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Injection of a 100-kW Uplink Signal into the Existing 34-Meter Beam-Waveguide System

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Results from a preliminary study of frequency-selective surface (FSS) options for injecting a 100-kW uplink signal into the existing 34-m beam-waveguide systems are described. The FSS approach is viewed as a backup to the preferred approach, which modifies the existing three-frequency (7.2-/8.4-/32-GHz) feed, increasing its 7.2-GHz uplink capability from 20 kW to 100 kW. Several options are considered, including a triplexing FSS system using separate high-pass 34-GHz and 8.45-GHz FSSs and an X-band (7.2-/8.45-GHz) only option consisting of a single FSS. Conclusions are drawn and suggestions for future work prior to implementation are presented.

I. Introduction

Currently the highest effective isotropic radiated power (EIRP) uplink command capability in the Deep Space Network (DSN) is the 20-kW uplink system on the 70-m antennas. No backup for this capability exists. In order to achieve equivalent EIRP on the 34-m beam-waveguide (BWG) antennas, an uplink capability of at least 80 kW is required. A technology effort is currently underway for modification of the existing X-/X-/Ka-band feed horn employed in the 34-m BWG antennas of the DSN [1], which will increase its power-handling capability from 20 kW to 80 kW continuous wave. In the event that an 80-kW X-/X-/Ka-band feed is not realized, an alternative system for injection of the high-power uplink on the 34-m antennas based on frequency-selective surfaces (FSSs) was also studied.

In this article, we discuss two FSS-based systems for the injection of the high-power uplink. The first allows only for simultaneous reception of the 8.45-GHz downlink band with the existing X-/X-/Ka-band feed, while transmitting in the 7.2-GHz band. This system provides no support for a simultaneous 32-GHz downlink. Several systems were studied for including simultaneous 8.45- and 32-GHz downlink support, again through the existing feed, along with the high-power uplink. For all systems, FSS designs were produced and the effect on system noise temperatures was estimated. None of the systems studied supports simultaneous 34.5-GHz uplink along with the high-power 7.2-GHz uplink.

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II. Summary of Possible 100-kW Uplink Systems Based on the Existing X-/X-/Ka-Band (7.2-/8.45-/32.0-GHz) Feed

Figure 1 depicts a simplified schematic of the existing feed system on the DSN 34-m BWG antennas. The X-/X-/Ka-band feed provides for simultaneous reception at both 8.45 and 32 GHz while transmitting up to 20 kW continuous wave (CW) at 7.2 GHz. All diplexing of these signals takes place within the feed itself. Simultaneous uplink at 34.5 GHz is also supported through the use of a five-layer FSS, as depicted in the figure [2]. As mentioned earlier, a parallel technology effort is underway with a goal of increasing the high-power capability of this feed to 80 to 100 kW CW. This is the simplest approach for increasing the 7.2-GHz uplink power capability of the 34-m antennas.

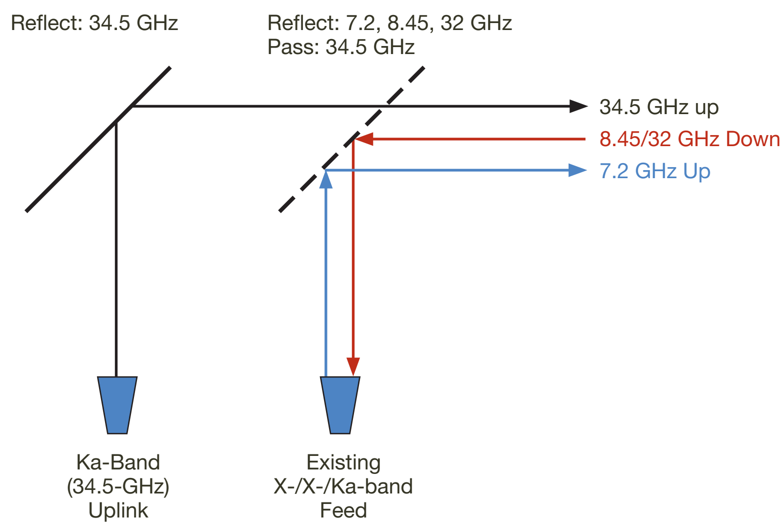

Figure 1. Schematic of existing 34-m BWG system based on the X-/X-/Ka-band feed.

In the event that the technology effort on the feed is unsuccessful, an alternative approach for injection of the 80-kW 7.2-GHz uplink into the antenna is required. Here we study the FSS-based system depicted in Figure 2. In this case, the 80- to 100-kW CW 7.2-GHz uplink signal is injected into the existing BWG system using either a single FSS or group of surfaces. Depending on the design of the FSS system, either simultaneous 8.45- and 32-GHz downlinks are supported, or an 8.45-GHz only downlink is supported. None of the systems studied here will support a simultaneous 34-GHz uplink. Since the additional FSSs will increase the system temperature in both the 8.45- and 32-GHz bands, it is envisioned that the proposed FSS system be retractable. This will allow for operation of the antenna with up to a 20-kW 7.2-GHz uplink with no performance penalty. For an 80-kW uplink, the FSS system is deployed in the BWG path, the 7.2-GHz uplink is injected through the FSS system, and reception at 32 and 8.45 GHz takes place through the existing X-/X-/Ka-band feed with some performance penalty. The remainder of this articles describes several FSS systems and provide estimates of the noise temperature contributions of each.

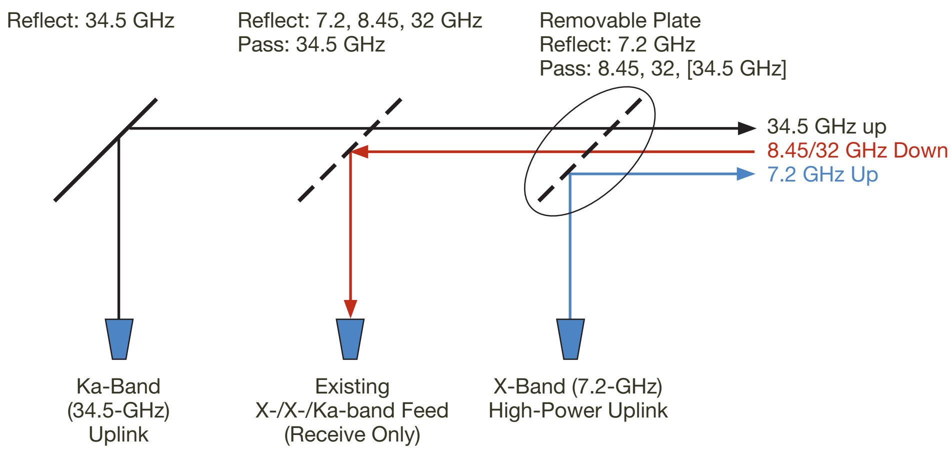

Figure 2. Existing 34-m BWG system modified to include FSS-based injection of a high-power (100-kW) X-band uplink.

III. X-Band (7.2-/8.45-GHz) Only System

The simplest FSS injection system would allow for simultaneous 8.45-GHz and 7.2-GHz downlink, with no 32-GHz capability. In this case, the required FSS is a single low-pass plate that has already been studied in the past [3]. For this effort, we optimized the existing design and computed the expected noise temperature contribution for illumination by a 29-dB gain corrugated feed. The optimization of the half-wave thick plate with rectangular apertures was completed using a commercial finite-element tool that allows for periodic boundary conditions [4]. The results of the optimization are depicted in Figures 3 and 4.

Figure 3 illustrates the near-perfect match of the FSS for both polarizations at the design frequency of 8.45 GHz. It also illustrates high-pass nature of the FSS, and the near total reflection of the transmit band at 7.2 GHz. Figure 4 illustrates the transmission coefficient for both polarizations. Transmission maximizes near the design frequency of 8.45 GHz. This figure also illustrates the imperfect reflection of the FSS at 7.2 GHz. A leak level of approximately –20 dB (1 percent) exists in the 7.2-GHz band. This leak is caused by evanescent coupling through the rectangular apertures, which are cut off in this frequency band. For an uplink power of 100 kW, the corresponding leaked power is 1 kW. This level is considered unacceptable, and the next section discusses a modified design for lower levels of leakage. Next we estimate the noise temperature of this FSS when it is illuminated by a 29-dB gain horn.

In general, the FSS is designed for plane-wave incidence at an angle corresponding to the central ray exciting the feed. The angle between this ray and the normal to the FSS is a design parameter, and is chosen to be 30 deg in this case. In any real application, the feed illuminating the FSS has finite gain, and hence a finite beamwidth. This implies that the FSS is actually illuminated by a ray bundle with the central ray having the maximum

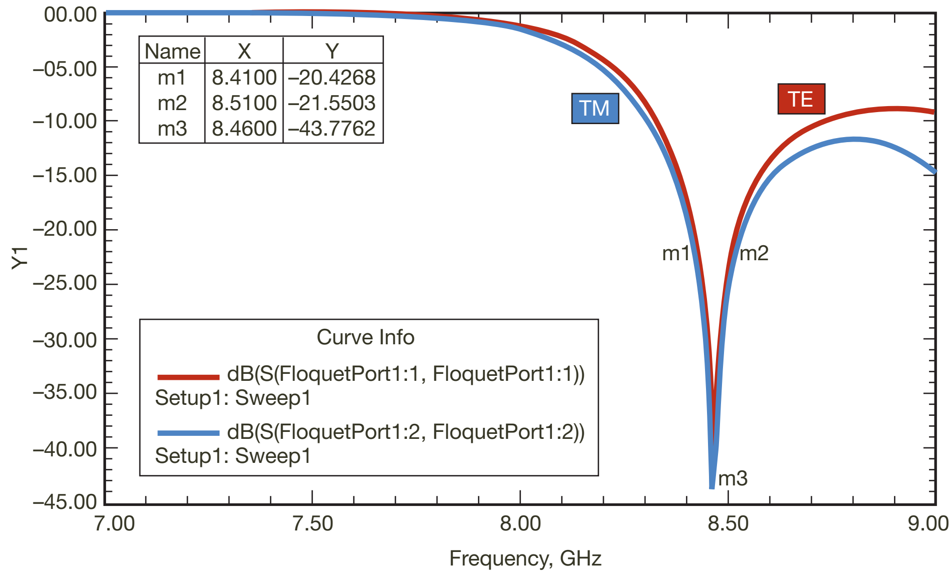

Figure 3. Reflection coefficient: original X-/X-band FSS.

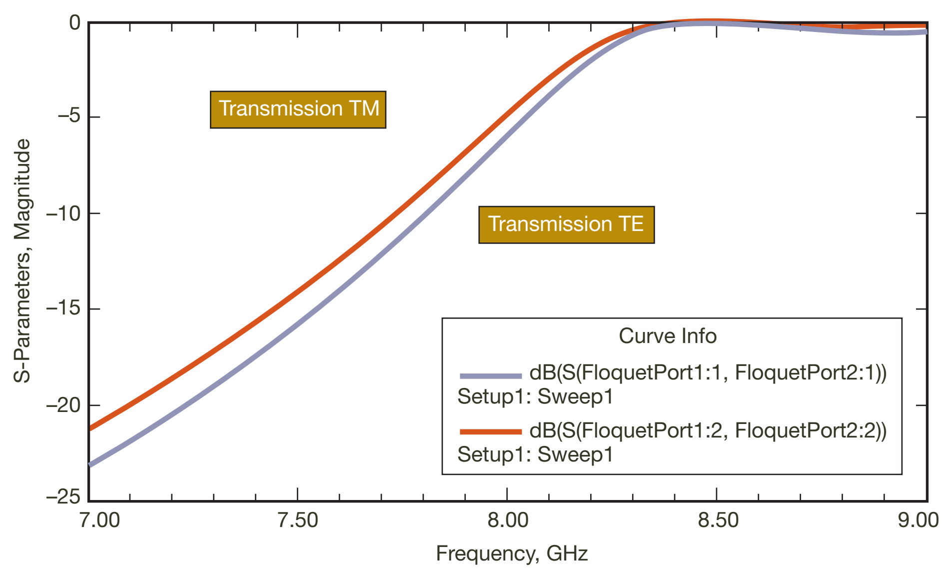

Figure 4. Transmission coefficient: original X-/X-band FSS.

amplitude. The width of the bundle is determined by the gain of the feed and decreases as the feed gain increases. Figure 5 shows a Cos^q pattern model for the standard 29-dB feed employed in the DSN. We see that significant power is contained in rays at angles of up to 5 deg for this pattern.

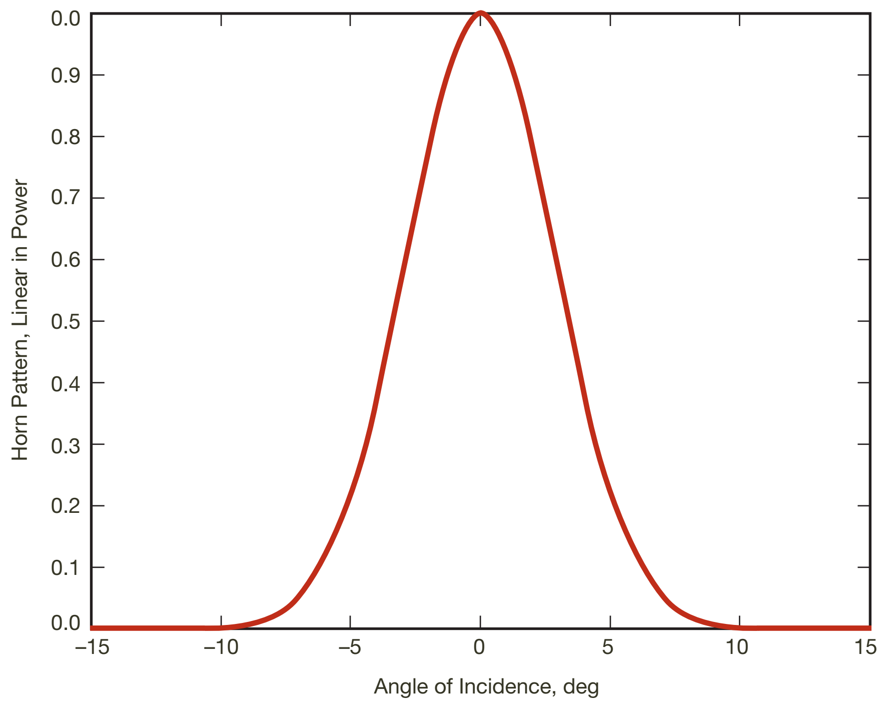

Figure 5. Feed radiation pattern.

Due to the finite beamwidth of the feed, the performance of the FSS for these angles of incidence is also important. These results are shown in Figure 6. The plot shows the reflection coefficient (average of the two polarizations) versus angle of incidence at frequencies covering the standard downlink band. As expected, the reflection is minimum at the designed angle of incidence and rises for larger angles. Minimum reflection at the nominal angle of interest, and over most angles, occurs at the nominal design frequency of 8.45 GHz. The results here represent an "effective reflection," and include not only reflection in the incident polarization, but also cross-polarized reflection and transmission in any higher higher-order Floquet modes. All of this energy is assumed to be unguided by the remaining optics and is ultimately terminated in a 300-K load.

Using the feed pattern and the angle-dependent reflection coefficients, the noise temperature contribution of the FSS may be estimated by multiplication of the pattern and reflection coefficient and integration over all angles of incidence. Since the input radiation is assumed to be circularly polarized, the average of the reflection coefficients for the two polarizations is appropriate for this calculation.

The results of this noise temperature calculation are shown over the entire 7- to 9-GHz band in Figure 7, and in more detail over the DSN band in Figure 8. Figure 7 shows that in the 7.2-GHz band, the plate has nearly total reflection and hence would contribute nearly 300 K to the system temperature. On the other hand, in the 8.4- to 8.5-GHz band, the contribution is quite low, as expected. We see from Figure 8 that the computed noise temperature contribution is approximately 2 K at the center of the band and rises to approximately

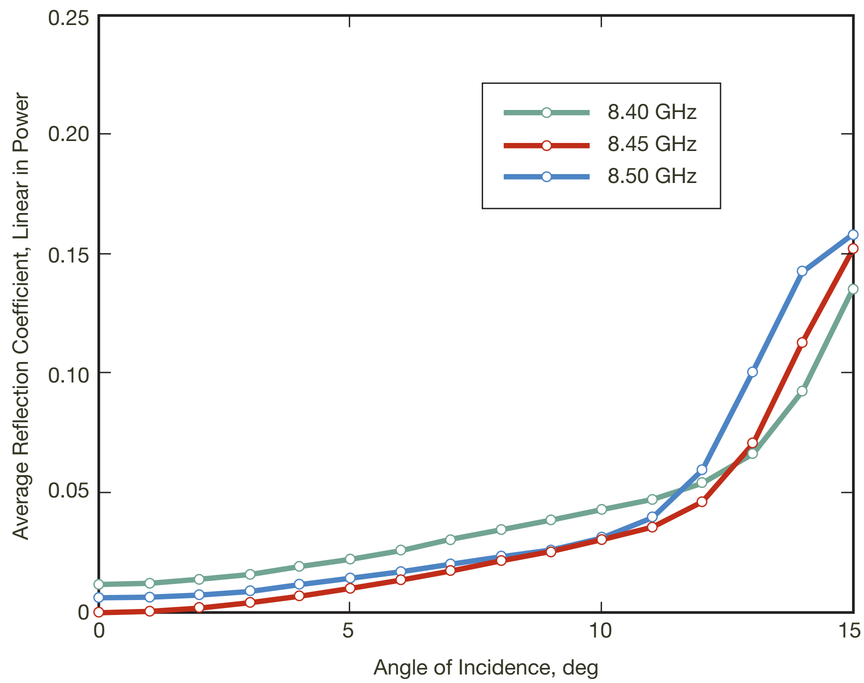

Figure 6. Reflection coefficient vs. angle of incidence: original X-/X-band FSS.

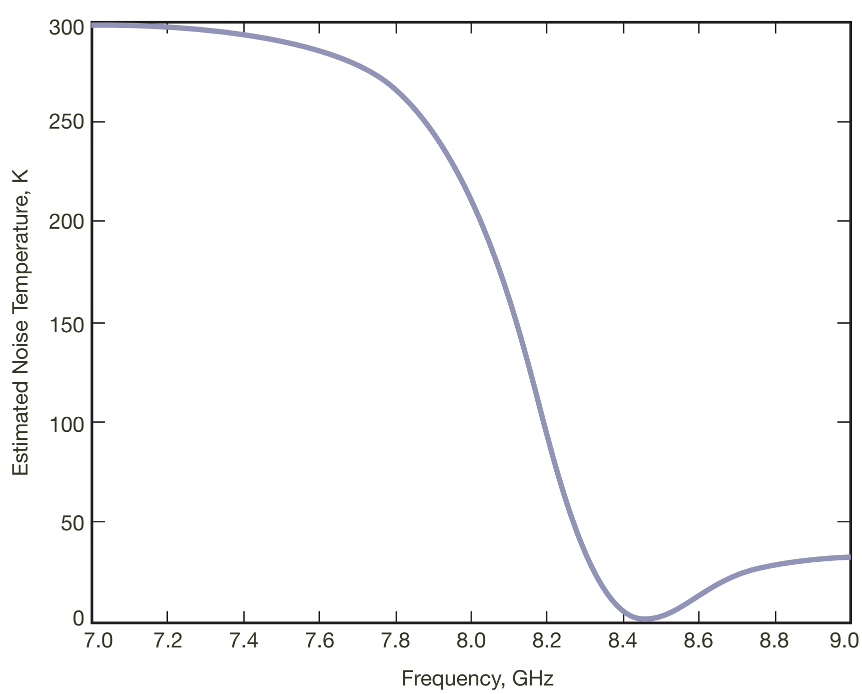

Figure 7. Noise temperature: original X-/X-band FSS.

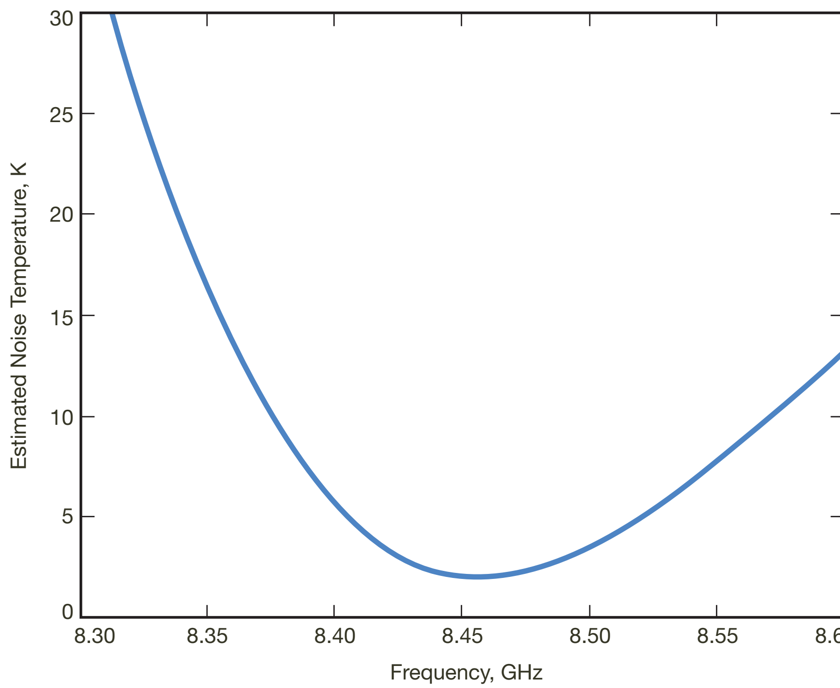

Figure 8. Noise temperature: original X-/X-band FSS (detail).

5 K at the band edges. Past experience indicates that these purely theoretical noise values should be considered as absolute minimums for the FSS contribution. They are, however, quite useful for comparing various FSS configurations for their relative noise contributions.

The major limitation of the previous FSS design is the high level of transmit power that leaks through the plate. Since this power leaks through evanescent coupling, it can be reduced greatly by using a thicker FSS. Increasing the thickness requires re-optimization of the aperture size and spacing. This was accomplished and the results for reflection and transmission for the new, thicker FSS are shown in Figures 9 and 10. Of particular interest is the leakage level of –33 dB at 7.2 GHz, which corresponds to a much more manageable 50 W for 100 kW of uplink power.

It is expected that some penalty in noise performance may result from this increase in FSS thickness and associated decrease in leakage. The noise performance of the thicker FSS is shown in Figures 11 and 12. In Figure 11, at 7.2 GHz we see essentially 300 K, indicating that very low levels of signal now leak through the FSS to be guided out the antenna. In Figure 12, we see the main effect of the increased plate thickness: decreased bandwidth. Ignoring the slight frequency shift, we find that the nominal noise temperature contribution at midband remains near 2 K, but the bandwidth is reduced and the noise temperature contribution rises to approximately 10 K at the edge of the ±50-MHz band.

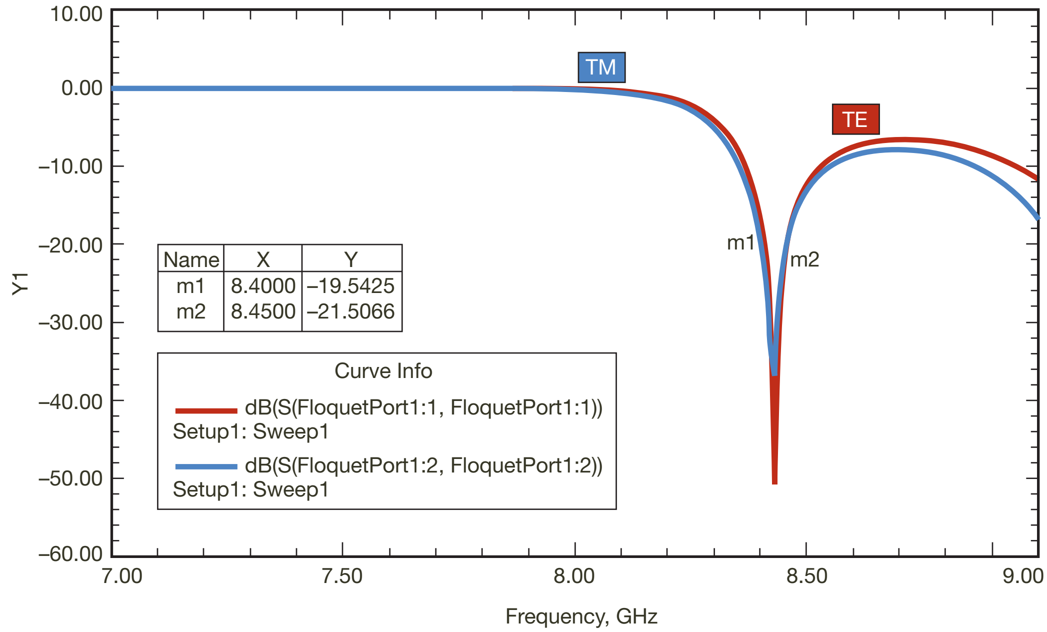

Figure 9. Reflection coefficient: thicker X-/X-band FSS.

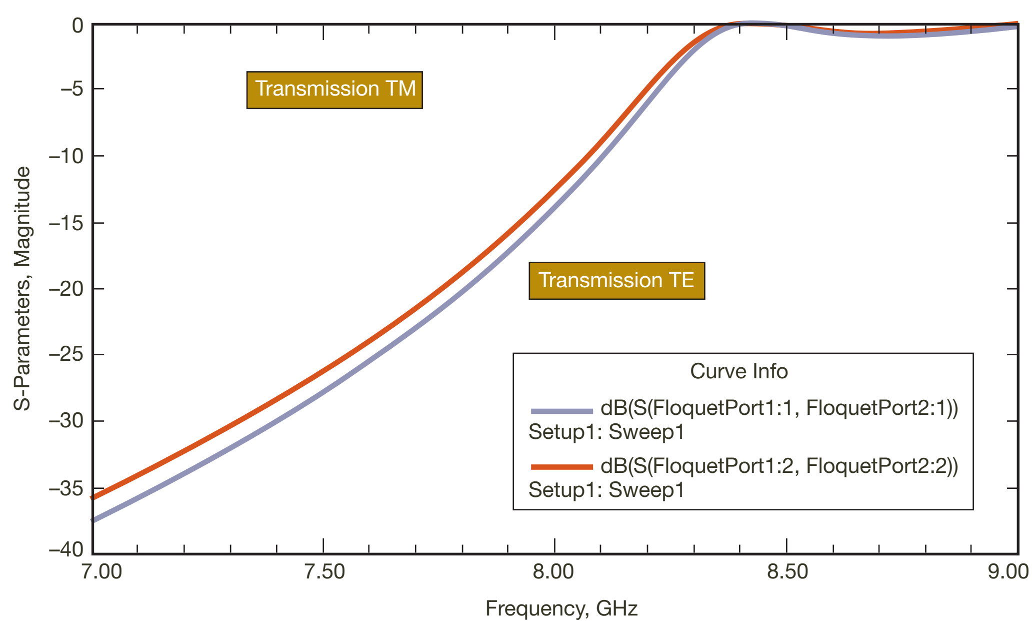

Figure 10. Transmission coefficient: thicker X-/X-band FSS.

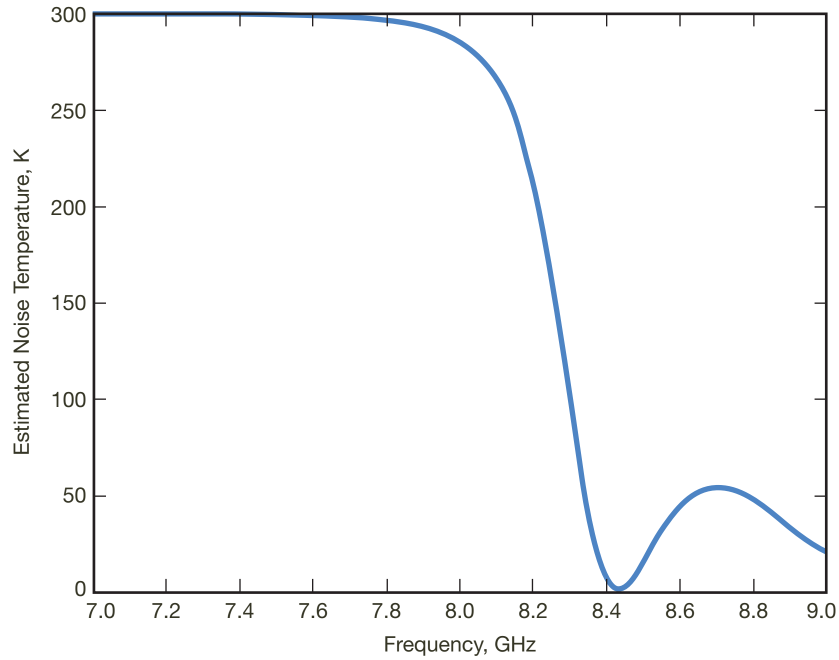

Figure 11. Noise temperature: thicker X-/X-band FSS.

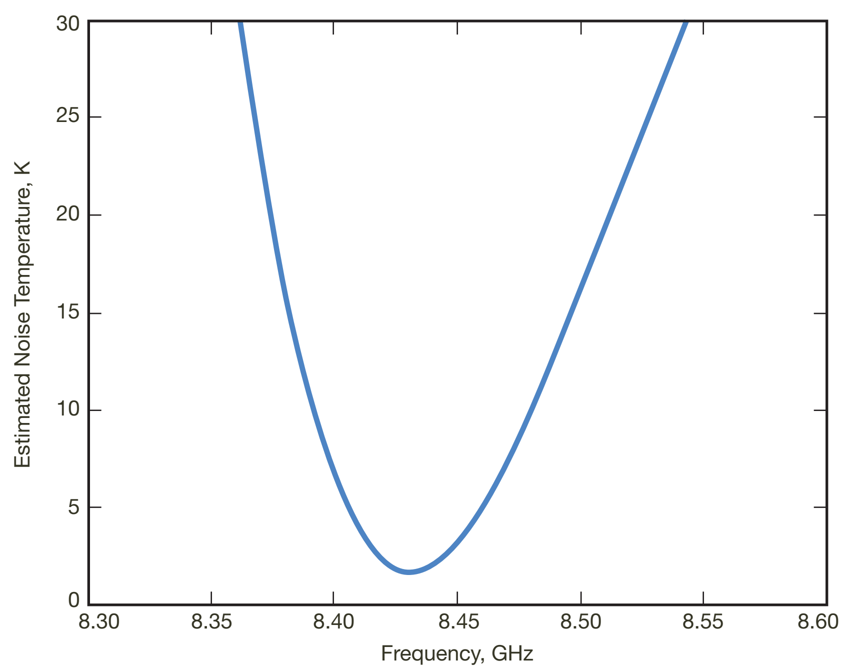

Figure 12. Noise temperature: thicker X-/X-band FSS (detail).

IV. X-/X-/Ka-Band (7.2-/8.45-/32.0-GHz) System Based on Separate Ka-Band (32-GHz) and X-Band (8.45-GHz) High-Pass FSSs

In this section, we describe one approach for creating an FSS configuration that allows both 32- and 8.45-GHz downlink simultaneously with 7.2-GHz uplink. When considering this problem, we limited the study to low-loss FSS systems compatible with very high-power (100-kW CW) operation. This effectively limits the design space to metal-only structures. Consideration was briefly given to dual-period single FSS structures with passbands at both 32 and 8.45 GHz, but ultimately no suitable design was found. A system employing a pair of 32-GHz surfaces appropriately spaced to resonate the 8.45-GHz band through was also studied. In this case, it was found that even for very thin 32-GHz FSS structures, the evanescent coupling at 8.45 GHz was insufficient to achieve the desired bandwidth. Instead, a triplexing FSS structure that first separates the X-band signals from the Ka-band downlink, extracts the X-band uplink, and then recombines the downlinks was chosen for further evaluation.

The FSS system considered is depicted schematically in Figure 13. In this case, we consider a pair of high-pass FSSs in series along with an 8.45-GHz high-pass surface configured as shown in the figure. Each 32-GHz surface is designed to pass the 32-GHz receive band, and reflect both 7.2 and 8.45 GHz.

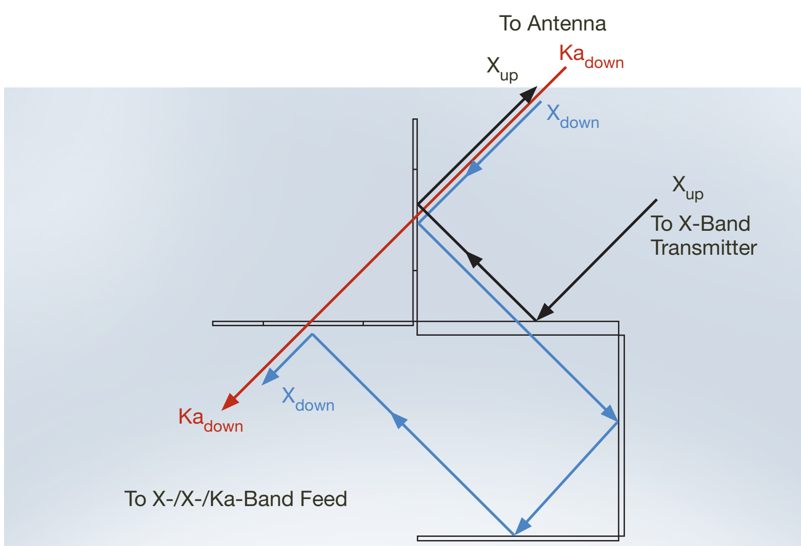

Figure 13. Side view of an FSS triplexer using two high-pass Ka-band FSS, one high-pass X-band FSS, and two flat plates.

A typical response is shown in Figure 14. The 32-GHz and 8.45-GHz downlink signals are incident on the first 32-GHz FSS, which passes the 32-GHz signal and reflects the 8.45-GHz signal. The 32-GHz downlink passes through a second, identical FSS and proceeds on to the existing X-/X-/Ka-band feed. The 8.45-GHz downlink passes through an 8.45-GHz FSS identical to that described in the previous section. This downlink is then re-directed back to the second 32-GHz FSS, which is used to re-combine it with the 32-GHz downlink where it proceeds to the X-/X-/Ka-band feed. The 8.45-GHz FSS is used to inject the 7.2-GHz uplink signal through reflection, as depicted in the figure. In this way, the FSS system extracts the downlink path from the uplink path and allows the existing X-/X-/Ka-band feed to be used to receive both the 32- and 8.45-GHz bands, while the 100-kW uplink is handled by a separate feed system.

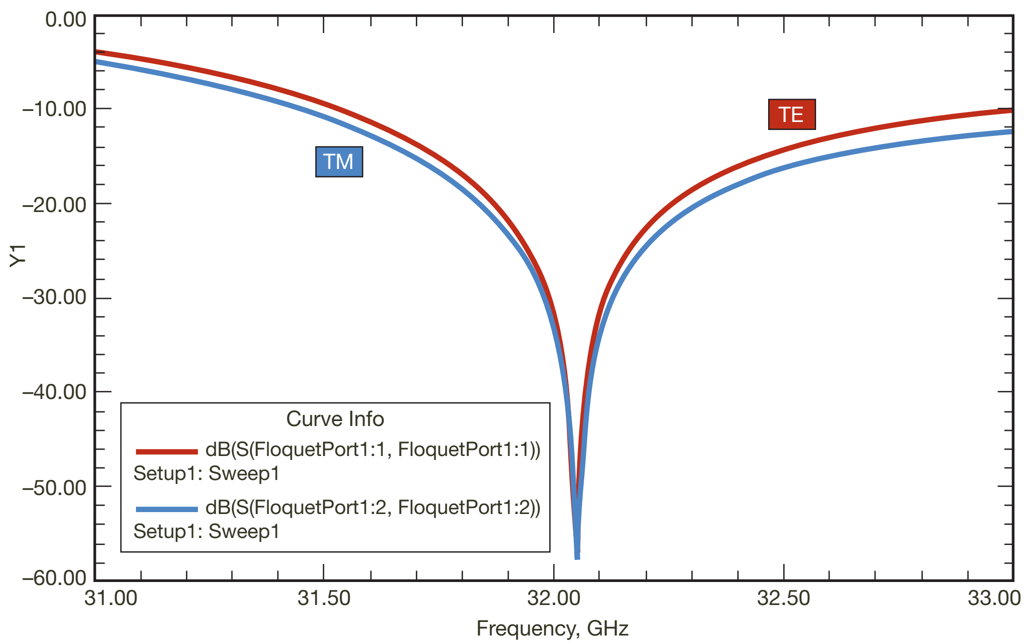

Figure 14. Reflection coefficient for a single, optimized Ka-band high-pass FSS.

Figures 15 and 16 show three-dimensional views of the three-FSS system configured for a 45-deg angle of incidence. The detailed view shows the 32-GHz apertures in two of the FSS structures, which are on the order of one half wavelength at 32 GHz, as well as the 8.45-GHz apertures in the X-band FSS. As illustrated, the system also requires two flat reflectors.

It is also possible to use the existing frequency selective surfaces discussed earlier in this report to realize the triplexer with an angle of incidence of 30 deg with respect to the FSS normals. This system is depicted in Figure 17.

The noise temperature contribution from this system may be estimated from the contributions of the individual surfaces. Since the 32-GHz FSS is a scaled version of the thin

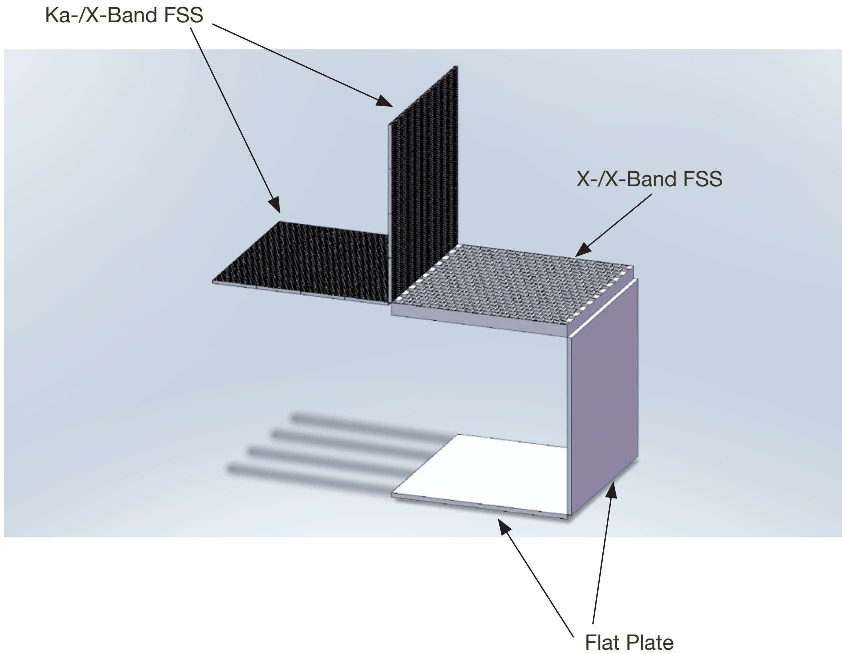

Figure 15. Three-dimensional view of the FSS triplexer.

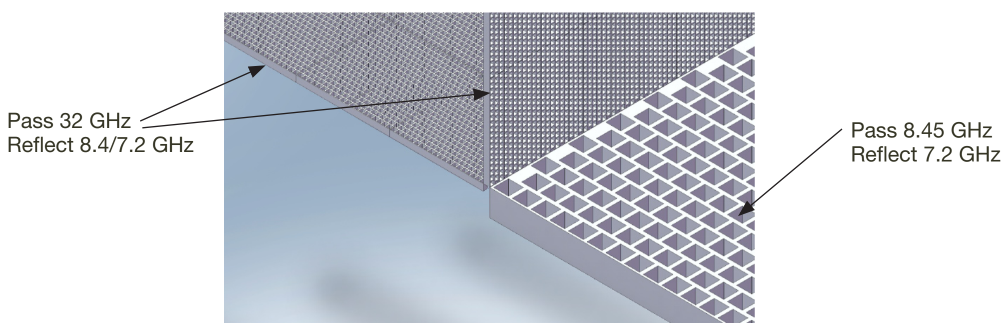

Figure 16. Three-dimensional view of the FSS triplexer: detail at the junction of the three FSSs.

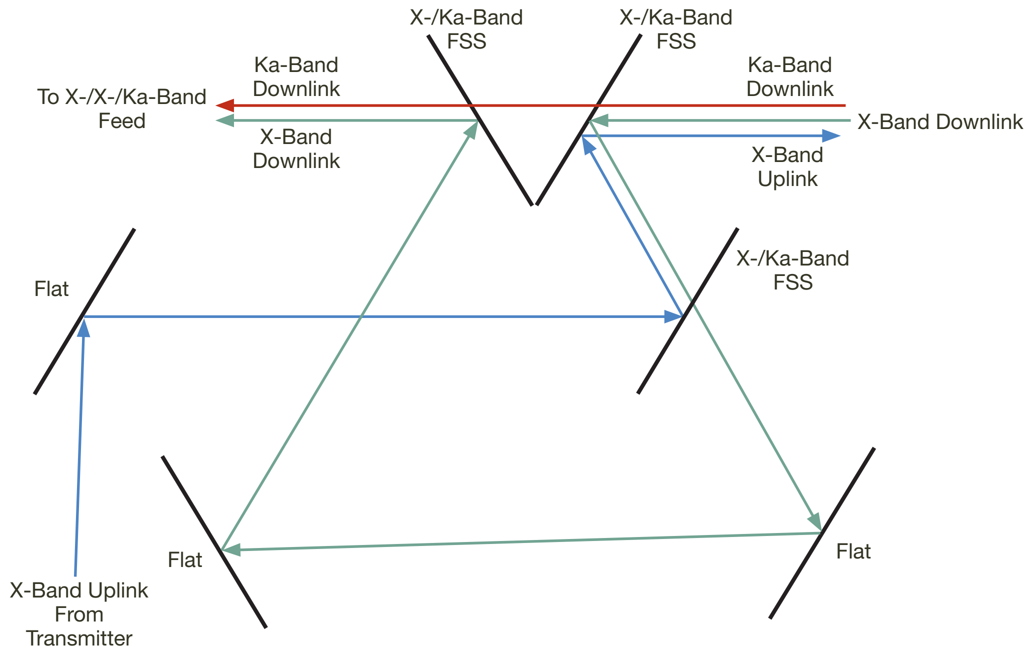

Figure 17. Side view of a 60-deg FSS triplexer using two high-pass Ka-band FSSs, one high-pass X-band FSS, and three flat plates.

8.45-GHz plate, we expect a contribution of 2 K at midband and 5 K at the band edges for each of the two surfaces. Thus, the contribution to the triplexer in the 32-GHz band is approximately 4 K at midband and 10 K at the band edges. For the 8.45-GHz contribution, we assume the thick FSS design, which contributes 2 K at midband and 10 K at the band edges. In addition, each of the two flat reflectors contributes 0.15 K, for a total of 2.3 K at midband and 10.3 K at the band edges. All estimates assume that the FSSs and flat reflectors are oversize, essentially eliminating the chance for spillover. If refocusing is necessary, the two flat mirrors may be replaced with curved mirrors as well. Finally, it should be repeated that it is envisioned that the entire FSS assembly would be retractable, allowing for the existing performance to remain unchanged for uplink powers of 20 kW or less. It should be stressed that no detailed mechanical layout for this structure in the BWG system has been completed and there may be challenges in this area. These details would be considered in detail when/if implementation of this option becomes necessary.

VI. Summary and Conclusions

Alternative approaches for injecting a 80- to 100-kW uplink signal into the 34-m BWG systems using FSSs have been studied. All systems employ the existing X-/X-/Ka-band feed for reception of the downlink and a separate, simple corrugated feed for the high-power uplink. It is envisioned that any FSS system would be fully retractable, allowing the existing system to be employed for uplink powers up to 20 kW CW. The estimated noise temperature contribution for a 8.45-GHz only receive system is approximately 2 K at midband

and 10 K at the band edges. A system that would allow simultaneous reception in the 32-GHz band as well would contribute 2.3 K at midband and 10.3 K at the band edges for the 8.45-GHz band, and 4 K at midband and 10 K at the band edges for the 32-GHz band. Future work in this area, to be undertaken in the implementation phase, would include re-optimization of the FSS apertures including the effects of rounded corners, which were ignored in this study since they will have a negligible effect on the overall reflection characteristics and noise temperature contribution.

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