

Chodorow 型耦合腔慢波结构色散特性和耦合阻抗理论分析*

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本文建立了 Chodorow 型耦合腔慢波结构的解析模型, 利用并矢格林函数结合矩量法求解了场匹配方程, 给出了色散方程和耦合阻抗的计算式, 并数值计算出一个 X 波段 Chodorow 型慢波结构的高频特性. 结果表明, 本文方法的色散特性以及耦合阻抗与仿真软件 HFSS 计算的结果有很好的 consistency, 且计算效率更高, 同时精度远高于等效电路法, 对工程设计有好的参考价值.

关键词: Chodorow 型耦合腔慢波结构, 色散特性, 耦合阻抗, 场匹配

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1 引言

耦合腔结构是全金属结构, 散热能力强, 工作电压高, 可以提供高的峰值功率和平均功率, 并且具有合适的频带宽度, 采用这种慢波结构的行波管在微波乃至毫米波段被广泛应用于雷达、通信、遥测等领域^[1-3]. 休斯 (Hughes) 型结构是目前最常用的耦合腔结构, 它每个圆盘上只有一个耦合槽, 相邻槽反相放置. Chodorow 结构同一圆盘上则有两个相互对称的耦合槽, 相邻两腔的槽方向排列一致^[4]. 二者相比, 后者带宽窄^[5], 但对于给定的工作频率, 其中微波沿慢波线的传输速度快于前者, 同步电压更高, 有可能得到更大的输出功率.

由于耦合腔几何形状的复杂性, 对其高频特性的研究通常采用等效电路法^[6-10], 这种方法是将腔体和耦合槽视为两个孤立的 LC 谐振电路系统进行求解^[11], 然而实际情况是腔和槽的场分布会相互影响, 进而影响等效集总参数. 虽然许多文献提

出在模型中加入某些参数以修正结果^[7,8], 但等效电路法仍然不能在整个频带内达到足够一致的精度, 并且不能给出腔中具体场分布. 因此, 有必要寻求更精确的计算方法. 文献 [12] 利用格林函数法完整地求解了休斯型耦合腔结构电特性与几何参量间的关系, 所得结果精度较高, 文献 [13] 利用这种方法计算了加载等离子体的休斯型耦合腔结构的色散特性. 本文在文献 [12] 的基础上, 采用场等效原理, 将 Chodorow 腔体划分为七个规则的区域, 每个区域中的场由界面上的电场表示, 利用格林函数法^[14] 得到各个区域中的场, 将两相邻区域公共界面上的场用场匹配方程联系起来, 用矩量法求解场匹配方程. 系统的特性用广义导纳矩阵的形式给出, 每个矩阵元仅是系统和几何参量的函数. 以一个 X 波段的 Chodorow 结构为例, 运用本文方法计算出其腔模和槽模的高频特性, 将计算结果与仿真软件 Ansoft HFSS^[15] 以及等效电路法^[6,7] 的计算结果进行了对比, 并对计算效率和方法误差进行相应分析.

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2 Chodorow 型耦合腔慢波结构理论分析

2.1 模型的建立

由场的叠加原理, 将双槽耦合腔慢波结构的一个腔体单元分成 $-2, -1, 0, 1, 2, 3, 4$ 等七个区域, 并用 S_0-S_9 表示相邻区域公共界面, 如图 1 所示. D 为耦合腔半径, d 为漂移管外半径, a 为漂移管内半径, F 为耦合槽中心半径, R 为耦合槽半径, g 为

漂移管间隙半宽度, h 为耦合腔半腔高, l 为耦合腔半壁厚, $L = l + h$ 为耦合腔半周期长度, θ_0 为耦合槽半张角.

设公共界面 S_i 上的切向电场为 e_i , 将其看作场源, 设波沿 $+Z$ 方向传播, 其相应的传播因子为 $e^{-j\beta z}$, 即 $e^{-j\varphi}$. 对 Chodorow 结构, 由于每个圆盘上两个槽的相对角度为 180° , 根据对称性, 通过每个圆盘上两个槽的能流和电场是一致的, HFSS 软件仿真发现 (如图 2 所示), 通过前一个圆盘上某个槽的电场和能流只会影响后一个圆盘上对应的槽, 而

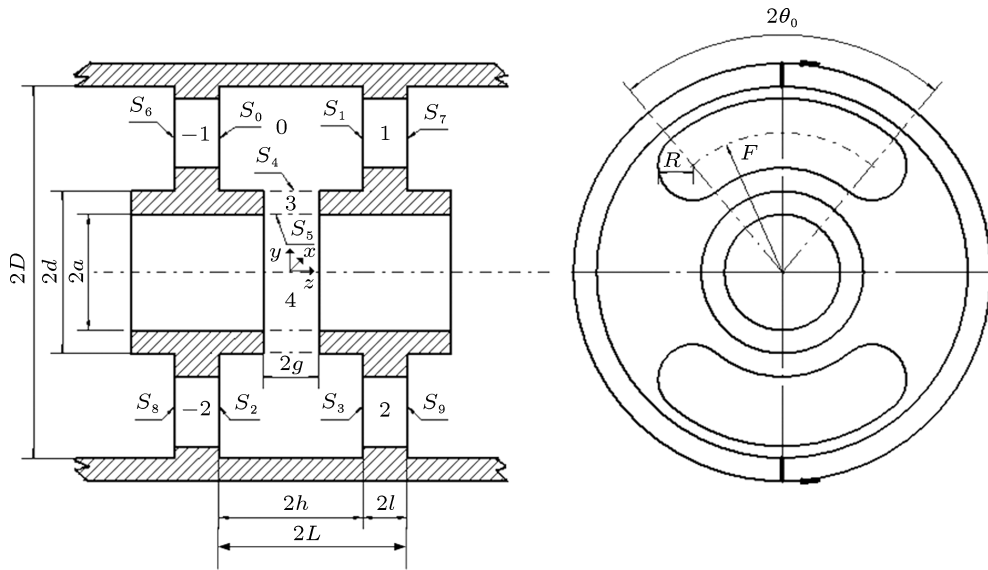


图 1 Chodorow 型耦合腔慢波结构

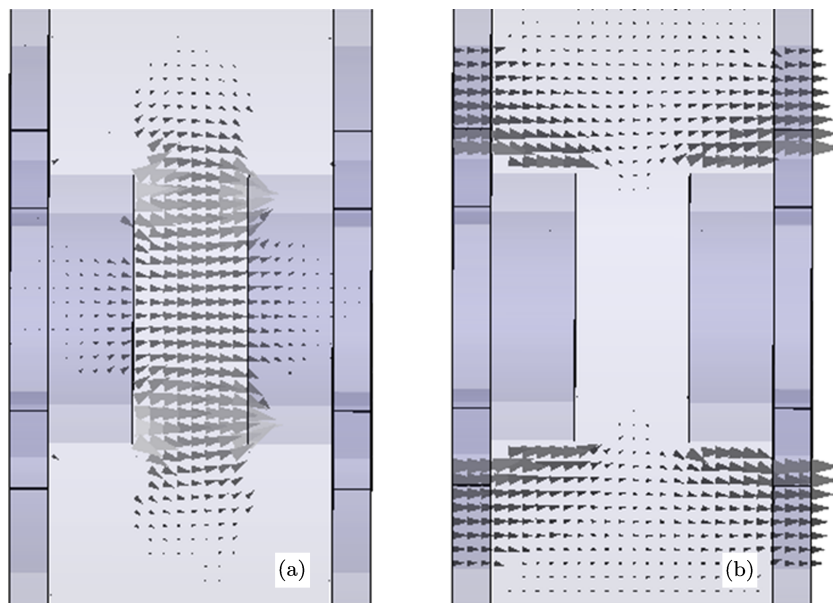


图 2 Chodorow 型耦合腔慢波结构 $y-z$ 面上的电场和能流分布 (a) 电场分布; (b) 能流分布

不会越过漂移管影响交叉槽. 由周期性定理及上述分析, 可将前后两腔的电场关系写作如下形式:

$$\begin{aligned} e_6 &= e_8 = e_1 e^{i\varphi} = e_3 e^{i\varphi}, \\ e_7 &= e_9 = e_0 e^{-i\varphi} = e_2 e^{-i\varphi}, \end{aligned} \quad (1)$$

式中, φ 为单腔相移. 在各区域中被这些等效场源激发的磁场为

$$\begin{aligned} H_{-1} &= L_{-1}\{e_6, e_0\} = L_{-1}\{e_1 e^{i\varphi}, e_0\}, \\ H_1 &= L_1\{e_1, e_7\} = L_1\{e_1, e_0 e^{-i\varphi}\}, \\ H_{-2} &= L_{-2}\{e_8, e_2\} = L_{-2}\{e_3 e^{i\varphi}, e_2\}, \\ H_2 &= L_2\{e_3, e_9\} = L_2\{e_3, e_2 e^{-i\varphi}\}, \\ H_0 &= L_0\{e_0, e_1, e_2, e_3, e_4\}, \\ H_3 &= L_3\{e_4, e_5\}, \quad H_4 = L_4\{e_5\}, \end{aligned} \quad (2)$$

式中, $L_i (i = -2, -1, 0, 1, 2, 3, 4)$ 均为电磁场矢量算子, 根据磁场切向分量在界面上的连续性, 列出场匹配方程:

$$\begin{aligned} L_0\{e_0, e_1, e_2, e_3, e_4\}_t|_{s_0} &= L_{-1}\{e_1 e^{i\varphi}, e_0\}_t|_{s_0}, \\ L_0\{e_0, e_1, e_2, e_3, e_4\}_t|_{s_1} &= L_1\{e_1, e_0 e^{-i\varphi}\}_t|_{s_1}, \\ L_0\{e_0, e_1, e_2, e_3, e_4\}_t|_{s_2} &= L_{-2}\{e_3 e^{i\varphi}, e_2\}_t|_{s_2}, \\ L_0\{e_0, e_1, e_2, e_3, e_4\}_t|_{s_3} &= L_2\{e_3, e_2 e^{-i\varphi}\}_t|_{s_3}, \\ L_0\{e_0, e_1, e_2, e_3, e_4\}_t|_{s_4} &= L_3\{e_4, e_5\}_t|_{s_4}, \\ L_3\{e_4, e_5\}_t|_{s_5} &= L_4\{e_5\}_t|_{s_5}. \end{aligned} \quad (3)$$

2.2 场匹配方程的求解

因为 $L_i (i = -2, -1, 0, 1, 2, 3, 4)$ 是仅与尺寸和频率有关的算子, 运用矩量法求解方程组 (3) 即可得到高频特性与几何参量间的关系. 根据不同界面上切向电场方向不同, 定义三组基函数 $\Psi_n, \Theta_n, \Phi_n (n = 0, 1, \dots, N, \dots)$. e_0, e_1 用 $\Psi_n (n = 0, 1, \dots, N, \dots)$ 展开, e_2, e_3 用 $\Theta_n (n = 0, 1, \dots, N, \dots)$ 展开, e_4, e_5 用 $\Phi_n (n = 0, 1, \dots, N, \dots)$ 展开, n 取无限大时得到方程组 (3) 的精确解实际计算中只取 $N+1$ 项:

$$\begin{aligned} e_0 &= \sum_n V_n \Psi_n, \quad e_1 = \sum_n U_n \Psi_n, \\ e_2 &= \sum_n V_n \Theta_n, \quad e_3 = \sum_n U_n \Theta_n, \\ e_4 &= \sum_n M_n \Phi_n, \quad e_5 = \sum_n N_n \Phi_n. \end{aligned} \quad (4)$$

式中, V_n, U_n, M_n, N_n 都是待定的展开系数, 根据对称性, 将 (3) 式中 S_2 和 S_3 面上的场匹配方程去掉, 简

化为

$$\begin{aligned} L_0\{e_0, e_1, e_2, e_3, e_4\}_t|_{s_0} &= L_{-1}\{e_1 e^{i\varphi}, e_0\}_t|_{s_0}, \\ L_0\{e_0, e_1, e_2, e_3, e_4\}_t|_{s_1} &= L_1\{e_1, e_0 e^{-i\varphi}\}_t|_{s_1}, \\ L_0\{e_0, e_1, e_2, e_3, e_4\}_t|_{s_4} &= L_3\{e_4, e_5\}_t|_{s_4}, \\ L_3\{e_4, e_5\}_t|_{s_5} &= L_4\{e_5\}_t|_{s_5}. \end{aligned} \quad (5)$$

将 (4) 式代入 (5) 式, 由于电磁场的线性特性, 可以根据叠加原理得到如下一组包含待定系数 V_n, U_n, M_n, N_n 的方程:

$$\begin{aligned} &\left(\sum_n V_n L_0\{\Psi_n, 0, 0, 0, 0\} + \sum_n U_n L_0\{0, \Psi_n, 0, 0, 0\} \right. \\ &+ \sum_n V_n L_0\{0, 0, \Theta_n, 0, 0\} + \sum_n U_n L_0\{0, 0, 0, \Theta_n, 0\} \\ &+ \left. \sum_n M_n L_0\{0, 0, 0, 0, \Phi_n\} \right)_{s_0} \\ &= \left(e^{i\varphi} \sum_n U_n L_{-1}\{\Psi_n, 0\} + \sum_n V_n L_{-1}\{0, \Psi_n\} \right)_{s_0}, \\ &\left(\sum_n V_n L_0\{\Psi_n, 0, 0, 0, 0\} + \sum_n U_n L_0\{0, \Psi_n, 0, 0, 0\} \right. \\ &+ \sum_n V_n L_0\{0, 0, \Theta_n, 0, 0\} + \sum_n U_n L_0\{0, 0, 0, \Theta_n, 0\} \\ &+ \left. \sum_n M_n L_0\{0, 0, 0, 0, \Phi_n\} \right)_{s_1} \\ &= \left(\sum_n U_n L_1\{\Psi_n, 0\} + e^{-i\varphi} \sum_n V_n L_1\{0, \Psi_n\} \right)_{s_1}, \\ &\left(\sum_n V_n L_0\{\Psi_n, 0, 0, 0, 0\} + \sum_n U_n L_0\{0, \Psi_n, 0, 0, 0\} \right. \\ &+ \sum_n V_n L_0\{0, 0, \Theta_n, 0, 0\} + \sum_n U_n L_0\{0, 0, 0, \Theta_n, 0\} \\ &+ \left. \sum_n M_n L_0\{0, 0, 0, 0, \Phi_n\} \right)_{s_4} \\ &= \left(\sum_n M_n L_3\{\Phi_n, 0\} + \sum_n N_n L_3\{0, \Phi_n\} \right)_{s_4}, \\ &\left(\sum_n M_n L_3\{\Phi_n, 0\} + \sum_n N_n L_3\{0, \Phi_n\} \right)_{s_5} \\ &= \left(\sum_n N_n L_4\{\Phi_n\} \right)_{s_5}. \end{aligned} \quad (6)$$

定义矢量 A, B 在界面 S 上的外积

$$\langle A, B \rangle = \int_S A \times B \cdot n dS, \quad (7)$$

这里 S 的方向定为区域的内法向.

采用伽略金法, 定义与展开函数相同的检验函数, 在 S_0, S_1 上取检验函数 $W_m = \Psi_m (m = 0, 1, \dots, N)$ 在 S_4, S_5 上取 $W_m = \Phi_m (m = 0, 1, \dots, N)$, 对方程组 (6) 的各式作外积, 得到如下几式:

$$\begin{aligned}
 & \sum_n V_n [\langle \Psi_m, L_0 \{ \Psi_n, 0, 0, 0, 0 \} \rangle_{s_0} + \langle \Psi_m, L_0 \{ 0, 0, \Theta_n, 0, 0 \} \rangle_{s_0} - \langle \Psi_m, L_{-1} \{ 0, \Psi_n \} \rangle_{s_0}] \\
 & + \sum_n U_n [\langle \Psi_m, L_0 \{ 0, \Psi_n, 0, 0, 0 \} \rangle_{s_0} + \langle \Psi_m, L_0 \{ 0, 0, 0, \Theta_n, 0 \} \rangle_{s_0} - e^{i\varphi} \langle \Psi_m, L_{-1} \{ \Psi_n, 0 \} \rangle_{s_0}] \\
 & + \sum_n M_n \langle \Psi_m, L_0 \{ 0, 0, 0, 0, \Phi_n \} \rangle_{s_0} = 0, \\
 & \sum_n V_n [\langle \Psi_m, L_0 \{ \Psi_n, 0, 0, 0, 0 \} \rangle_{s_1} + \langle \Psi_m, L_0 \{ 0, 0, \Theta_n, 0, 0 \} \rangle_{s_1} - e^{-i\varphi} \langle \Psi_m, L_1 \{ 0, \Psi_n \} \rangle_{s_1}] \\
 & + \sum_n U_n [\langle \Psi_m, L_0 \{ 0, \Psi_n, 0, 0, 0 \} \rangle_{s_1} + \langle \Psi_m, L_0 \{ 0, 0, 0, \Theta_n, 0 \} \rangle_{s_1} - \langle \Psi_m, L_1 \{ \Psi_n, 0 \} \rangle_{s_1}] \\
 & + \sum_n M_n \langle \Psi_m, L_0 \{ 0, 0, 0, 0, \Phi_n \} \rangle_{s_1} = 0, \\
 & \sum_n V_n [\langle \Phi_m, L_0 \{ \Psi_n, 0, 0, 0, 0 \} \rangle_{s_4} + \langle \Phi_m, L_0 \{ 0, 0, \Theta_n, 0, 0 \} \rangle_{s_4}], \\
 & + \sum_n U_n [\langle \Phi_m, L_0 \{ 0, \Psi_n, 0, 0, 0 \} \rangle_{s_4} + \langle \Phi_m, L_0 \{ 0, 0, 0, \Theta_n, 0 \} \rangle_{s_4}] \\
 & + \sum_n M_n [\langle \Phi_m, L_0 \{ 0, 0, 0, 0, \Phi_n \} \rangle_{s_4} - \langle \Phi_m, L_3 \{ \Phi_n, 0 \} \rangle_{s_4}] - \sum_n N_n \langle \Phi_m, L_3 \{ 0, \Phi_n \} \rangle_{s_4} = 0, \\
 & \sum_n M_n \langle \Phi_m, L_3 \{ \Phi_n, 0 \} \rangle_{s_5} + \sum_n N_n [\langle \Phi_m, L_3 \{ 0, \Phi_n \} \rangle_{s_5} - \langle \Phi_m, L_4 \{ \Phi_n \} \rangle_{s_5}] = 0. \tag{8}
 \end{aligned}$$

定义导纳矩阵元:

$$\begin{aligned}
 Y_{00,mn} &= \langle \Psi_m, L_0 \{ \Psi_n, 0, 0, 0, 0 \} \rangle_{s_0} - \langle \Psi_m, L_{-1} \{ 0, \Psi_n \} \rangle_{s_0}, & Y_{60,mn} &= \langle \Psi_m, L_{-1} \{ \Psi_n, 0 \} \rangle_{s_0}, \\
 Y_{10,mn} &= \langle \Psi_m, L_0 \{ 0, \Psi_n, 0, 0, 0 \} \rangle_{s_0}, & Y_{20,mn} &= \langle \Psi_m, L_0 \{ 0, 0, \Theta_n, 0, 0 \} \rangle_{s_0}, \\
 Y_{30,mn} &= \langle \Psi_m, L_0 \{ 0, 0, 0, \Theta_n, 0 \} \rangle_{s_0}, & Y_{40,mn} &= \langle \Psi_m, L_0 \{ 0, 0, 0, 0, \Phi_n \} \rangle_{s_0}, \\
 Y_{11,mn} &= \langle \Psi_m, L_0 \{ 0, \Psi_n, 0, 0, 0 \} \rangle_{s_1} - \langle \Psi_m, L_1 \{ \Psi_n, 0 \} \rangle_{s_1}, & Y_{71,mn} &= \langle \Psi_m, L_1 \{ 0, \Psi_n \} \rangle_{s_1}, \\
 Y_{01,mn} &= \langle \Psi_m, L_0 \{ \Psi_n, 0, 0, 0, 0 \} \rangle_{s_1}, & Y_{21,mn} &= \langle \Psi_m, L_0 \{ 0, 0, \Theta_n, 0, 0 \} \rangle_{s_1}, \\
 Y_{31,mn} &= \langle \Psi_m, L_0 \{ 0, 0, 0, \Theta_n, 0 \} \rangle_{s_1}, & Y_{41,mn} &= \langle \Psi_m, L_0 \{ 0, 0, 0, 0, \Phi_n \} \rangle_{s_1}, \\
 Y_{04,mn} &= \langle \Phi_m, L_0 \{ \Psi_n, 0, 0, 0, 0 \} \rangle_{s_4}, & Y_{14,mn} &= \langle \Phi_m, L_0 \{ 0, \Psi_n, 0, 0, 0 \} \rangle_{s_4}, \\
 Y_{24,mn} &= \langle \Phi_m, L_0 \{ 0, 0, \Theta_n, 0, 0 \} \rangle_{s_4}, & Y_{34,mn} &= \langle \Phi_m, L_0 \{ 0, 0, 0, \Theta_n, 0 \} \rangle_{s_4}, \\
 Y_{44,mn} &= \langle \Phi_m, L_0 \{ 0, 0, 0, 0, \Phi_n \} \rangle_{s_4} - \langle \Phi_m, L_3 \{ \Phi_n, 0 \} \rangle_{s_4}, & Y_{54,mn} &= \langle \Phi_m, L_3 \{ 0, \Phi_n \} \rangle_{s_4}, \\
 Y_{45,mn} &= \langle \Phi_m, L_3 \{ \Phi_n, 0 \} \rangle_{s_5}, & Y_{55,mn} &= \langle \Phi_m, L_3 \{ 0, \Phi_n \} \rangle_{s_5} - \langle \Phi_m, L_4 \{ \Phi_n \} \rangle_{s_5}. \tag{9}
 \end{aligned}$$

将 (9) 式代入 (8) 式得

$$\begin{aligned}
 & \sum_n (Y_{00,mn} + Y_{20,mn})V_n + \sum_n (Y_{10,mn} + Y_{30,mn} - e^{i\varphi} Y_{60,mn})U_n + \sum_n Y_{40,mn}M_n = 0, \\
 & \sum_n (Y_{01,mn} + Y_{21,mn} - e^{-i\varphi} Y_{71,mn})V_n + \sum_n (Y_{11,mn} + Y_{31,mn})U_n + \sum_n Y_{41,mn}M_n = 0, \\
 & \sum_n (Y_{04,mn} + Y_{24,mn})V_n + \sum_n (Y_{14,mn} + Y_{34,mn})U_n + \sum_n Y_{44,mn}M_n - \sum_n Y_{54,mn}N_n = 0, \\
 & \sum_n Y_{45,mn}M_n + \sum_n Y_{55,mn}N_n = 0, \quad m, n = 0, 1, \dots, N. \tag{10}
 \end{aligned}$$

根据 (9) 式得到广义导纳矩阵元的对称关系:

$$\begin{aligned}
 Y_{00,mn} &= Y_{11,mn}, & Y_{10,mn} &= Y_{01,mn}, & Y_{20,mn} &= Y_{31,mn}, & Y_{30,mn} &= Y_{21,mn}, \\
 Y_{60,mn} &= Y_{71,mn}, & Y_{40,mn} &= -Y_{41,mn}, & Y_{04,mn} &= Y_{24,mn} = -Y_{14,mn} = -Y_{34,mn}. \tag{11}
 \end{aligned}$$

将 (11) 式代入 (10) 式再将方程组用矩阵形式表示为

$$\begin{aligned} (Y_{00} + Y_{20})V + (Y_{10} + Y_{30} - e^{i\varphi}Y_{60})U + Y_{40}M &= 0, \\ (Y_{10} + Y_{30} - e^{-i\varphi}Y_{60})V + (Y_{00} + Y_{20})U - Y_{40}M &= 0, \\ 2Y_{04}V - 2Y_{04}U + Y_{44}M - Y_{54}N &= 0, \quad Y_{45}M + Y_{55}N = 0, \end{aligned} \quad (12)$$

其中, Y_{00} — Y_{55} 均为 $N+1$ 阶方阵, 各矩阵元仅与几何尺寸和频率相关, 基函数一旦给出后, 各导纳矩阵元的具体形式可由格林函数法求出 (见附录). 方程组中待求系数 V — N 为 $N+1$ 维列向量.

2.3 色散特性及耦合阻抗的具体形式

方程组 (12) 具有非零解的条件是系数矩阵行列式的值为零, 即

$$\begin{vmatrix} Y_{00} + Y_{20} & Y_{10} + Y_{30} - e^{i\varphi}Y_{60} & Y_{40} & 0 \\ Y_{10} + Y_{30} - e^{-i\varphi}Y_{60} & Y_{00} + Y_{20} & -Y_{40} & 0 \\ 2Y_{04} & -2Y_{04} & Y_{44} & -Y_{54} \\ 0 & 0 & Y_{45} & Y_{55} \end{vmatrix} = 0. \quad (13)$$

对双槽耦合腔链系统, 改变 φ 的值, 由 (13) 式求出相应的频率即为它的色散关系.

各公共界面上切向电场的基函数应是一组线性无关且能充分描述切向电场性质的函数组合^[16], 根据边界上切向电场的性质, 定义下列基函数^[17,18]:

$$\begin{aligned} \Psi_0 &= \frac{\hat{r}}{r} \cos\left(\frac{\pi\theta}{2\theta_0}\right), \\ \Theta_0 &= \frac{\hat{r}}{r} \cos\left(\frac{\pi(\theta - \pi)}{2\theta_0}\right), \\ \Phi_n &= \hat{z} \sqrt{\frac{1 + \delta_n}{2}} \cdot \frac{1}{g} \cos\left(\frac{n\pi z}{g}\right), \end{aligned} \quad (14)$$

式中

$$\delta_n = \begin{cases} 1, n = 0, \\ 0, n > 0. \end{cases}$$

这里为了简化计算, 耦合槽边界上的基函数只取一项 Ψ_0 和 Θ_0 . Φ_n 是一组在 $(-g, g)$ 上完备且正交的函数组.

在轴上第 s 次空间谐波耦合阻抗定义为

$$K_s = |A_s|^2 / 2\beta_s^2 P, \quad (15)$$

式中 A_s 是第 s 次空间谐波振幅, β_s 是第 s 次空间谐波波数, P 为系统中传输的功率.

考虑到轴上的自然边界条件, 诺依曼函数消失,

电子注通道间隙电场可写作

$$E_z = \sum_{s=-\infty}^{\infty} A_s \begin{cases} J_0(\gamma_s r) & k > |\beta_s| \\ I_0(\gamma_s r) & k < |\beta_s| \end{cases} e^{-j\beta_s z}. \quad (16)$$

在 $r = a$ 处满足边界条件

$$E_z|_{r=a} = \begin{cases} e_s, & |z| < g, \\ 0, & g \leq |z| \leq L, \end{cases} \quad (17)$$

那么

$$\begin{aligned} & \sum_{s=-\infty}^{\infty} A_s \begin{cases} J_0(\gamma_s a) & k > |\beta_s| \\ I_0(\gamma_s a) & k < |\beta_s| \end{cases} e^{-j\beta_s z} \\ &= \sum_{n=0}^{\infty} N_n \sqrt{\frac{1 + \delta_n}{2}} \cdot \frac{1}{g} \cos\left(\frac{n\pi z}{g}\right), \quad |z| < g. \end{aligned} \quad (18)$$

在 (18) 式两边同乘以 $e^{j\beta_q z}$ 并在区间 $(-g, g)$ 上积分, 仅当 $q = s$ 时, 有

$$\begin{aligned} A_s &= \frac{1}{L} \sum_{n=0}^{\infty} N_n \frac{(-1)^n}{1 - (n\pi/\beta_s g)^2} \\ & \quad \times \sqrt{\frac{1 + \delta_n}{2}} \frac{\sin(\beta_s g)}{\beta_s g} \\ & \quad \times \begin{cases} J_0^{-1}(\gamma_s a) & k > |\beta_s| \\ I_0^{-1}(\gamma_s a) & k < |\beta_s| \end{cases}, \end{aligned} \quad (19)$$

式中, $\gamma_s^2 = k^2 - \beta_s^2$.

对耦合腔结构, 慢波能量的传输通道是耦合槽, 因此, 忽略电子注通道能量传输的作用, 由 Poynting

定理及对称性得系统中传输的功率

$$\begin{aligned}
 P &= \frac{1}{2} \operatorname{Re} \int_{S_1} (e_1 \times H_1^*) \cdot dS \\
 &+ \frac{1}{2} \operatorname{Re} \int_{S_3} (e_3 \times H_2^*) \cdot dS \\
 &= \operatorname{Re} \int_{S_1} (e_1 \times H_1^*) \cdot dS \\
 &= \operatorname{Re} \left(\int_{S_1} \left[\sum_m U_m \Psi_m \right] \times \left[\left(\sum_n U_n L_1 \{ \Psi_n, 0 \} \right. \right. \right. \\
 &\quad \left. \left. \left. + e^{-i\varphi} \sum_n V_n L_1 \{ 0, \Psi_n \} \right) \right]_{S_1}^* \cdot dS_1 \right) \\
 &= \operatorname{Re} \left(e^{i\varphi} \sum_{m,n} U_m V_n^* Y_{71,mn}^* \right) \\
 &= \operatorname{Re} (e^{i\varphi} U_0 V_0^* Y_{60}^*).
 \end{aligned} \tag{20}$$

在轴上第 s 次空间谐波耦合阻抗为

$$\begin{aligned}
 K_s &= |A_s|^2 / 2\beta_s^2 P \\
 &= \frac{\left| \frac{1}{L} \sum_{n=0}^{\infty} \frac{N_n}{U_0} \frac{(-1)^n}{1 - (n\pi/\beta_s g)^2} \sqrt{\frac{1 + \delta_n}{2}} \frac{\sin(\beta_s g)}{\beta_s g} \begin{cases} J_0^{-1}(\gamma_s a) & k > |\beta_s| \\ I_0^{-1}(\gamma_s a) & k < |\beta_s| \end{cases} \right|^2}{2\beta_s^2 \operatorname{Re} \left(e^{i\varphi} \left(\frac{V_0}{U_0} \right)^* Y_{60}^* \right)}.
 \end{aligned} \tag{21}$$

3 计算结果及讨论

为验证本文方法的正确性, 将上述理论推导得到的色散特性及耦合阻抗, 即 (13) 式和 (21) 式, 用 MATLAB 实现数值计算. 以 X 波段为例, 耦合腔慢波结构的几何尺寸设置如表 1 所示. 图 3 给出了 Chodorow 结构高频特性计算结果与仿真软件 HFSS^[15] 以及等效电路法^[6,7] 的计算结果对比. 将 HFSS 的计算结果作为参考值, 可以看出, 本文理论计算的精度明显高于等效电路法. 图 3(a) 显示理论计算腔模和槽模的色散特性最大误差分别不超过 0.5% 和 4%, 而等效电路法这两个误差分别达到了 3% 和 16%, 图 3(b) 中给出了 -1 次空间谐波耦合阻抗的计算结果, 理论计算与软件仿真基本一致, 而等效电路法则在低频端有较大误差, 从而验证了场论方法分析双槽耦合腔慢波结构特性的准确性.

表 1 耦合腔慢波结构尺寸表

参数	几何尺寸
耦合腔半径 D/mm	7.8
漂移管外半径 d/mm	3.5
漂移管内半径 a/mm	2.5
耦合槽中心半径 F/mm	5.4
耦合槽半径 R/mm	1.5
漂移管间隙半宽度 g/mm	1.5
耦合腔半腔高 h/mm	3.7
耦合腔半壁厚 l/mm	1
耦合槽半张角 $\theta_0/(\circ)$	47.5°

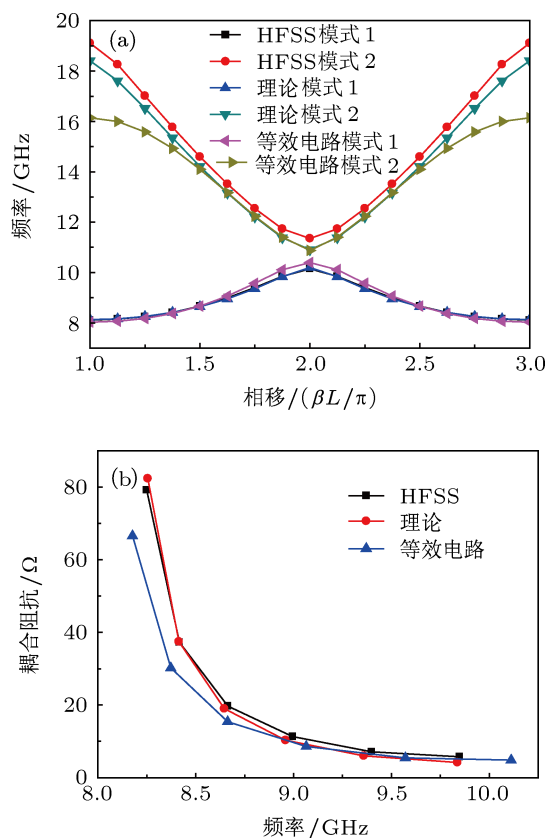


图 3 Chodorow 结构软件仿真与理论以及等效电路法计算得到的高频特性对比 (a) 色散特性; (b) -1 次谐波耦合阻抗

与等效电路法相比, 本文方法除具有精确度高的优点外, 计算中的普适性也使得其在实际应用中更为方便, 包括: 1) 可以对各个模式的色散特性以及各次谐波的耦合阻抗进行计算, 而等效电路法腔模和槽模的计算需要不同的公式且只能计算总阻

抗,上一节图 3(b) 中的等效电路法的耦合阻抗曲线是通过 Connolly 给出的总阻抗与耦合阻抗间的关系式得到的,这个式子也是通过场论分析得到的^[19]; 2) 在等效电路法中,需要考虑电子注通道的存在对漂移头处电场的加强作用,加入一个修正参数调节间隙电容,这个参数是与频率和几何尺寸相关的经验值,对结果影响很大^[8],使用本文方法则仅需输入几何参数即可直接运算得到结果.从计算时间上看,虽然不及等效电路法高效,但与软件仿真相比,本文方法却能够有效节省机时,如上面的计算过程中 e_4 和 e_5 取迭代次数为 3,其他级数项取前 10×10 项,计算时间约为 3 min,仅为 HFSS 的 1/4,再增加迭代次数,结果的相对变化小于 0.1%,计算时间却会持续增加,当 e_4 和 e_5 取迭代次数为 7 时约需 7 min (测试计算机为 E7500@2.93 GHz, 2G DDR2).

本文方法理论上是利用边界条件严格求解 Maxwell 方程的,然而在实际计算中,存在以下两个方面的近似: 1) 在定义基函数时,为了减少计算量,耦合槽边界上的基函数由无限项 Ψ_n 和 Θ_n 被简化为一项,即 Ψ_0 和 Θ_0 ; 2) 格林函数法只能计

算各规则区域中的场,因此,在本文方法中,腰形槽被近似作扇形槽.这种角度的近似又有两种方式,如图 4 所示.图 4(a) 近似前后耦合槽面积一致 $2\theta' = 2\theta_0 + 90^\circ \cdot R/F$; 图 4(b) 近似后的扇形耦合槽面积增加 $2\theta' = 2\theta_0 + (360^\circ/\pi) \cdot R/F$.为了考察这些近似造成的误差,图 5 比较了 Chodorow 结构在不同计算方法和不同耦合槽近似方式下的色散特性,以 HFSS 计算的腰形槽结构的结果作参考值,首先比较耦合槽近似方式的影响.可以看出, HFSS 计算的以方式 (a) 近似的扇形槽耦合腔结构的色散曲线与参考值达到了高度的一致性,即只要保持面积一致,耦合槽的形状不会对计算结果产生大的影响. HFSS 计算的以方式 (b) 近似的扇形槽耦合腔结构的色散曲线低于参考值,并且低频端的误差大于高频端.这是由于耦合槽面积的增加导致了槽谐振频率的降低造成的.接着比较耦合槽边界上基函数的简化造成的影响.从图中可以看出采用本文方法计算的以方式 (a) 近似的扇形槽耦合腔结构的色散曲线高于参考值,因为这里耦合槽近似前后耦合槽面积一致,所以误差只可能是由于耦合槽边界上基函

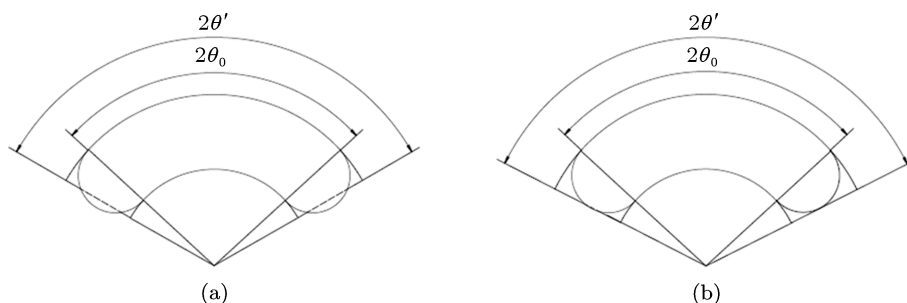


图 4 腰形槽近似作扇形槽 (a) 近似前后耦合槽面积一致; (b) 近似后的扇形耦合槽面积增加

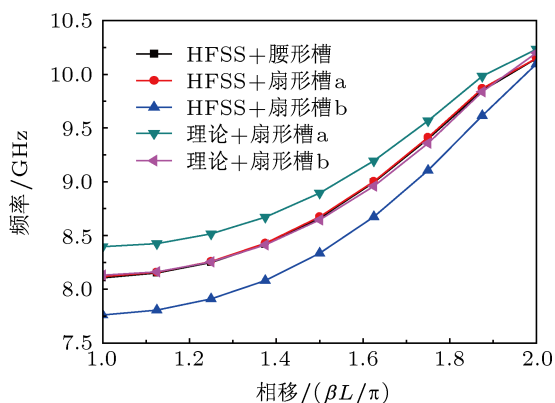


图 5 不同计算方法在不同耦合槽近似方式下的色散特性对比

(b) 近似的扇形槽耦合腔结构的色散曲线则与参考曲线基本重合,在这一计算过程中,同时具有两种近似,说明在考察的频段范围内,高精度可能是两种近似引起的误差相互抵消所致.

4 结论

本文用经典的场匹配法结合并矢格林函数,推导出 Chodorow 型耦合腔慢波结构的色散特性和耦合阻抗计算式.利用数值方法在 X 波段对色散特性和耦合阻抗进行了计算.结果表明,本文计算结果与仿真软件 HFSS 的计算结果相符合,二者腔模和

槽模的色散特性最大误差分别不超过 0.5% 和 4%, 轴上的 -1 次空间谐波耦合阻抗在全频段基本一致, 精度远高于等效电路法. 此外, 本文方法计算效率很高, 仅需 HFSS 仿真时间的 1/4 即可得到足够精度的结果. 误差的分析表明, 以本文方法计算时, 耦合槽边界上基函数的简化会导致腔模色散特性频率偏高, 而以增大面积的扇形槽替代腰形槽会导

致腔模色散特性频率偏低, 因此两种误差的相互抵消在所计算的频段范围内有效地改善了计算精度.

附录

导纳矩阵元的具体形式 (由于耦合槽边界上的场只用一项基函数展开, 矩阵 $Y_{00}, Y_{10}, Y_{20}, Y_{30}$ 和 Y_{60} 简化为一个矩阵元, Y_{40} 退化为行向量, Y_{04} 退化为列向量)

$$\begin{aligned}
 Y_{00} = & -i\omega\varepsilon_0 \left\{ \sum_{p,q} \frac{(2-\delta_p)\{S_p[\lambda_{pq}(F+R)]-S_p[\lambda_{pq}(F-R)]\}^2\eta_p^2}{2\pi\lambda_{pq}^2 k_{\lambda_{pq}} I_{\lambda_{pq}}} \cdot \begin{cases} 1/\tan(2k_{\lambda_{pq}}h) & k > \lambda_{pq} \\ -1/\tanh(2k_{\lambda_{pq}}h) & k < \lambda_{pq} \end{cases} \right. \\
 & + \sum_{p,q} \frac{k_{\mu_{pq}}\eta_p^2 p^2}{\pi k^2 \mu_{pq}^2 I_{\mu_{pq}}} \left[\int_{F-R}^{F+R} T_p(\mu_{pq}r) \frac{1}{r} dr \right]^2 \cdot \begin{cases} 1/\tan(2k_{\mu_{pq}}h) & k > \mu_{pq} \\ 1/\tanh(2k_{\mu_{pq}}h) & k < \mu_{pq} \end{cases} + \frac{8\theta'^2}{\pi^3 k I_0} \left(\ln \frac{F+R}{F-R} \right)^2 \frac{1}{\tan(2kh)} \\
 & \left. + \sum_q \frac{\pi^2 k \tau_q}{4\theta' k^2 \tau_q^2 I_{\alpha q}} \left(\int_{F-R}^{F+R} T_\alpha(\tau_q r) \frac{1}{r} dr \right)^2 \cdot \begin{cases} 1/\tan(2k_{\tau_q}l) & k > \tau_q \\ 1/\tanh(2k_{\tau_q}l) & k < \tau_q \end{cases} \right\}, \\
 S_p(\lambda_{pq}r) = & J_p(\lambda_{pq}r)N_p(\lambda_{pq}d) - N_p(\lambda_{pq}r)J_p(\lambda_{pq}d), \quad p=0,1,2,\dots, q=1,2,\dots \\
 S_p(\lambda_{pq}D) = & 0, \quad k_{\lambda_{pq}} = \sqrt{|k^2 - \lambda_{pq}^2|}, \\
 T_p(\mu_{pq}r) = & J_p(\mu_{pq}r)N'_p(\mu_{pq}d) - N_p(\mu_{pq}r)J'_p(\mu_{pq}d), \quad p=1,2,3,\dots, q=1,2,\dots \\
 T'_p(\mu_{pq}D) = & 0, \quad k_{\mu_{pq}} = \sqrt{|k^2 - \mu_{pq}^2|}, \\
 T_\alpha(\tau_q r) = & J_\alpha(\tau_q r)N'_\alpha[\tau_q(F-R)] - N_\alpha(\tau_q r)J'_\alpha[\tau_q(F-R)], \quad q=1,2,\dots \quad \alpha = \frac{\pi}{2\theta'} \\
 T'_\alpha[\tau_q(F+R)] = & 0, \quad k_{\tau_q} = \sqrt{|k^2 - \tau_q^2|}, \\
 I_{\lambda_{pq}} = & \int_d^D S_p^2(\lambda_{pq}r)rdr, \quad I_{\mu_{pq}} = \int_d^D T_p^2(\mu_{pq}r)rdr, \quad I_{\alpha q} = \int_{F-R}^{F+R} T_\alpha^2(\tau_q r)rdr, \quad I_0 = \ln\left(\frac{D}{d}\right), \\
 \eta_p = & \int_{-\theta'}^{\theta'} \cos(p\theta) \cos\left(\frac{\pi\theta}{2\theta'}\right) d\theta = \frac{4\pi\theta'}{\pi^2 - 4p^2\theta'^2} \cos(p\theta'), \\
 Y_{10} = & i\omega\varepsilon_0 \left\{ \sum_{p,q} \frac{(2-\delta_p)\{S_p[\lambda_{pq}(F+R)]-S_p[\lambda_{pq}(F-R)]\}^2\eta_p^2}{2\pi\lambda_{pq}^2 k_{\lambda_{pq}} I_{\lambda_{pq}}} \cdot \begin{cases} 1/\sin(2k_{\lambda_{pq}}h) & k > \lambda_{pq} \\ -1/\sinh(2k_{\lambda_{pq}}h) & k < \lambda_{pq} \end{cases} \right. \\
 & + \sum_{p,q} \frac{k_{\mu_{pq}}\eta_p^2 p^2}{\pi k^2 \mu_{pq}^2 I_{\mu_{pq}}} \left[\int_{F-R}^{F+R} T_p(\mu_{pq}r) \frac{1}{r} dr \right]^2 \cdot \begin{cases} 1/\sin(2k_{\mu_{pq}}h) & k > \mu_{pq} \\ 1/\sinh(2k_{\mu_{pq}}h) & k < \mu_{pq} \end{cases} \\
 & \left. + \frac{8\theta'^2}{\pi^3 k I_0} \left(\ln \frac{F+R}{F-R} \right)^2 \frac{1}{\sin(2kh)} \right\}, \\
 Y_{20} = & -i\omega\varepsilon_0 \left\{ \sum_{p,q} \frac{(2-\delta_p)\{S_p[\lambda_{pq}(F+R)]-S_p[\lambda_{pq}(F-R)]\}^2(-1)^p\eta_p^2}{2\pi\lambda_{pq}^2 k_{\lambda_{pq}} I_{\lambda_{pq}}} \cdot \begin{cases} 1/\tan(2k_{\lambda_{pq}}h) & k > \lambda_{pq} \\ -1/\tanh(2k_{\lambda_{pq}}h) & k < \lambda_{pq} \end{cases} \right. \\
 & + \sum_{p,q} \frac{k_{\mu_{pq}}(-1)^p\eta_p^2 p^2}{\pi k^2 \mu_{pq}^2 I_{\mu_{pq}}} \left[\int_{F-R}^{F+R} T_p(\mu_{pq}r) \frac{1}{r} dr \right]^2 \cdot \begin{cases} 1/\tan(2k_{\mu_{pq}}h) & k > \mu_{pq} \\ 1/\tanh(2k_{\mu_{pq}}h) & k < \mu_{pq} \end{cases} \\
 & \left. + \frac{8\theta'^2}{\pi^3 k I_0} \left(\ln \frac{F+R}{F-R} \right)^2 \frac{1}{\tan(2kh)} \right\}, \\
 Y_{30} = & i\omega\varepsilon_0 \left\{ \sum_{p,q} \frac{(2-\delta_p)\{S_p[\lambda_{pq}(F+R)]-S_p[\lambda_{pq}(F-R)]\}^2(-1)^p\eta_p^2}{2\pi\lambda_{pq}^2 k_{\lambda_{pq}} I_{\lambda_{pq}}} \cdot \begin{cases} 1/\sin(2k_{\lambda_{pq}}h) & k > \lambda_{pq} \\ -1/\sinh(2k_{\lambda_{pq}}h) & k < \lambda_{pq} \end{cases} \right. \\
 & + \sum_{p,q} \frac{k_{\mu_{pq}}(-1)^p\eta_p^2 p^2}{\pi k^2 \mu_{pq}^2 I_{\mu_{pq}}} \left[\int_{F-R}^{F+R} T_p(\mu_{pq}r) \frac{1}{r} dr \right]^2 \cdot \begin{cases} 1/\sin(2k_{\mu_{pq}}h) & k > \mu_{pq} \\ 1/\sinh(2k_{\mu_{pq}}h) & k < \mu_{pq} \end{cases} \\
 & \left. + \frac{8\theta'^2}{\pi^3 k I_0} \left(\ln \frac{F+R}{F-R} \right)^2 \frac{1}{\sin(2kh)} \right\},
 \end{aligned}$$

$$\begin{aligned}
 & + \frac{8\theta'^2}{\pi^3 k I_0} \left(\ln \frac{F+R}{F-R} \right)^2 \frac{1}{\sin(2kh)} \Bigg\}, \\
 Y_{60} = & -i\omega\epsilon_0 \sum_q \frac{\pi^2 k_{\tau q}}{4\theta' k^2 \tau_q^2 I_{\alpha q}} \left(\int_{F-R}^{F+R} T_{\alpha}(\tau_q r) \frac{1}{r} dr \right)^2 \cdot \begin{cases} 1/\sin(2k_{\tau q} l) & k > \tau_q \\ 1/\sinh(2k_{\tau q} l) & k < \tau_q \end{cases}, \\
 Y_{40,0n} = & 4i\omega\epsilon_0 \frac{\theta'}{\pi h} \left\{ \frac{\delta_n}{F_{00}(d,D)} \int_{F-R}^{F+R} F_{10}(r,D) dr + \sum_{s=1}^{\infty} \frac{(-1)^{n+s} \sqrt{2(1+\delta_n)} \operatorname{sinc}(s\pi g/h)}{(1-(nh/sg)^2) F_{0s}(d,D)} \int_{F-R}^{F+R} F_{1s}(r,D) dr \right\}, \\
 F_{1s}(r,r') = & \begin{cases} J_1(\gamma_s r) N_0(\gamma_s r') - J_0(\gamma_s r') N_1(\gamma_s r) & k > s\pi/h \\ I_1(\gamma_s r) K_0(\gamma_s r') + I_0(\gamma_s r') K_1(\gamma_s r) & k < s\pi/h \end{cases}, \\
 F_{0s}(r,r') = & \gamma_s \begin{cases} J_0(\gamma_s r) N_0(\gamma_s r') - J_0(\gamma_s r') N_0(\gamma_s r) & k > s\pi/h \\ I_0(\gamma_s r) K_0(\gamma_s r') - I_0(\gamma_s r') K_0(\gamma_s r) & k < s\pi/h \end{cases}, \\
 \gamma_s = & \sqrt{|k^2 - (s\pi/h)^2|}, \\
 Y_{04,m0} = & i\omega\epsilon_0 \frac{\sqrt{2(1+\delta_m)} (-1)^m}{g} \left\{ \frac{2\theta' \sin(kg)}{\pi k^2 I_0 \sin(kh) (1 - (m\pi/kg)^2)} \ln \frac{F+R}{F-R} \right. \\
 & \left. + \sum_q \frac{\{S_0[\lambda_{0q}(F+R)] - S_0[\lambda_{0q}(F-R)]\} \eta_0 d S'_0(\lambda_{0q} d) A_{k\lambda_{0q}}}{2\lambda_{0q}^2 k_{\lambda_{0q}}^2 J_{\lambda_{0q}}} \right\}, \\
 A_{k\lambda_{0q}} = & \begin{cases} \frac{\sin(k\lambda_{0q} g)}{\sin(k\lambda_{0q} h) (1 - (m\pi/k\lambda_{0q} g)^2) - \sinh(k\lambda_{0q} g)} & k > \lambda_{0q}, \\ \frac{\sinh(k\lambda_{0q} h)}{\sinh(k\lambda_{0q} h) (1 + (m\pi/k\lambda_{0q} g)^2)} & k < \lambda_{0q}, \end{cases} \\
 Y_{44,mm} = & -i\omega\epsilon_0 \pi d \left\{ 4\delta_m \delta_n \frac{F_{10}(d,D)}{h F_{00}(d,D)} + \sum_{s=1}^{\infty} \frac{4(-1)^{m+n} \sqrt{(1+\delta_m)(1+\delta_n)} \operatorname{sinc}^2(s\pi g/h)}{h(1-(mh/sg)^2)(1-(nh/sg)^2)} \frac{F_{1s}(d,D)}{F_{0s}(d,D)} \right. \\
 & \left. - (1+\delta_m)^2 \delta_{m-n} \frac{F_{1n}(d,a)}{g F_{0n}(d,a)} \right\},
 \end{aligned}$$

$F_{1n}(r,r')$, $F_{0n}(r,r')$ 与 $F_{1s}(r,r')$, $F_{0s}(r,r')$ 的形式相同, 仅把 h 换成 g ,

$$\begin{aligned}
 Y_{54,mm} = & i\omega\epsilon_0 \pi d (1+\delta_m)^2 \delta_{m-n} \frac{F_{1n}(d,d)}{g F_{0n}(a,d)}, \\
 Y_{45,mm} = & i\omega\epsilon_0 \pi a (1+\delta_m)^2 \delta_{m-n} \frac{F_{1n}(a,a)}{g F_{0n}(d,a)}, \\
 Y_{55,mm} = & -i\omega\epsilon_0 \pi a \left\{ (1+\delta_m)^2 \delta_{m-n} \frac{F_{1n}(a,d)}{g F_{0n}(a,d)} - \sum_{s=-\infty}^{\infty} \frac{2(-1)^{m+n} \sqrt{(1+\delta_m)(1+\delta_n)} \operatorname{sinc}^2(\beta_s g)}{\gamma_s L (1 - (m\pi/\beta_s g)^2) (1 - (n\pi/\beta_s g)^2)} \right. \\
 & \left. \times \begin{cases} J_1(\gamma_s a)/J_0(\gamma_s a) & k > |\beta_s| \\ I_1(\gamma_s a)/I_0(\gamma_s a) & k < |\beta_s| \end{cases} \right\}, \\
 \beta_s = & \frac{\phi + 2s\pi}{2L}, \quad \gamma_s = \sqrt{|k^2 - \beta_s^2|}.
 \end{aligned}$$

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Analysis of the dispersion and interaction impedance for a coupled cavity slow wave structure with double in-line slots in TWT*

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Abstract

An analytical model is presented in this paper for a coupled cavity slow-wave structure (CCSWS) with double in-line slots, also known as the "Chodorow" structure. Under matching boundary conditions in conjunction with Green's function techniques and moment method (MOM), the formulae for discussing the high frequency characteristics of the SWS, including dispersion and interaction impedance, are given. The frequency characteristics for an X band Chodorow structure are calculated using these formulae, Ansoft HFSS code and equivalent circuit model. Results show that the dispersion and interaction impedance obtained with the formulae are in good agreement with those calculated by Ansoft HFSS code, while its calculation rate is more rapid than that with the code, and its calculation precision is higher than that with equivalent circuit method, which is helpful for the engineering design.

Keywords: Chodorow structure coupled cavity SWS, dispersion, interaction impedance, field matching method

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