TDA Progress Report 42-129 May 15, 1997

A New All-Metal Low-Pass Dichroic Plate

W. A. Imbriale
Communications Ground Systems Section

A new type of dichroic plate is described that can be completely transparent at lower frequencies and can reflect the higher frequencies without the use of a dielectric substrate. The basic concept of the new design is to use slots in a moderately thick metallic plate for the transmit band and to use chokes in the slot to reflect the upper frequency bands. Thus, the dichroic plate is transparent at the lower frequency band and reflective at the upper frequency bands without using a dielectric. An experimental plate designed to be transparent at 8.4 to 8.45 GHz (X-band) and reflective at 31 to 35 GHz (Ka-band) using a single-depth choke was fabricated and tested. For X-band, the calculated and measured resonance frequency for the transverse magnetic (TM) mode and the transverse electric (TE) mode differed by less than 0.3 percent. The transmission coefficient at Ka-band (measure of reflectivity) was better than −30 dB for TE and −40 dB for TM.

I. Introduction

The objective of this research was to develop an all-metal dichroic plate that is reflective at the higher frequency bands and transparent at the lower bands. Conventional dichroics accomplish this frequency response by supporting a metallic resonant element on a dielectric substrate. The concerns with the conventional methods are the power handling capacity of the thin metallic layer as well as the loss in the dielectric.

The basic concept of the new design is to use slots in a moderately thick metallic plate for the transmit band and to use chokes in the slot to reflect the upper frequency bands. Thus, the dichroic plate is transparent at the lower frequency band and reflective at the upper frequency bands without using a dielectric. An additional advantage is the very wide bandwidth for the reflective bands.

A test plate consisting of a moderately thick plate with a periodic pattern of thin linear resonant slots was fabricated. A typical dichroic plate geometry is shown in Fig. 1. It consists of a moderately thick metallic plate with a periodic pattern of resonant slots. The slots are chosen to be resonant at the lower frequency band so that the plate is transparent at these frequencies. Orthogonal slots used for circular polarization are shown. If only linear polarization were required, the orthogonal slots would not be necessary. Since the plate surface is mostly metal, it would be predominantly reflective at the higher frequency bands, with the reflectivity loss related to the ratio of the area of the slots to the total area. Hence, it would be a fairly good reflector at all the higher frequencies irrespective of the plate thickness. To enhance the reflectivity at a selected set of higher frequencies, the thickness of the plate is used to insert a high-frequency choke. Shown in Fig. 1 is a single-depth choke. More complex choke geometries could be used to achieve the desired frequency response.

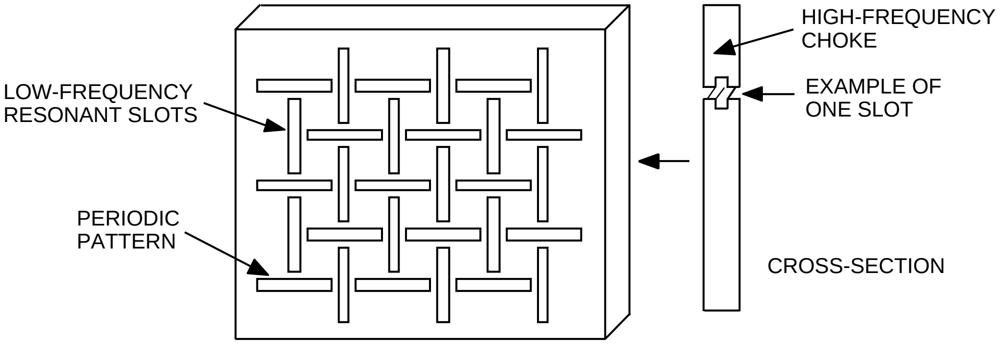

Fig. 1. A typical dichroic plate geometry.

II. Design Objectives

The NASA Deep Space Network (DSN) has a need for various dichroic plates having insertion losses as low as 0.04 dB at a narrow passband and the ability to handle up to 500 kW of power [1]. In addition, the plate must meet the low insertion loss requirements at a 30-deg incident angle simultaneously for both parallel and perpendicular polarizations. Because a thin dichroic plate may not be mechanically suitable for the high power requirements, thick-plate dichroic designs are preferred. Also, the conventional method of obtaining the required frequency response by supporting a thin metallic element on a dielectric substrate may not handle the high power requirements and has a higher loss in the passband. The frequencies of interest are as follows:

Band	Range
X-band downlink	8400–8450 MHz
X-band uplink	7145–7190 MHz
Ka-band downlink	31.7–32.2 GHz
Ka-band uplink	34.0–34.5 GHz

Two different designs were under consideration for DSN applications: (1) reflect Ka-band up and down and pass X-band down or (2) reflect Ka-band up and down, X-band up, and pass X-band down. The characteristics of each design are discussed in the following.

A. Reflect Ka-Band Up and Down and Pass X-Band Down

This design (a typical response is shown in Fig. 2) results in a relatively thin plate (5.33 mm) when using a single choke and provides good bandwidth for both X-band and Ka-band. The basic design parameters are shown in Fig. 3. The plate is designed to operate at a 30-deg incident angle. The calculated X-band performance is shown in Fig. 4. The performance meets the requirement of a 0.04-dB loss over the X-band downlink frequencies for both the parallel and the perpendicular polarizations. Ka-band performance is shown in Fig. 5. As seen in the figure, the transmission coefficient is better than -32 dB over the entire Ka-band (both transmit and receive).

B. Reflect Ka-band Up and Down, X-Band Up, and Pass X-Band Down

This design provides for diplexing X-band frequencies while using the dichroic plate. A good separation is possible between the X-band transmit and receive frequencies, but because a thick dichroic plate is required, the receive X-band frequency band is very narrow. Since the plate is thick, it offers significant

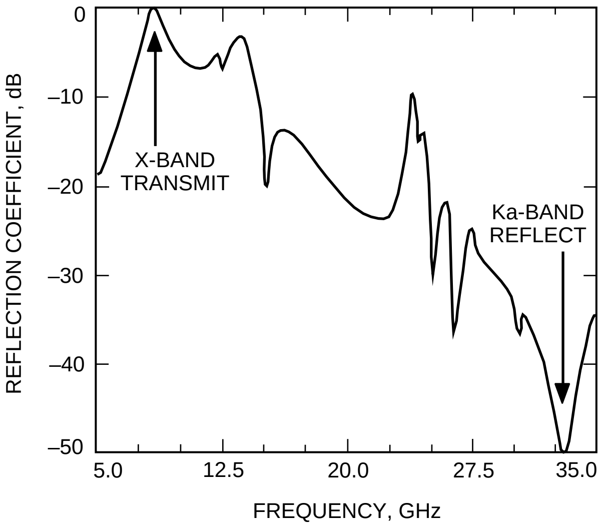

Fig. 2. Typical performance of the reflect Ka-band up and down and pass X-band down design.

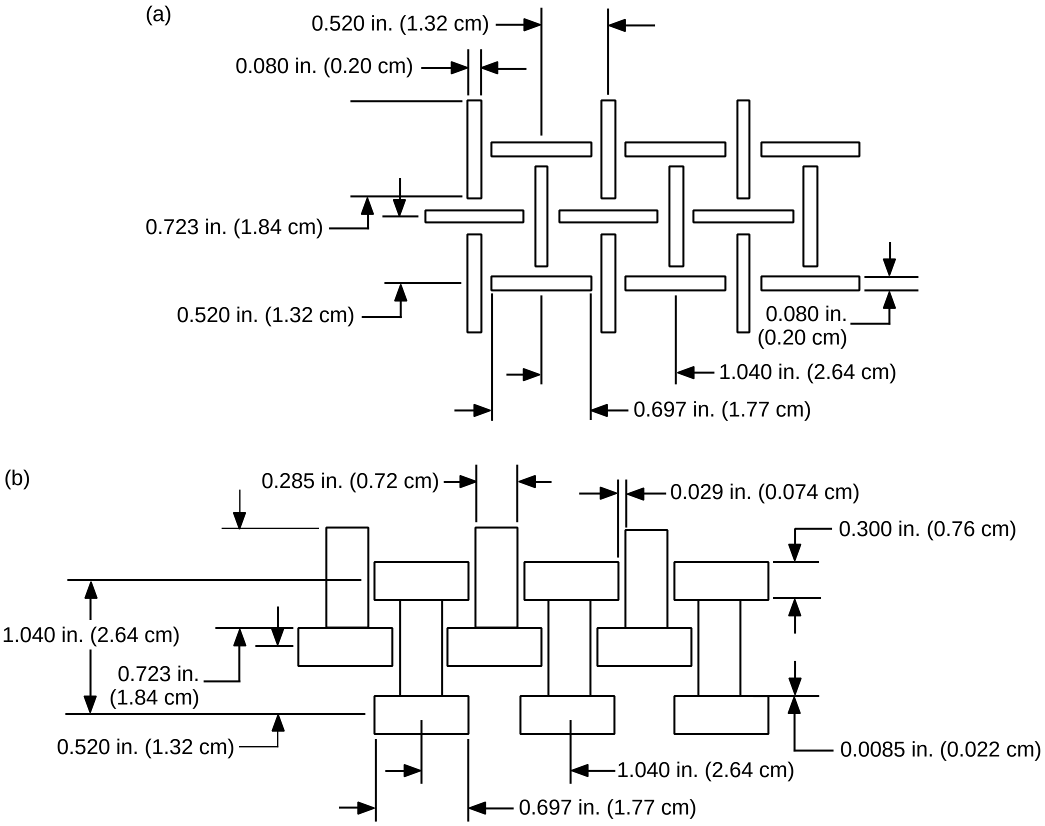

Fig. 3. Design parameters for reflecting DSN Ka-band and passing DSN X-band receive (plate 1): (a) 0.06-in.-thick (0.15-cm) top and bottom layers and (b) 0.09-in.-thick (0.23-cm) center layer.

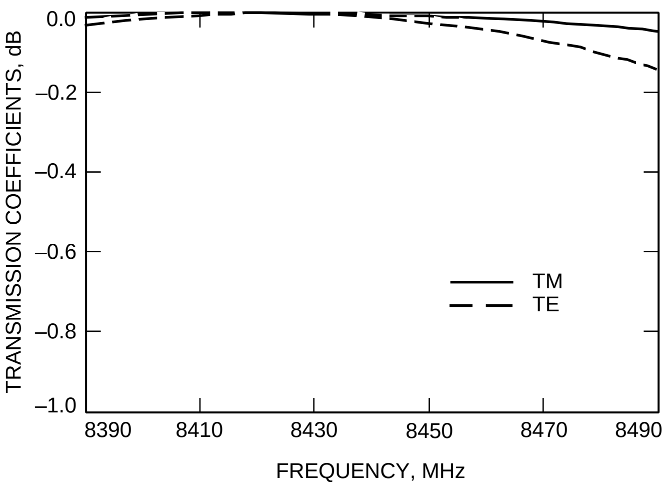

Fig. 4. X-band performance for plate 1: TE and TM transmission coefficients.

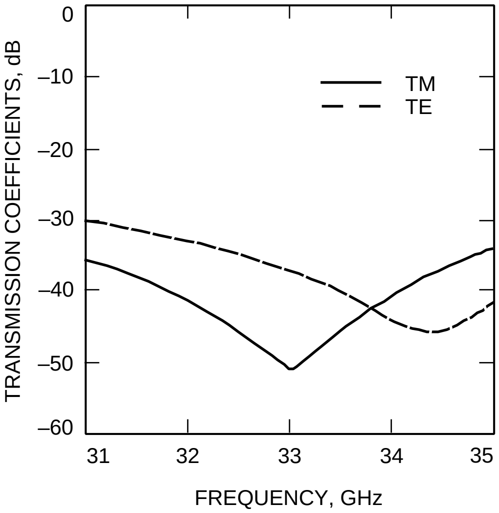

Fig. 5. Ka-band performance for plate 1.

possibilities for designing the Ka-band chokes. However, the single choke design for plate 1 appears to be quite adequate. The basic design parameters are shown in Fig. 6 and the calculated X-band performance in Fig. 7. There is greater than a 35-dB isolation between the transmit and receive frequencies. The performance for Ka-band (although not shown) is similar to plate 1 in that it is better than a −32-dB transmission coefficient over the entire frequency band.

C. Prototype Plate

Manufacture of a thick plate is accomplished by stacking multiple layers of plates with the appropriate slot geometries. For use as a curved surface, the plate could be manufactured as a thin membrane of slots that is shaped to the desired curve. The chokes are then small metallic attachments, only slightly larger than needed for the choke. For the example shown in Fig. 1, three layers would be required.

A typical performance curve is shown in Fig. 2. The plate was designed to be transparent at X-band and reflective at Ka-band using a single-depth choke. This type of design would be an excellent choice for the DSN. An experimental plate was fabricated and tested.

The agreement between the analytical and measured results was excellent. The measured X-band TE- and TM-mode resonances were within 0.3 percent of the calculated results. For the choked plots, the TE transmission coefficient was better than −30 dB, and the TM transmission coefficient was better than −40 dB for the 33- to 35-GHz Ka-band. For comparison, a nonchoked plate of the same thickness was fabricated and demonstrated only a −16-dB transmission coefficient.

III. Analysis

The analysis of a thick dichroic plate with stepped-rectangular apertures is based upon a model-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 model-matching method, one obtains the scattering matrix of the dichroic plate. The basic equations are given in [2–6], and the technique will only be summarized here.

The analysis of a thick dichroic plate consisting of rectangular holes with stepped apertures consists of two parts. The thick frequency-selective surface with rectangular-aperture analysis portion determines

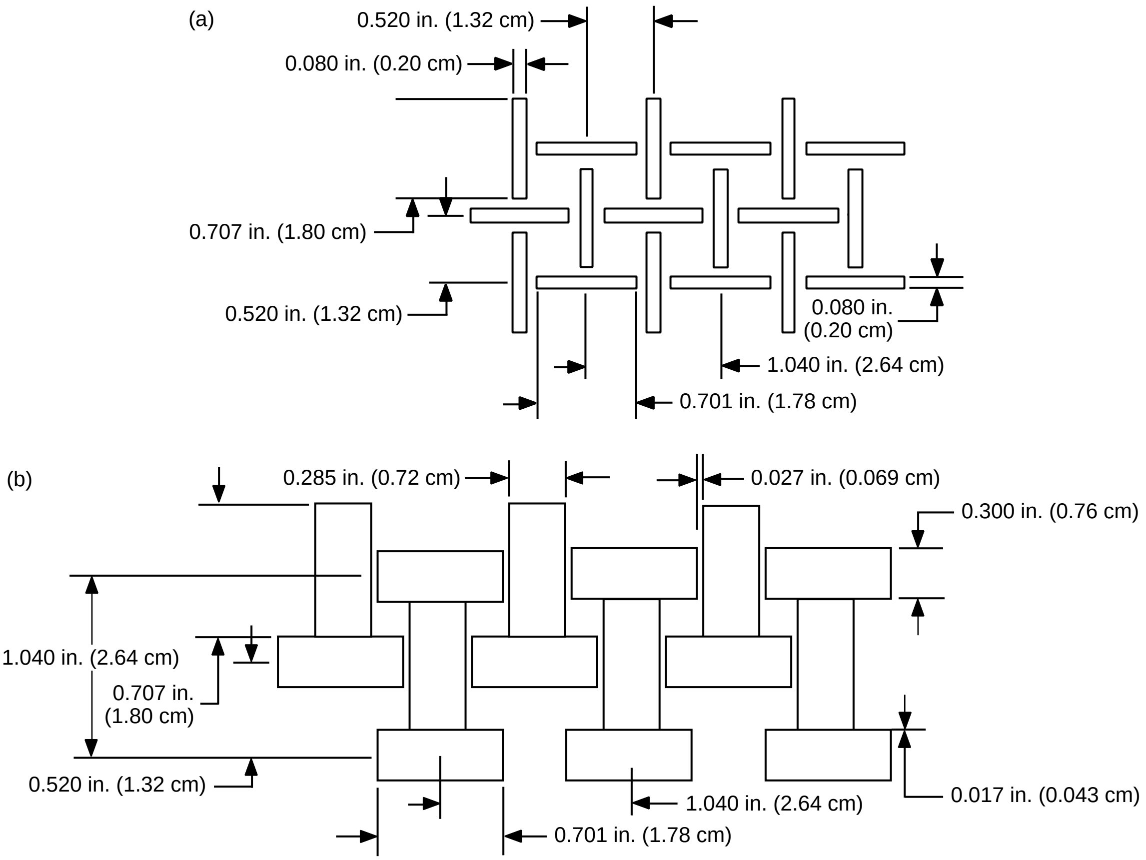

Fig. 6. Design parameters for diplexing X-band transmit and receive while passing Ka-band (plate 2): (a) a 0.06-in.-thick (0.15-cm) top layer and 1-in.-thick (2.54-cm) bottom layer and (b) a 0.09-in.-thick (0.23-cm) center layer.

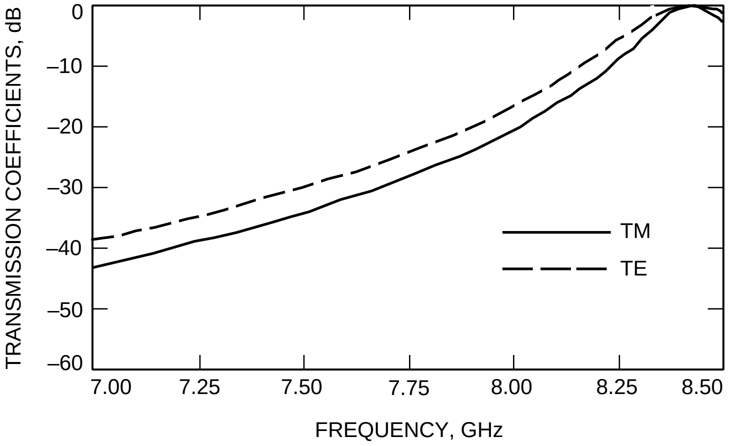

Fig. 7. X-band performance for plate 2.

the scattering matrix of the free-space and waveguide junction, and the rectangular waveguide analysis portion determines 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.

A. Thick Dichroic Plate With Rectangular Holes

The analysis of a thick dichroic plate with rectangular holes is carried out in a series of steps. First, a model of a half-space infinite array is constructed. A complete set of basis functions with unknown coefficients is developed for the waveguide region (waveguide modes) and for the free-space region (Floquet modes) in order to represent the electromagnetic fields [2]. Next, the boundary conditions are applied at the interface between these two regions. The relationship between the rectangular holes, the array lattice of an infinite dichroic plate, and the incident wave is shown in Fig. 8. The method of moments is used to compute the unknown mode coefficients [3,4]. The scattering matrix of the half-space infinite array then is calculated. The reference plane of the scattering matrix is moved half-a-plate thickness in the negative z-direction. Finally, a dichroic plate of finite thickness is synthesized by positioning two plates of half thickness back to back. The total matrix is obtained by cascading the scattering matrices of the two half-space infinite arrays.

B. Rectangular Waveguide

The rectangular waveguide analysis is similar to the cascading technique described in [7] except that rectangular apertures are used instead of circular apertures. The code described in [6] was used for the design and analysis of the three-layer dichroic plate.

IV. Fabrication

A three-layer X-/Ka-band dichroic plate was fabricated to validate the transmission and reflection characteristics of a thick plate consisting of rectangular slots with a single choke. The plate was similar, but not identical, to the plate described for reflecting Ka-band and transmitting X-band. The actual design parameters of the three-layer plate are shown in Fig. 9.

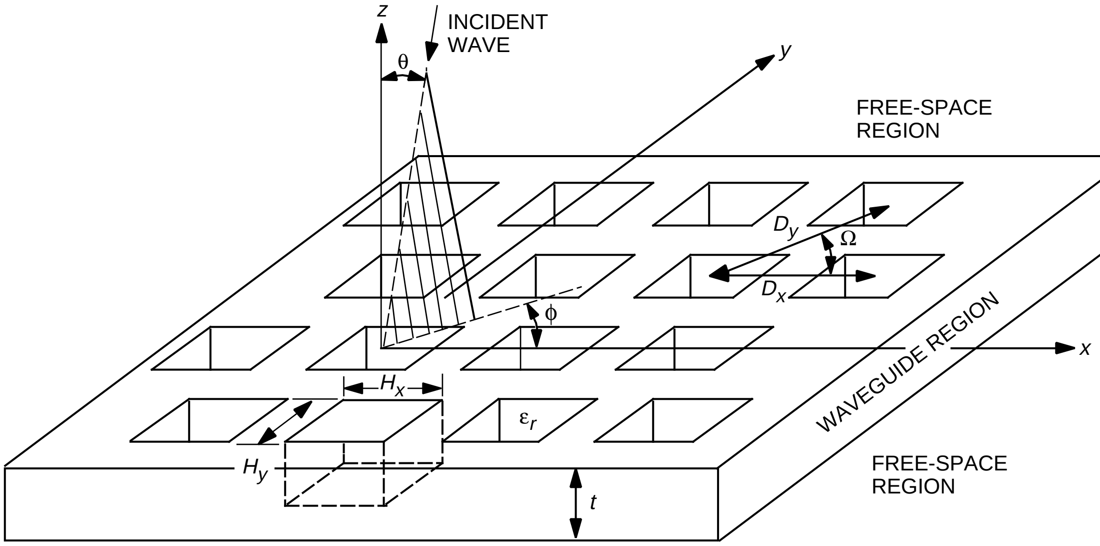

Fig. 8. The geometry of a thick dichroic plate with rectangular holes.

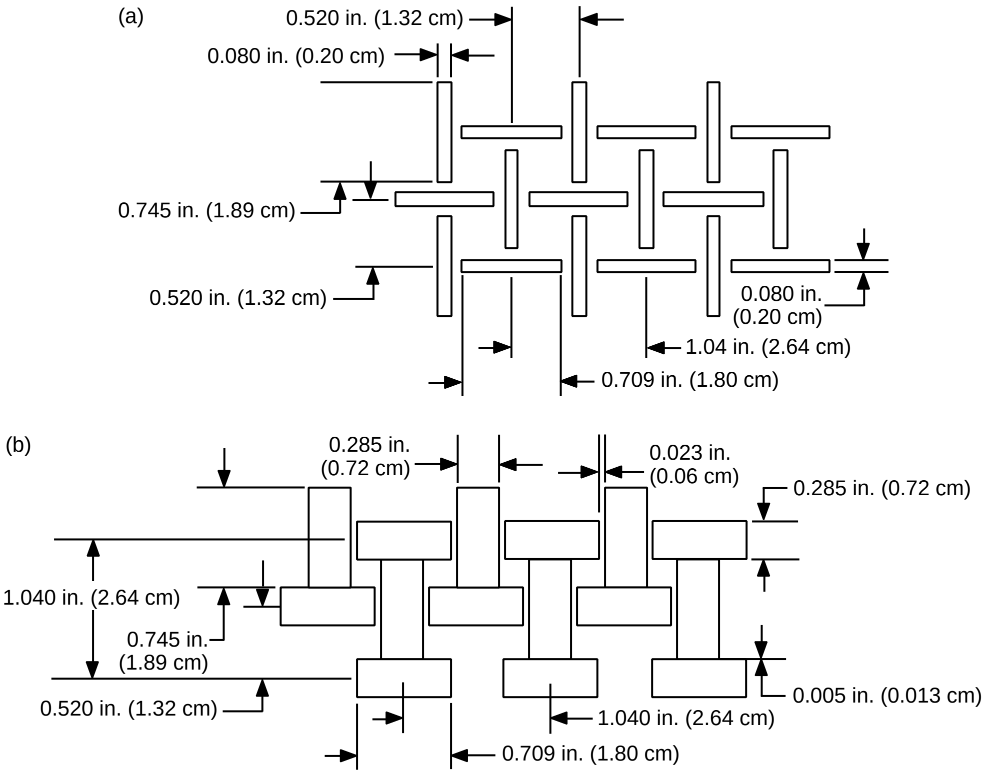

Fig. 9. The parameters of the prototype dichroic plate.

The prototype X-/Ka-band dichroic plate was a 375 mm-by-375 mm three-layer copper plate with a 350 mm-by-350 mm perforated area. The three layers are shown in Fig. 10. The advantage of having only two different aperture sizes is a reduction of the fabrication cost. Since multiple metal sheets can be stacked together to be wire electrical-discharge machined when the sheets have an identical pattern, only two sets of sheets need to be run through the machine. Previous dichroic plate fabrication dictated that, due to the tight tolerance and the cost, the wire electrical-discharge machine was the best way to fabricate rectangular apertures. The three-layer plate required a way to combine the layers into a solid structure. Holes in all four corners of the three plates were used to align the rectangular apertures and the three plates. Three-mil-thick silver foil was put on both sides of the inner plate. The plates were then aligned with the four aligning pins originally used to locate the rectangular apertures. The fusing was accomplished in a reduced atmosphere of a hydrogen oven. Regular copper is not adequate for this technique since the oxygen-free copper goes to the surface during the brazing process. Previous test results dictated that only oxygen-free copper (less than 0.001 percent) was acceptable.

A second dichroic plate was fabricated that had only one layer (no chokes) and the thickness of the three-layer plate. This provided a method to measure the contribution of the chokes to the Ka-band reflection coefficients.

V. Measurements

The reflection and transmission coefficients of the dichroic plate were measured on a Hewlett Packard 8510 network analyzer (Fig. 11). Two orthogonal linear polarizations, TE and TM, were measured. (When the electrical field of the wave is perpendicular to the plane of incidence, it is called TE polarized; if the magnetic field of the wave is perpendicular to the plane of incidence, it is called TM polarized.)

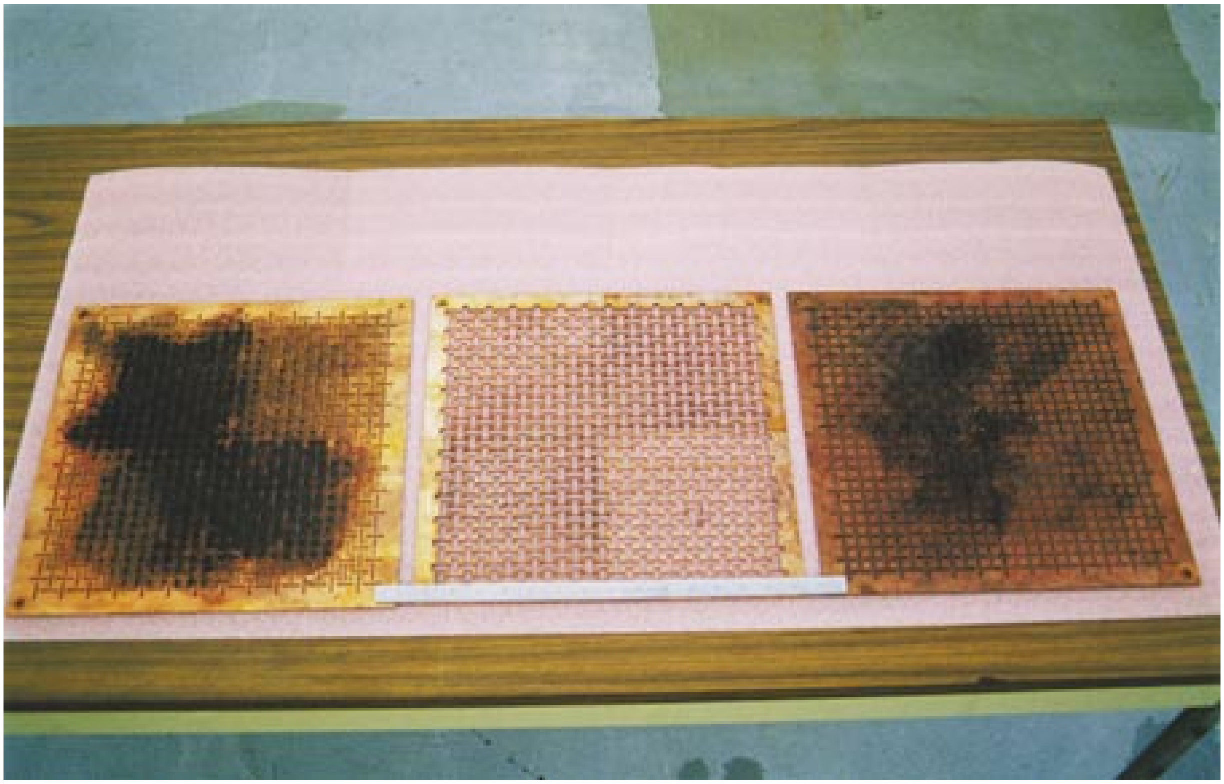

Fig. 10. The three layers of the dichroic plate.

For X-band, a 22-dBi corrugated horn was located approximately 40 cm away from the dichroic plate along a 30-deg angle of incidence. A second horn was placed 150 cm from the dichroic plate along the direction of the reflected beam. The reflection response curve shows the resonant frequencies for TE and TM linear polarizations, respectively (Figs. 12 and 13). Both the measured and calculated values are shown. The calculated resonant frequencies (passband) differ by less than 0.3 percent. The single-layer plate also was measured, and the results were virtually identical to those for the three-layer plate, indicating that the Ka-band chokes have very little effect on the X-band performance.

A transmission measurement for TE and TM polarizations at Ka-band was made to check the performance of the reflecting band. The 22-dBi horn was located approximately 400 cm away from the dichroic plate, which was tilted 30 deg from normal. For reference, the transmission coefficients first were measured without the dichroic plate. Then the transmission coefficients were measured again with the dichroic plate between the two horns. Both the one-layer (no chokes) and the three-layer plates were measured. Comparisons between the calculated and measured results are shown in Fig. 14 for TE and Fig. 15 for TM polarization and demonstrate the significant improvement with the new three-layer dichroic plate. Observe that for TM polarization both the calculated and measured results are below −33 dB over the entire 31- to 35-GHz band. For TE polarization, the transmission coefficient is below −27 dB over the entire band. For comparison, for the one-layer plate, the typical performance is only −16 dB over the band.

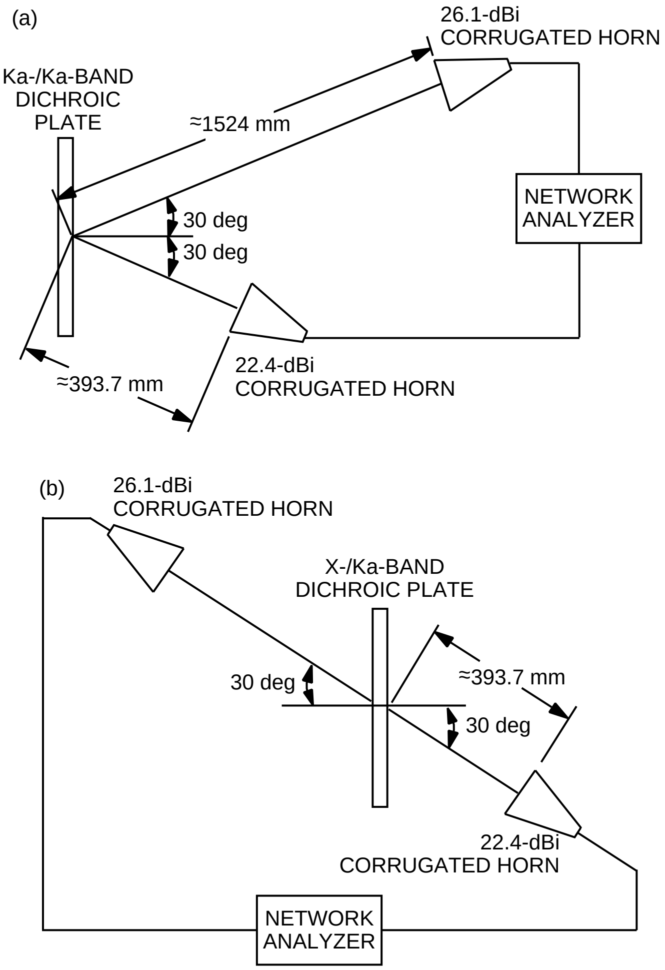

Fig. 11. Typical experimental setups for (a) reflection measurements and (b) transmission measurements.

VI. Conclusions

A prototype all-metal, three-layer X-/Ka-band dichroic plate was successfully designed, fabricated, and tested. The plate is reflective at the higher frequency and transparent at the lower frequency without the need for a dielectric substrate. The theoretical and experimental results show good agreement in predicting the performance of the dichroic plate. Two designs useful for DSN frequency bands were presented.

Acknowledgments

The author would like to thank H. Reilly for overseeing the fabrication, P. Stanton and H. Reilly for performing the measurements, and J. C. Chen for supplying the computer program used for the analysis.

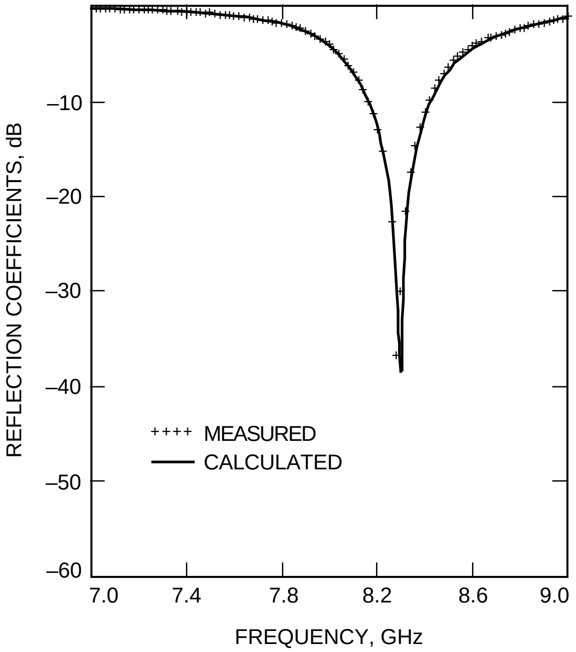

Fig. 12. Measured and calculated TE reflection coefficients for X-band.

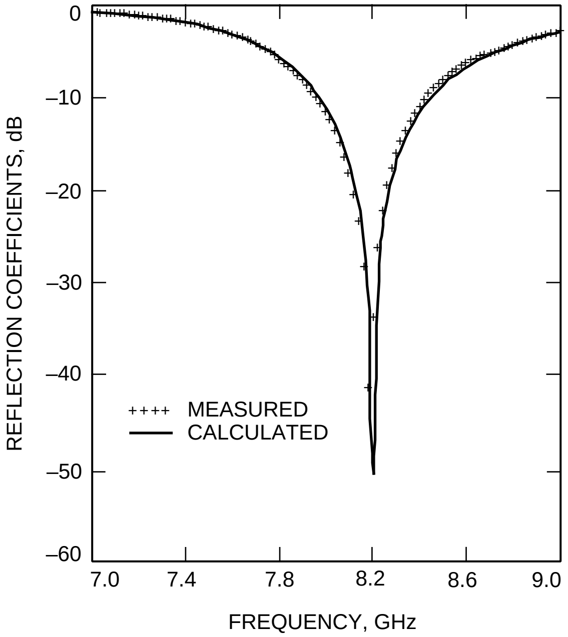

Fig. 13. Measured and calculated TM reflection coefficients for X-band.

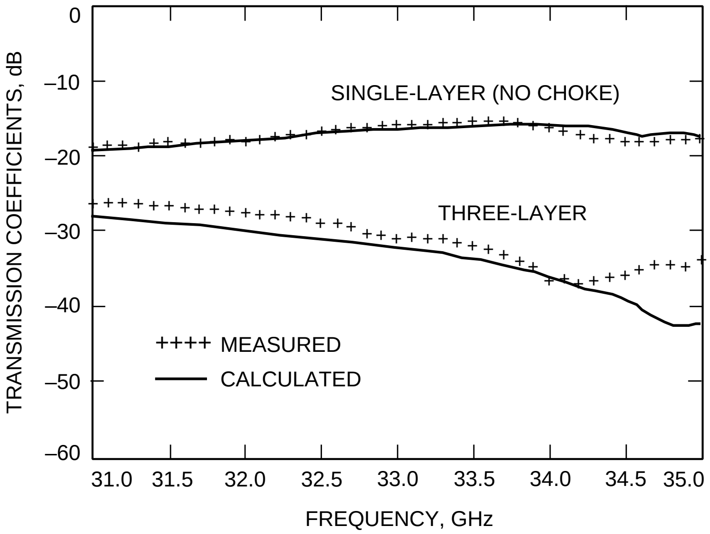

Fig. 14. Measured and calculated TE transmission coefficients for Ka-band.

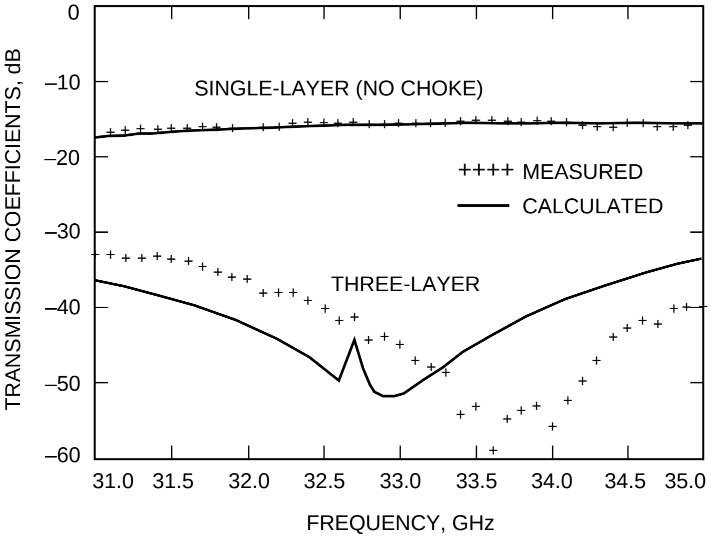

Fig. 15. Measured and calculated TM transmission coefficients for Ka-band.

References

[1] T. Y. Otoshi and M. M. Franco, "Dual Passband Dichroic Plate for X-band," *The Telecommunications and Data Acquisition Progress Report 42-94, April–June 1988*, Jet Propulsion Laboratory, Pasadena, California, pp. 110–134, August 15, 1988.

[2] N. Amitay, V. Galindo, and C. P. Wu, *Theory and Analysis of Phased Array Antennas*, New York: Wiley-Interscience, 1972.

[3] C. C. Chen, "Transmission Through a Conducting Screen Perforated Periodically With Apertures," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, no. 9, pp. 627–633, September 1970.

[4] C. C. Chen, "Transmission of Microwaves Through Perforated Flat Plates of Finite Thickness," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, no. 1, pp. 1–6, January 1973.

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

[6] J. C. Chen, "Feasibility Study of a Ka-/Ka-Band Dichroic Plate With Stepped Rectangular Apertures," *The Telecommunications and Data Acquisition Progress Report 42-112, October–December 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–7, February 15, 1993.

[7] G. L. James, "Analysis and Design of TE11 to HE11 Corrugated Cylindrical Waveguide Mode Converters Using Ring-Loaded Slots," *Trans. IEEE*, vol. MTT-29, pp. 1059–1066, 1981.