A Superior Low Frequency Analysis for Beam Waveguide Antennas

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I. Introduction

Beam waveguide (BWG) technology offers wide frequency band coverages, improved G/T performance for ultra low noise ground antennas by providing a more stable operating environment for masers, advantages in maintenance and operations, and reduced life cycle cost for ground station antennas. For these reasons, there has been a trend to adopt the beam waveguide design in new ground station antenna projects. Examples are the Japanese 45m and 64m antennas at Nobeyama and Usuda, and various 30m Class Intelsat and Comsat ground antennas. Additionally, the NASA/JPL/Deep Space Network (DSN) is building a 34m BWG antenna at Goldstone, CA, with more to come.

The beam waveguide feed operating principle is based on geometric optics (GO). By using a pair of properly shaped and positioned mirrors, the radiation pattern of a feedhorn can be reproduced at a point in space that is some distance away from the physical location of the feedhorn. For finite size BWG systems at finite frequencies, some loss and some pattern distortions are experienced. At present, such effects are predicted from diffraction analysis developed for mirrors in open space. Common analysis techniques are Gaussian mode analysis and physical optics analysis (PO). In the real situation, the BWG mirrors are enclosed by metal walls for safety when transmitting and for sensitivity (noise temperature) and RFI when receiving. The absence of the wall in the current analysis models leads to an error whose magnitude is not well understood, especially at lower frequencies when the wall diameter is 20 wavelengths or less. In practice, this means one is always forced to make decisions about, for example, building a 6-ft or 8-ft diameter BWG system based on weak assumptions. Such decisions often have major impacts on antenna microwave/structural performances and project cost tradeoffs.

In this paper, a new analysis is presented of BWG antennas which considers the presence of the wall. The results from this analysis have revealed some new understandings of the performance degradation mechanisms in a BWG antenna and have pointed to potentially significant design improvements. Some of these ideas are discussed in this paper. Full realization of all benefits from BWG wall analysis and design concepts will take some time. Hopefully, the discussions in this paper will induce further innovative ideas and designs.

II. New BWG Antenna Analysis that Considers the Wall Presence

The new BWG wall analysis presented in this paper is conceptually similar to the physical optics (PO) analysis used in reflector antenna analysis. Conceptually, both PO and the BWG wall analysis can be thought of as a superpositioning process whereby the radiation field of a current distribution is found by integrating the radiation field of point sources. For BWG analysis, the approach in this paper is based on a very elegant dyadic Green's formulation discussed in Tai [1]. We begin with the one-mirror BWG system. The field scattered by the BWG mirror in the waveguide can be written as

$$\overline{E} = (-)\, jw\mu \int \overline{\overline{G}}_1 \ (\overline{R} | \overline{R}') \cdot \overline{K}\ ds' \tag{1}$$

where $\overline{\overline{G}}_1 \ (\overline{R} \,|\, \overline{R}')$ is the dyadic Green's function which satisfies Maxwell's equations and the boundary conditions of the metal BWG wall, i.e., no field exists outside the BWG wall. For a cylindrical waveguide, the dyadic Green's function has been derived and is given in Eq. (15), p. 89 of [1].

III. Numerical Results and Assessment

The results of the wall analysis of a 34m antenna under construction (designated as DSS 13 in NASA/JPL/DSN) are shown in Fig. 1. The projected mirror diameter is approximately 2.4m, or approximately 19 wavelengths at the analysis frequency of 2.295 GHz. These initial results revealed some exciting potential for BWG antenna design improvement. A significant finding is that there are only a few significant modes propagating between the two curved mirrors. This is in spite of the fact that the waveguide diameter is 19 wavelengths, and that a large number of modes are theoretically above their cutoff frequencies. As is shown in the table in Fig. 1, the EM field scattered from mirror 1 consists of mainly TE_{11} and TM_{11} modes. This is not surprising, as the incident field is assumed to be from a horn with symmetric radiation pattern, similar to that of a corrugated horn. By normalizing the mode power to the TE_{11} mode, we see the third and fourth significant modes, TE_{21} and TM_{21}, are already about 30 dB down in power.

Given that hundreds of modes may propagate, one must view this result with some caution. It is encouraging that the results described above are in qualitative agreement with some results in [2]. By expanding the reflected field from a curved mirror in Gaussian modes, Gans finds that the field can be represented approximately by just two Gaussian modes, namely TEM_{00} and TEM_{01}. One notes that the field line of the TEM_{00} Gaussian mode bears striking similarity to that of the aperture field of a dual (TE_{11} and TM_{11}) mode horn, with the two modes in appropriate amplitude and phase relationships. One notes further that the TEM_{01} Gaussian mode field lines are similar to the TE_{21} cylindrical waveguide mode. The results in [2] thus are in qualitative agreement with the present analysis with regard to the scattered field from mirror 1 in the immediate neighborhood of mirror 1. However, Gaussian modes and cylindrical waveguide modes propagate with distinctly different characteristics between mirrors 1 and 2. This is the major difference between a Gaussian mode analysis and the present analysis. Here is one significant difference, for example. The dominant Gaussian TEM_{00} is seen to be more like two cylindrical waveguide modes. For large mirror separations, there will be phase slippage between the two cylindrical waveguide modes not predicted by the TEM_{00} mode. Clearly, the Gaussian mode analysis is appropriate for BWG systems not enclosed by metal walls. In practice, it is generally accepted that Gaussian mode analysis and physical optics can be applied to enclosed BWG systems with good results under the very near-field approximation,

$$L \leq C \bullet \left(\frac{D^2}{\lambda}\right) \tag{2}$$

where L is the distance between mirrors and 1 and 2, D is the mirror diameter, λ is the wavelength, and C is a constant generally taken as between 0.1 to 0.2 [3]. The present analysis is valid when the BWG system is enclosed in metal walls and does not appear to be bound by Eq. (2), at least in principle.

A discussion follows of the mechanisms that cause performance degradation in an enclosed BWG system. These are (1) mode generation, (2) mode dispersion, (3) spillover loss at each mirror, (4) multiple scattering between mirrors, and (5) dissipative loss in the wall. Let us start by assuming that an HE_{11} mode horn or equivalently a dual TE_{11} and TM_{11} mode horn is illuminating mirror 1. Each curved mirror may be viewed as a mode generator whose scattered field contains unwanted higher order modes in the sense that at the output end of the BWG system, only the TE_{11} and TM_{11} modes in the correct complex ratio are desired. The most severe limiting factor appears to be mode dispersion, i.e., different modes propagating with different phase velocity in the BWG, causing the various modes to appear in wrong phases at the output of the BWG system. Undoubtedly, the present analysis provides the correct basis for calculating mode dispersion in an enclosed system compared to any existing analysis approach, e.g., Gaussian mode, PO, GTD, etc. At present, we do not model mechanisms (4), (5), although an analysis of the dissipative loss that ignores mechanisms (3) and (4) is within reach in the context of the present analysis. We point out that ignoring the multiple scattering mechanism nonetheless yields good results, as it appears to be much less important than mode generation and dispersion effects in a first-order analysis.

Turning our attentions'to design improvements, the greater accuracy of the wall analysis model at lower frequencies should enable more cost-effective designs of BWG antennas. Specifically, the diameter of the BWG tube can be optimally designed. Having a larger BWG tube than is necessary means the reflector and its backup structure must be raised higher from the elevation axis. This increases the moment of the reflector and backup structure about the elevation axis and hence reduces the antenna's pointing performance in wind, which must be compensated for by a heavier and more expensive design. Alternatively, a reduced antenna wind pointing performance must be accepted. In addition, the analytical results showing that there are likely only a few significant modes between mirrors 1 and 2 suggest some further potential improvements to the BWG antenna and feed design. Since most of the power is in the TE_{11} and TM_{11} modes and the differential propagating phase of the modes can be computed, it appears possible to design a dual-mode or multimode horn to compensate for the mode generation and mode dispersion effects discussed earlier. This is currently under investigation.

References

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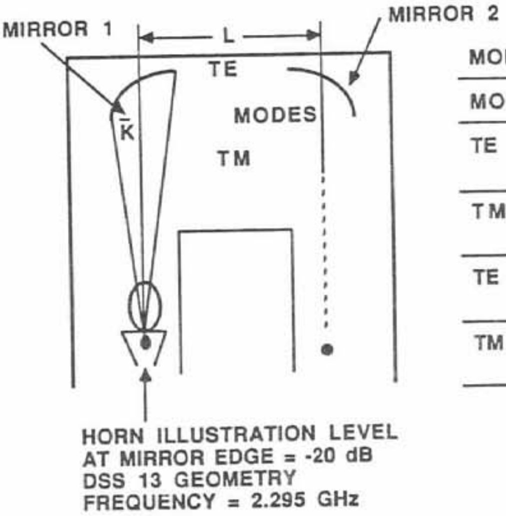

MODE POWER CONTENTS:

MODE	MODE COEFFICIENTS	
TE 11 EVEN	0.24 + j.88	0 dB
TM 11 ODD	0.25 - j.07	-10.9 dB
TE 21 EVEN	-0.01 - j.03	-29.6 dB
TM 21 ODD	-0.02 - j.0	-33.2 dB
⋮		

Figure 1. Results of One-Mirror BWG System Wall Analysis