Mode Filter Design for the NLC Overmoded RF Power Transport System[ℵ]

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Abstract

The RF power transmission system being designed at SLAC for the "Next Linear Collider" proposes three inch diameter circular waveguide for straight line power transmission in the TE_{01} mode at a frequency of 11.424 GHz. Bends or other departures from straight line transmission will typically involve down tapering and conversion to TE_{10} rectangular waveguide. Such elements are excellent reflectors for the many unwanted modes which can propagate in the transport waveguide, so that a rather dense set of higher order mode resonances is anticipated in transport sections between pairs of them. Absorbers which couple to the longitudinal currents of higher order modes is one way to mitigate adverse effects. In this paper we apply numerical analysis to various structures so as to quantitatively determine their effect upon the propagation of each such mode.

1. Introduction

The structures which we study in this paper have the general configuration illustrated in Fig. 1.

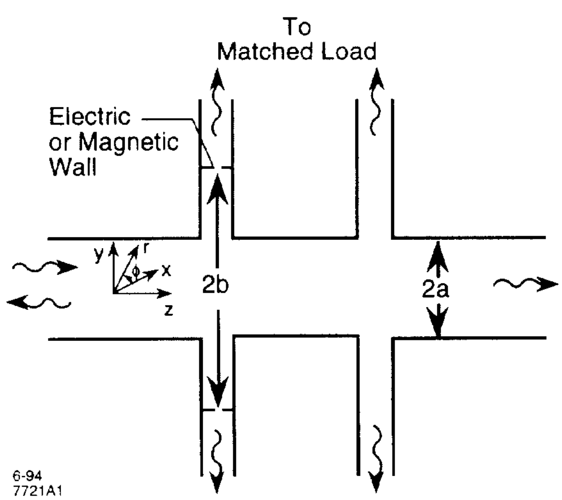

Figure 1: Two Gap Example of Mode Filter Configuration

The structure, which is assumed to be rotationally symmetric about the z axis, consists of a set of discs separated by gaps. The discs have a common inner radius equal to the radius of the circular waveguide for which the structure is designed. Because of the rotational symmetry the fields even in the presence of the gaps may be characterized by the usual azimuthal mode number m. The gaps are to be thought of as radial waveguides with gap width chosen so that for any specified m value there is only a single radially propagating mode, and it is assumed that the gaps are terminated at some adequately large radius by a matched load. Thus at an adequate distance from the gap-waveguide junction the field in the gap consists (except, as discussed below, for the TE $m = 0$ case) solely of a single radially propagating outgoing wave to be referred to as the gap wave. The gap wave has only a z component of electric field and only transverse magnetic field components, and in any particular gap the field components are independent of z. It follows that the gap wave is driven by the azimuthal magnetic field of the incident waveguide mode. The $m = 0$ modes retain their pure TE or TM character in presence of the gaps, but TE and TM are mixed for all higher values of m. Since pure TE excludes the gap wave, fields in the gap are exponentially damped for the TE_{0n} modes and may be considered to be negligible at the matched loads. Thus the only effect of the gaps on these modes is to reflect them and to scatter them among themselves, and it is important to design the gaps so as to minimize these effects. The substance of this paper is confined to theory and computation, so that questions of how the matched loads are to be incorporated and how the structure is to be assembled and supported are not addressed. A parallel experimental program is in progress but will not be discussed here. We have used two distinct computational approaches to compute the S parameters, viz., a 2-D time domain module in MAFIA 3.20 [1], and a semi-analytic mode matching method. These two methods are presented in sections two and three, respectively. Results will be discussed in section 4.

2. The MAFIA Calculations

The time domain MAFIA 3.20 module permits the launching of a specified mode as well as decomposition of the reflected and transmitted modes at the port boundaries. In the two gap design, illustrated in Fig. 1, matched conditions are assumed for all outgoing waves. The S parameters are calculated by launching a wave from the left with an envelope adiabatically rising in time. The wave transmitted and reflected at the ports is decomposed into modes and the S matrix is stored for all time steps. Once steady state conditions are attained all S parameters are averaged with respect to time over a considerable number of wave periods. The electric field profile in the structure

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resulting from an incident TM_{01} mode is illustrated in figure 2. The field pattern in the circular waveguide indicates substantial conversion to TM_{02}.

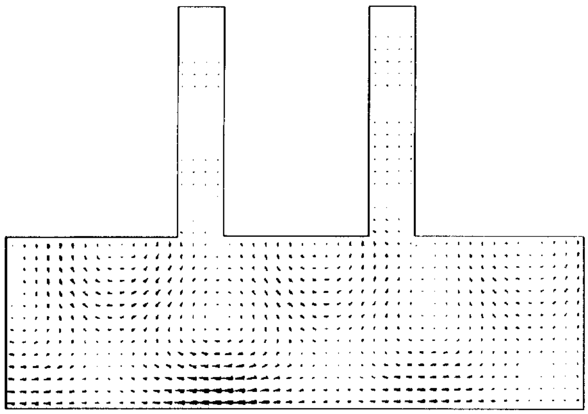

Figure 2: Electric field calculated with MAFIA due to an incident TM_{01} mode

3. The Mode Matching Method

The procedure [2] is based upon the computation of the generalized 2-port S matrix for a single matched gap from a complete expansion of waveguide fields at waveguide transition regions. The multigap case is obtained from the single gap case using cascading methods [3]. To obtain the S matrix for the single matched gap we adopt a procedure which reduces the problem to one in which the matched load is replaced by a lossless termination. Specifically, we specify an outer radius b and first assume that the gap is terminated by an electric (i.e. conducting) wall there. We compute the S matrix for the small radius to large radius junction (boundary enlargement) in the standard way [4] and cascade it with the symmetric large radius to small radius junction (boundary reduction) which completes the gap. We denote the resultant S matrix by S^e. A second S matrix, S^h, is obtained in a similar manner by specifying a magnetic wall at radius b (i.e. $H_\phi = 0$ instead of $E_z = 0$). As shown below, one can determine a complex constant α such that the matched load S matrix, S^M, is given by:

$$S^M = (S^h - \alpha S^e)/(1-\alpha) \tag{1}$$

Let F_i symbolically represent the solution of Maxwell's Equations associated with a unit incoming amplitude in the ith mode in the magnetic wall case and E_i the value of E_z at the magnetic wall which that solution yields. Let G_i and H_i be the corresponding electric wall solution and associated value of H_ϕ at the electric wall. Then $(F_i - \alpha_i G_i)/(1-\alpha_i)$ represents a solution of Maxwell's Equations with unit incoming wave in the i'th mode, with:

$$E_z(r=b) = E_i \tag{2}$$

and

$$H_\phi(r=b) = -\alpha_i H_i \tag{3}$$

In order that the solution represent an outgoing wave in the gap we must have:

$$(H_\phi / E_z)_{r=b} = -jY_0[\ln H_m^{(2)}]' \tag{4}$$

which yields:

$$\alpha_i = jY_0[\ln H_m^{(2)}]' E_i / H_i \tag{5}$$

Here Y_0 is $\sqrt{\varepsilon/\mu}$, and $H_m^{(2)}$ is the Hankel function of the second kind and order m evaluated, after taking the logarithmic derivative, at argument kb. It follows from the relation of solutions of Maxwell's Equations to the S matrix that:

$$S_{ki}^M = (S_{ki}^h - \alpha_i S_{ki}^e)/(1-\alpha_i) \tag{6}$$

However, since all three S matrices in the above expression are symmetric under interchange of i and k, we must have $\alpha_i = \alpha_k$, and hence α has no dependence on the incoming wave mode. In order to evaluate α, one arbitrarily chooses an input mode and evaluates E_i and H_i using the same modal expansion and algebraic methods that were used in constructing the S matrices. By choosing different modes we have confirmed the independence of the choice proved above. So long as b is chosen large enough the result should also be independent of its value even though S^h, S^e, and α are not. We have confirmed this numerically.

4. Application to Mode Filter Designs

We have chosen a gap width of 0.250 inches for all of the calculations. This leads to a minimum higher order mode decay constant in the gaps of 11 inch^{-1}. Since the radii difference b-a has always been taken to be at least one inch, the single propagating mode condition is always well satisfied.

The diameters of the waveguides are 1.865 inches and 2.93 inches. The guides are connected to one another by smooth tapers, the smaller diameter being used for components such as bends, mode transducers, and the like. We have studied mode filters for both diameters. We have so far confined ourselves to uniform gap spacings. For the 1.865 inch case we have used 0.790 inches for the length of the circular waveguide section between two gaps. This length was chosen to minimize TE_{01} reflection for the two gap case. Indeed, the mode matching method yields SWRs of 1.0918, 1.00014, 1.00061, and 1.0015 for 1, 2, 4 and 8 gaps, respectively. The corresponding length for the larger guide was 0.604 inches and was chosen to minimize TE_{01} transmission loss (from reflection and backward and forward scattering to TE_{02}) in the four gap case. Further, the computed results reveal the transmission loss for 1, 2, 4, and 8 slots to be -29.84, -27.24, -44.46, and -38.36 dB, respectively. Excluding second order rotational degeneracy there are 9 unwanted modes for the smaller diameter and 22 for the larger one. In this report we present only the loss figure for each incident unwanted mode (see Tables I and II). Here the loss figure is defined as the fraction of the incident power absorbed in the matched loads. Results for both methods are presented where available. The agreement is seen to be satisfactory.

Table I: Loss Figures for Various Incident Unwanted Modes for the 1.865 Inch Case at 11.424 GHz.(MAFIA results in the first row, mode matching in the second)

Mode	1 Gap	2 Gaps	4 Gaps	8 Gaps
TM01	0.0846	0.130	0.340	
	0.0839	0.129	0.336	0.642
TM02	0.401	0.675	0.692	
	0.402	0.676	0.684	0.719
TE11	0.0821	0.131	0.289	
	0.0815	0.130	0.283	0.532
TE12	0.0040	0.0077	0.0102	
	0.0032	0.0072	0.0099	0.0249
TM11	0.305	0.607	0.873	
	0.306	0.608	0.872	0.955
TE21	0.0939	0.286	0.599	
	0.0931	0.281	0.597	0.836
TM21	0.397	0.553	0.778	
	0.399	0.556	0.780	0.799
TE31	0.218	0.434	0.700	
	0.224	0.444	0.701	0.910
TE41	0.228	0.363	0.631	
	0.229	0.360	0.642	0.859

Perusal of the tables indicates that the loss is quite substantial for most modes for four gaps. The notable exceptions are the TE_{mn} modes for n greater than one. These modes have very weak transverse magnetic field at the walls and hence can not be effectively damped by a structure of type studied here. We have looked at much larger numbers of gaps, and except for m = 0 the damping becomes substantial. Also the transmission loss for the incident wave and the loss of forward scattered power tends to increase more rapidly than the loss figure with the number of gaps. In carrying out this study we have had in mind perhaps four gaps. Whether it is practical to substantially increase this number in a bakeable vacuum system can be determined only after the power absorbing configuration has been developed.

We note that the mode filter itself acts as a weak source of weakly damped modes. Thus, a TM_{11} mode incident on the mode filter scatters some power into other m = 1 modes including the weakly damped TE_{12}. Therefore, it may be preferable to install the mode filter in the smaller guide because there we have only one such mode instead of five. The m = 5, 6, and 7 modes would then be undamped, but it may well be the case that these are not excited.

Table II: Loss Figure for Various Incident Unwanted Modes for the 2.93 Inch Case (MAFIA results in the first column and mode matching in all others)

Mode	1 Gap	1 Gap	2 Gaps	4 Gaps	8 Gaps
TM01	0.0679	0.0669	0.126	0.118	0.161
TM02	0.0900	0.0892	0.187	0.548	0.798
TM03	0.338	0.340	0.637	0.721	0.734
TM11	0.135	0.133	0.251	0.554	0.822
TM12	0.218	0.222	0.352	0.495	0.447
TE11	0.0474	0.0472	0.0963	0.174	0.276
TE12	0.00353	0.00368	0.00626	0.0135	0.0449
TE13	0.00102	0.000386	0.00117	0.00253	0.00342
TM21	0.110	0.108	0.194	0.327	0.592
TM22	0.311	0.317	0.633	0.675	0.713
TE21	0.0599	0.0585	0.116	0.134	0.222
TE22	0.00599	0.00608	0.0101	0.0563	0.157
TM31	0.211	0.214	0.351	0.623	0.859
TE31	0.126	0.126	0.225	0.400	0.728
TE32	0.0113	0.016	0.0208	0.0504	0.149
TM41	0.286	0.291	0.424	0.638	0.791
TE41	0.144	0.144	0.228	0.398	0.681
TM51	0.416	0.419	0.637	0.702	0.715
TE51	0.0704	0.0696	0.183	0.484	0.802
TE61	0.240	0.245	0.373	0.548	0.836
TE71	0.218	0.207	0.416	0.654	0.874

The tools which have been developed to obtain the results reported here will enable us to explore the properties of a variety of configurations. Our next step will be to investigate the effect of an increase in gap width. The amount of mode filtering required to mitigate deleterious effects needs to be studied both theoretically and experimentally. It is our hope that the detailed information provided by this type of analysis will assist in that program.

5. References

[1] T. Weiland, *Recent Advances and Applications of the MAFIA Codes*, AIP Conf. Proc. 297, Computational Accelerator Physics, pp 291-302, 1994

[2] All of the discussion in this section refers to the S Matrix for a specified azimuthal number m. Further, the complex constant α defined below is m dependent.

[3] R. Mittra and S.W. Lee, *Analytical Techniques in the Theory of Guided Waves*. New York: MacMillan, 1971, pp 207-217.

[4] A. Wexler, *Solution of Waveguide Discontinuities by Modal Analysis*, IEEE Trans. Microwave Theory Techn., MTT-15, pp. 508-517, 1967.