the transmitted CP power is about 0.01 to 0.15 dB with ellipticity of 1.3 to 1.65 dB over the passband, and total reflected power is below −37 dB with ellipticity of 2.09 dB (Figs. 6 and 7).

A tolerance study was also done over the downlink and uplink bandwidths (Table 2). The large aperture dimensions (A_1 and B_1), small aperture dimensions (A_2 and B_2), length of each step (L_1 and L_2), and thickness of the iris-like step were examined in the tolerance study. One dimension was varied by ±0.0127 mm (or ±0.0254 mm) at a time, while the rest of the dimensions were kept at the design size. The last row in Table 2 is the performance at the design dimensions without any variation. For example, the transmission coefficient for TM polarization

[1] The Thick Frequency Selective Surface With Rectangular Aperture program was written by J. C. Chen, Jet Propulsion Laboratory, Pasadena, California, and was submitted to COSMIC, University of Georgia, 382 E. Broad St., Athens, Georgia 30602.

[2] The Rectangular Waveguide Program was written by D. J. Hoppe, Radio Frequency and Microwave Subsystems Section, and F. Manshadi, Ground Antennas and Facilities Engineering Section, Jet Propulsion Laboratory, Pasadena, California.

changes from 0.10 ±0.09 (tenth row, seventh column) to 0.21 ±0.2 dB (fourth row, seventh column) over the bandwidth when B_1 is decreased by 0.0127 mm. The performance of the dichroic plate is more sensitive to changes in the dimensions of the large apertures than the small apertures. Changing the length of the apertures has little effect on the performance of both uplink and downlink. Overall, variation in the dimensions of the dichroic plate with stepped apertures has less impact on the performance of the downlink than the uplink.

IV. Conclusion

The analysis of the performance of a dichroic plate with stepped apertures indicates that it is a feasible choice for the Ka-/Ka-band dichroic plate. The stepped aperture is a new technique in dichroic plate design, therefore the fabrication technique and experiment method require further study. Also, the accuracy of the new program needs to be verified. Fabrication of a test Ka-/Ka-band dichroic plate is the next step in understanding its performance.

Acknowledgment

The author thanks P. Stanton for the suggestion of using stepped apertures in the Ka-/Ka-band dichroic plate design.

References

[1] J. C. Chen, "Analysis of a Thick Dichroic Plate With Rectangular Holes at Arbitrary Angle of Incidence," *The Telecommunications and Data Acquisition Progress Report 42-104, vol. October–December 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 9–16, February 15, 1991.

[2] R. Mittra, T. Itoh, and T. S. Li, "Analytical and Numerical Studies of the Relative Convergence Phenomenon Arising in the Solution of an Integral Equation by the Moment Method," *IEEE Transactions on Microwave Theory and Technique*, vol. MTT-20, no. 2, pp. 96–104, February 1972.

[3] J. C. Chen, "X-/Ka-Band Dichroic Plate Design and Grating Lobe Study," *The Telecommunications and Data Acquisition Progress Report 42-105, vol. January–March 1991*, Jet Propulsion Laboratory, Pasadena, California, pp. 21–30, May 15, 1991.

Table 1. Transmission coefficients for *TE* and *TM* polarizations and relative phase shift between *TE* and *TM* polarizations for a Ka-/Ka-band dichroic plate with stepped rectangular waveguide.

Ka-band	Frequency, GHz	Transmission coefficients, dB		Relative phase shift, deg
		TE	*TM*	
Downlink	31.8	−47.94	−46.24	8.033
	32.0	−44.27	−42.56	7.505
	32.3	−38.28	−36.46	6.496
Uplink	34.2	−0.102	−0.193	10.468
	34.5	−0.013	−0.062	10.495
	34.7	−0.025	−0.168	8.450

Table 2. Tolerance study for Ka-/Ka-band dichroic plate with stepped rectangular apertures.

Dimensions of stepped aperture, mm	Variation,[a] mm	Ka-band downlink (31.8 to 32.3 GHz) reflection[b]			Ka-band uplink (34.2 to 34.7 GHz) transmission[c]		
		TE, dB	*TM*, dB	Δ phase, deg	*TE*, dB	*TM*, dB	Δ phase, deg
A_1, 4.6126	+0.0127	0.00 ±0.00	0.00 ±0.00	4.98 ±1.19	0.03 ±0.02	0.10 ±0.09	1.92 ±0.05
	−0.0127	0.00 ±0.00	0.00 ±0.00	9.43 ±0.39	0.09 ±0.08	0.06 ±0.05	21.12 ±2.05
B_1, 4.6228	+0.0127	0.00 ±0.00	0.00 ±0.00	9.35 ±0.41	0.06 ±0.05	0.08 ±0.08	20.38 ±2.54
	−0.0127	0.00 ±0.00	0.00 ±0.00	5.27 ±1.08	0.06 ±0.04	0.21 ±0.20	0.80 ±0.44
A_2, 3.8100	+0.0127	0.00 ±0.00	0.00 ±0.00	7.23 ±0.78	0.06 ±0.05	0.10 ±0.09	7.99 ±0.06
	−0.0127	0.00 ±0.00	0.00 ±0.00	7.30 ±0.75	0.06 ±0.04	0.10 ±0.09	1.07 ±1.23
B_2, 3.9268	+0.0127	0.00 ±0.00	0.00 ±0.00	7.34 ±0.73	0.06 ±0.03	0.11 ±0.10	11.21 ±1.14
	−0.0127	0.00 ±0.00	0.00 ±0.00	7.22 ±0.79	0.06 ±0.04	0.11 ±0.11	8.19 ±0.81
I, 0.5080	+0.0127	0.00 ±0.00	0.00 ±0.00	7.26 ±0.77	0.06 ±0.04	0.10 ±0.10	9.52 ±1.04
	−0.0127	0.00 ±0.00	0.00 ±0.00	7.27 ±0.77	0.06 ±0.05	0.10 ±0.09	9.40 ±0.98
L_1, 9.8044	+0.0254	0.00 ±0.00	0.00 ±0.00	7.26 ±0.77	0.05 ±0.04	0.09 ±0.08	9.55 ±1.06
	−0.0254	0.00 ±0.00	0.00 ±0.00	7.27 ±0.77	0.06 ±0.05	0.11 ±0.10	9.42 ±0.98
L_2, 9.1440	+0.0254	0.00 ±0.00	0.00 ±0.00	7.27 ±0.77	0.06 ±0.05	0.10 ±0.09	9.39 ±1.01
	−0.0254	0.00 ±0.00	0.00 ±0.00	7.26 ±0.77	0.05 ±0.04	0.10 ±0.09	9.52 ±1.00
	0.000[d]	0.00 ±0.00	0.00 ±0.00	7.26 ±0.77	0.06 ±0.04	0.10 ±0.09	9.45 ±1.00

[a] One dimension of the aperture is varied by ±0.0127 mm (or 0.0254 mm), while the other dimensions of the aperture remain the same size.

[b] The third and fourth columns indicate the magnitude of the reflection coefficients over the downlink bandwidth for *TE* and *TM* polarizations, respectively, and the fifth column indicates the relative phase shift between these two polarizations over the downlink bandwidth.

[c] The sixth and seventh columns indicate the magnitude of the transmission coefficients over the uplink bandwidth for *TE* and *TM* polarizations respectively, and the eighth column indicates the relative phase shift between these two polarizations over the uplink bandwidth.

[d] This row indicates the performances of the Ka-/Ka-band dichroic plate at the designed dimensions with no variations.

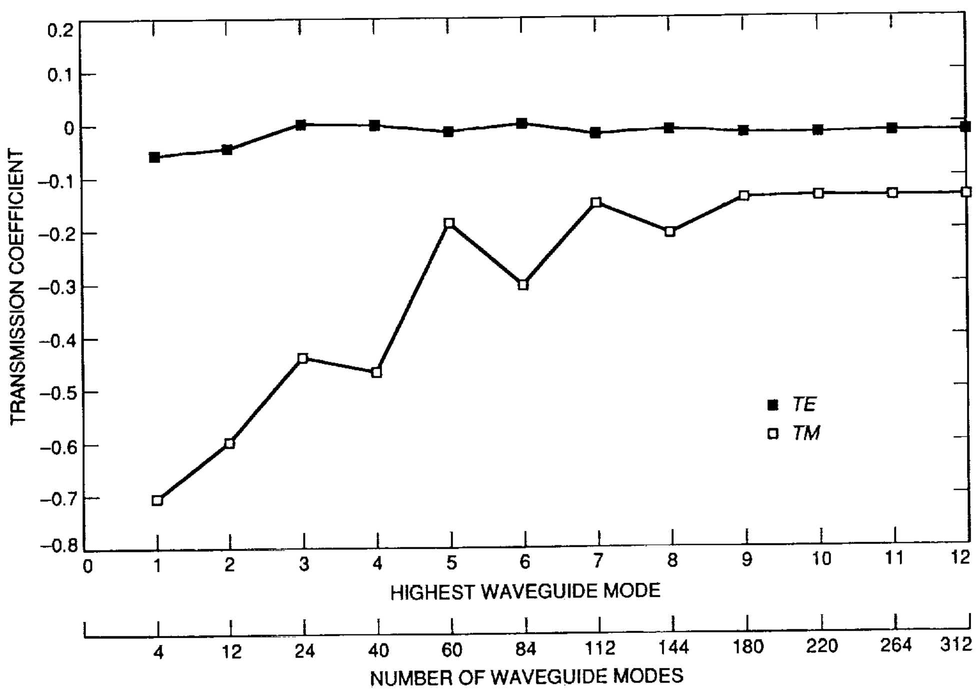

Fig. 1. Convergence of the calculated transmission coefficient versus the number of waveguide modes used at 34.7 GHz.

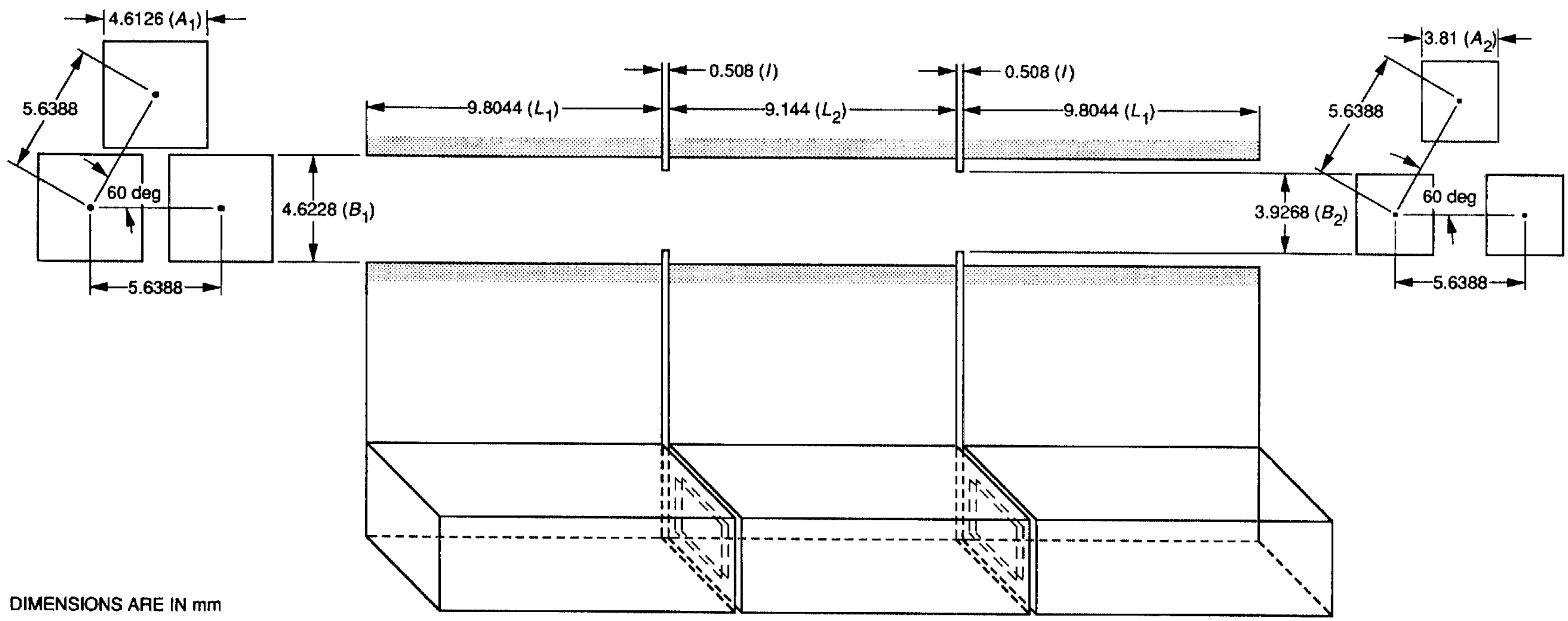

Fig. 2. Geometry of Ka-/Ka-band dichroic plate.

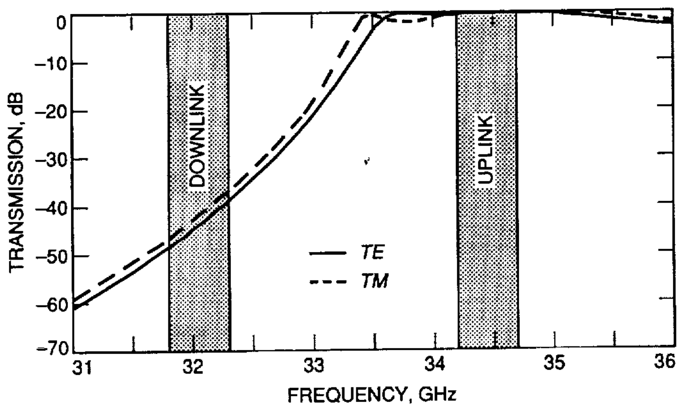

Fig. 3. Transmission coefficient versus frequency for Ka-/Ka-band dichroic plate with stepped rectangular apertures for *TE* and *TM* polarizations.

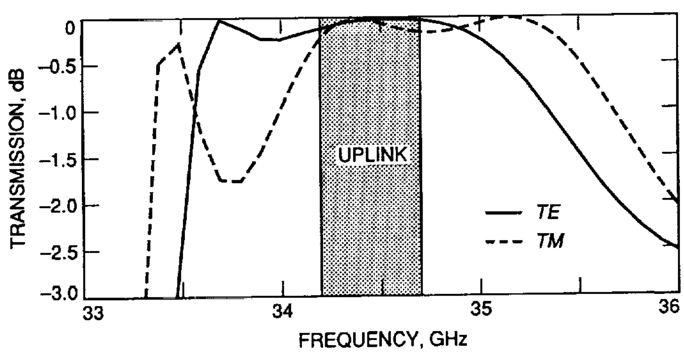

Fig. 4. Transmission coefficient versus frequency for Ka-/Ka-band dichroic plate with stepped rectangular apertures for *TE* and *TM* polarizations at Ka-band uplink.

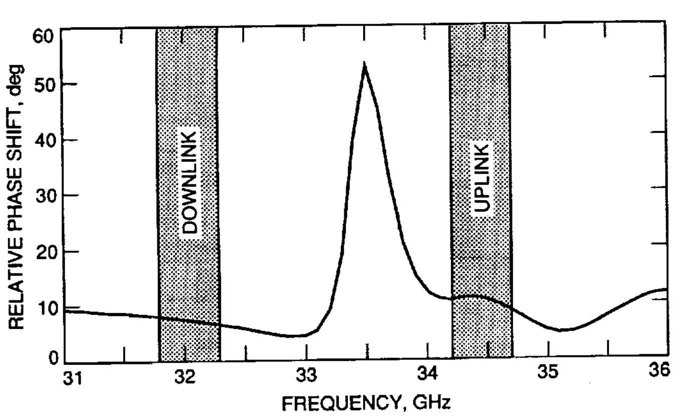

Fig. 5. Relative phase shift versus frequency for Ka-/Ka-band dichroic plate with stepped rectangular apertures.

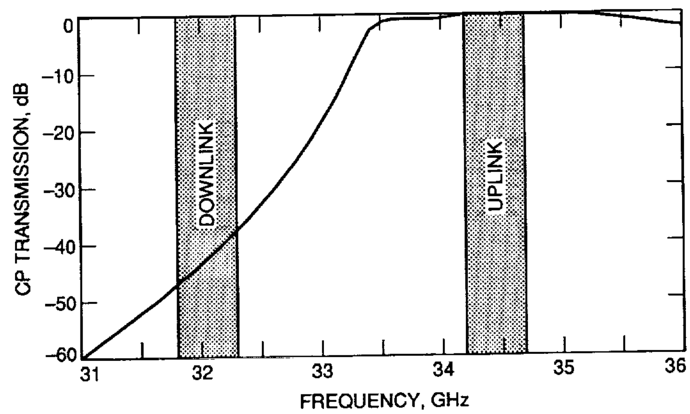

Fig. 6. Transmission power versus frequency for Ka-/Ka-band dichroic plate with stepped rectangular apertures for circularly polarized wave incidence.

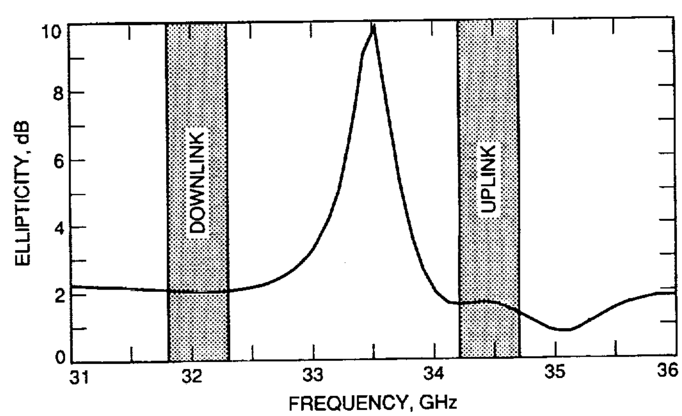

Fig. 7. Ellipticity versus frequency for Ka-/Ka-band dichroic plate with stepped rectangular apertures for circularly polarized wave.