

对接波导的缝隙耦合特性*

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摘要 本文介绍由长缝隙耦合的端头对接的波导接头的电特性. 利用伽略金法求解缝隙口面上等效磁流, 获得散射场及其等效参量的通用表达式. 波导尺寸, 缝隙尺寸和位置是任意的, 给出了数值计算实例和实验数据, 二者相吻合.

关键词: 波导接头; 耦合; 缝隙; 矩量法

1. 前言

在天线馈线或微波测量中, 需要把各种器件对接起来组成一个系统. 实际上, 有时难以把两个器件口对口的直接连接起来, 而需要一个过渡接头. 具有大孔耦合的波导段或接头是一种实用的接头, 不仅如此, 在波导气体放电管和滤波器等微波器件中也常采用大孔耦合结构. 由于小孔耦合机理和工程应用已较成熟, 所以人们常以小孔耦合理论为基础进行修正来说明大孔耦合特性; 或者利用等效电路的方法, 假定缝隙处于谐振状态来讨论长缝隙电特性. 本文利用场的边界条件和等效原理建立较严格的积分方程, 采用矩量法求出等效磁流数值解, 获得散射场和等效参数.

2. 等效磁流的求解

图1是本文研究的具有缝隙耦合的对接波导的结构示意图; 图2为纵向剖面; 图3为缝隙及其在横截面上位置坐标; 图4为缝隙腔剖面, M_1 , M_2 是缝隙面上等效磁流密度, $M = E \times \hat{n}$.

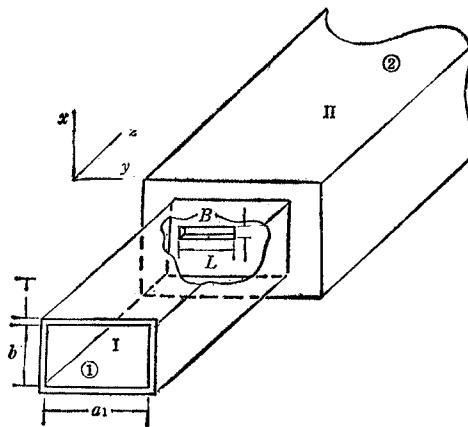


图1 对接波导结构示意图

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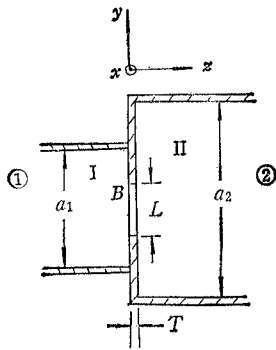


图2 对接波导纵向剖面图

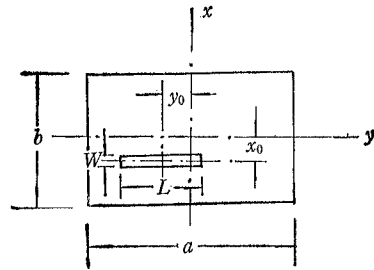


图3 缝隙及其位置坐标

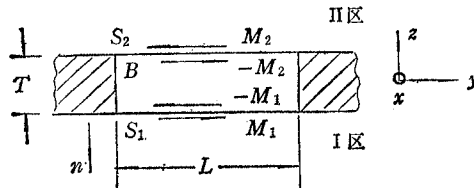


图4 缝隙腔和等效磁流

根据缝隙面 S_1 和 S_2 上磁场连续条件,有

$$-H_y^I + H_y^B = 2H_{iy}, \quad \mathbf{r} \in S_1 \tag{1}$$

$$H_y^{II} - H_y^B = 0, \quad \mathbf{r} \in S_2 \tag{2}$$

其中 H_{iy} 为入射场的磁场 y 向分量, H_y^I 为 M_1 在 I 区的散射场, H_y^{II} 为 M_2 在 II 区的散射场, H_y^B 为 M_1 和 M_2 在 B 区的散射场.

利用磁流对应的位函数 $F = \iint \bar{\mathbf{G}} \cdot \mathbf{M} dS$, 及其与场的关系可得

$$H_y = \frac{1}{j\omega\mu} \left(k^2 + \frac{d^2}{dy^2} \right) \iint_{S_k} G^{yy} \mathbf{M} dS'_k \tag{3}$$

于是可把(1)和(2)式写成算符方程

$$(L_{11}^I + L_{11}^B)M_1(\mathbf{r}') + L_{22}M_2(\mathbf{r}') = 2H_{iy}(\mathbf{r}) \tag{4}$$

$$L_{21}M_1(\mathbf{r}') + (L_{22}^{II} + L_{22}^B)M_2(\mathbf{r}') = 0 \tag{5}$$

其中

$$\left. \begin{aligned} L_{11}^I \\ L_{11}^B \end{aligned} \right\} = \frac{-1}{j\omega\mu} \left(k^2 + \frac{d^2}{dy^2} \right) \iint_{S_1} \left\{ \begin{aligned} G_{11}^{yy}(\mathbf{r}, \mathbf{r}') \\ G_{21}^{yy}(\mathbf{r}, \mathbf{r}') \end{aligned} \right\} dS'_1$$

$$L_{12} = \frac{1}{j\omega\mu} \left(k^2 + \frac{d^2}{dy^2} \right) \iint_{S_2} G_B^{yy}(\mathbf{r}, \mathbf{r}') dS'_2$$

$$L_{21} = L_{12} |_{S_2, S'_2 \rightarrow S_1, S'_1}$$

$$\left. \begin{aligned} L_{22}^{II} \\ L_{22}^B \end{aligned} \right\} = \frac{-1}{j\omega\mu} \left(k^2 + \frac{d^2}{dy^2} \right) \iint_{S_2} \left\{ \begin{aligned} G_{II}^{yy}(\mathbf{r}, \mathbf{r}') \\ G_B^{yy}(\mathbf{r}, \mathbf{r}') \end{aligned} \right\} dS'_2$$

式中各区域的并矢格林函数 G^{yy} 可引用文献[1]和[2]的结果。

我们令磁流源为

$$M_k = \sum_{q=1}^N a_q^{(k)} f_q^{(k)}, \quad f_q^{(k)} = \sin \frac{q\pi}{L} \left(y' + \frac{L}{2} \right), \quad k=1, 2 \quad (6)$$

取检验函数

$$g_p^{(k)} = \sin \frac{p\pi}{L} \left(y + \frac{L}{2} \right), \quad k=1, 2 \quad (7)$$

对(4)和(5)式取内积, 可将其化成矩阵方程

$$\left[\begin{bmatrix} [A^I] & [B] \\ [C] & [D^{II}] \end{bmatrix} + \begin{bmatrix} [A^B] & [0] \\ [0] & [D^B] \end{bmatrix} \right] \begin{bmatrix} [a^{(1)}] \\ [a^{(2)}] \end{bmatrix} = \begin{bmatrix} [h] \\ [0] \end{bmatrix} \quad (8)$$

经过推导获得(8)式中各元素的表达式

$$\begin{aligned} A_{pq}^I &= \langle g_p^{(1)}, L_{11}^{I(q)} \rangle_{S_1} \\ &= \frac{2W^2}{\omega\mu ab} \sum_{n=0}^{\infty} \sum_{m=1}^{\infty} \left[S_a \left(\frac{n\pi W}{2b} \right) \cos \frac{n\pi}{b} \left(x_0 + \frac{W}{2} \right) \right]^2 \left[k^2 - \left(\frac{m\pi}{a} \right)^2 \right] \\ &\quad \times \frac{\varepsilon_{0n} \frac{p\pi}{L} \frac{q\pi}{L} U_{mn}^{-1}}{\left[\left(\frac{m\pi}{a} \right)^2 - \left(\frac{p\pi}{L} \right)^2 \right] \left[\left(\frac{m\pi}{a} \right)^2 - \left(\frac{q\pi}{L} \right)^2 \right]} \left[\sin \frac{m\pi}{a} y_0 - (-1)^p \sin \frac{m\pi}{a} (y_0 + L) \right] \\ &\quad \times \left[\sin \frac{m\pi}{a} y_0 - (-1)^q \sin \frac{m\pi}{a} (y_0 + L) \right] \quad (9) \end{aligned}$$

$$A_{pq}^B = \langle g_p^{(1)}, L_{11}^{B(q)} \rangle_{S_1} = \frac{1}{j\omega\mu} \frac{WL}{2} k_L \cot k_L T \delta_{pq} \quad (10)$$

式中

$$U_{mn} = \begin{cases} \sqrt{k^2 - k_{mn}^2}, & k^2 \geq k_{mn}^2; \quad k_{mn}^2 = \left(\frac{m\pi}{a} \right)^2 + \left(\frac{n\pi}{b} \right)^2; \\ -j\sqrt{k_{mn}^2 - k^2}, & k^2 < k_{mn}^2 \end{cases}$$

$$k_L^2 = k^2 - \left(\frac{p\pi}{L} \right)^2; \quad \delta_{pq} = \begin{cases} 0, & p \neq q \\ 1, & p = q \end{cases}; \quad \varepsilon_{0n} = \begin{cases} 2, & n \neq 0 \\ 1, & n = 0 \end{cases}$$

$$B_{pq} = \langle g_p^{(1)}, L_{12}^{I(q)} \rangle_{S_1} = \frac{-1}{j\omega\mu} \frac{WL}{2} k_L (\sin k_L T)^{-1} \delta_{pq} \quad (11)$$

$$C_{pq} = \langle g_p^{(2)}, L_{21}^{I(q)} \rangle_{S_2} = B_{pq} \quad (12)$$

$$D_{pq}^{II} = A_{pq}^I |_{a,b,x_0,y_0 \rightarrow a_2,b_2,x_2,y_2} \quad (13)$$

$$D_{pq}^B = A_{pq}^B \quad (14)$$

$$\begin{aligned} h_p &= \langle g_p^{(1)}, 2H_{iy} \rangle_{S_1} \\ &= \frac{-2W p\pi/L}{\left(\frac{\pi}{a} \right)^2 - \left(\frac{p\pi}{L} \right)^2} \left[\cos \frac{\pi}{a} \left(y_0 - \frac{L}{2} \right) - (-1)^p \cos \frac{\pi}{a} \left(y_0 + \frac{L}{2} \right) \right] \quad (15) \end{aligned}$$

(9)和(15)式中有关 a, b, x_0, y_0 分别对应 a_1, b_1, x_1, y_1 。

如果波导壁厚度 $T \rightarrow 0$, 问题就变得更加简单了, 这时 $a^{(1)} = a^{(2)} = a^{(0)}$, (8)式应改成

$$[[A^I] + [D^{II}]]a^{(0)} = [h] \tag{16}$$

3. 散射场和等效参数

获得 M_1 和 M_2 之后, 利用(3)式可求得散射场

$$H_y^I = \frac{1}{j\omega\mu} \sum_{q=1}^N a_q^{(1)} \left(k^2 + \frac{d^2}{dy^2} \right) \iint_{S_1} G_y^y(\mathbf{r}, \mathbf{r}') f_q(\mathbf{r}') dS_1' \tag{17}$$

$$H_y^{II} = H_y^I \Big|_{a_q^{(1)}, a_1, b_1, y_1, z \rightarrow a_q^{(2)}, a_2, b_2, y_2, -z} \tag{18}$$

利用求得的散射场, 并假定波导中仅传输 H_{10} 模, 由波导 I 的①口激励, 得到的散射参量为

$$S_{11} = 1 + \frac{2W}{\omega\mu a_1 b_1} \sqrt{k^2 - \left(\frac{\pi}{a_1}\right)^2} \left\{ \sum_{q=1}^N a_q^{(1)} \frac{q\pi/L}{\left(\frac{\pi}{a_1}\right)^2 - \left(\frac{q\pi}{L}\right)^2} \left[\cos \frac{\pi}{a_1} \left(y_1 - \frac{L}{2} \right) - (-1)^q \cos \frac{\pi}{a_1} \left(y_1 + \frac{L}{2} \right) \right] \right\} \tag{19}$$

$$S_{21} = \frac{-2W}{\omega\mu a_2 b_2} \sqrt{k^2 - \left(\frac{\pi}{a_2}\right)^2} \left\{ \sum_{q=1}^N a_q^{(2)} \frac{q\pi/L}{\left(\frac{\pi}{a_2}\right)^2 - \left(\frac{q\pi}{L}\right)^2} \left[\cos \frac{\pi}{a_2} \left(y_2 - \frac{L}{2} \right) - (-1)^q \cos \frac{\pi}{a_2} \left(y_2 + \frac{L}{2} \right) \right] \right\} \tag{20}$$

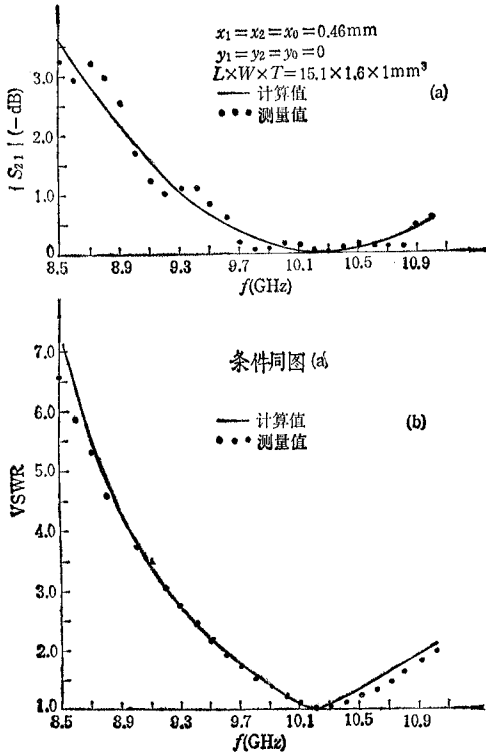


图5 共轴波导接头的 $|S_{21}|$ 和 VSWR 随 f 的变化

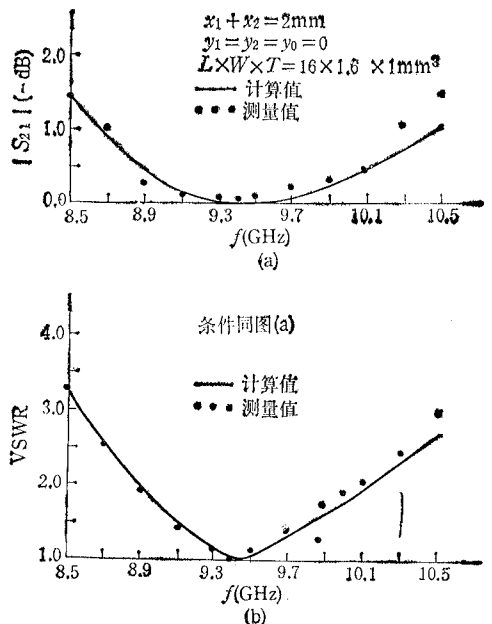


图6 窄边错开波导接头的 $|S_{21}|$ 和 VSWR 随 f 的变化

4. 数值计算和实验结果

在 X 波段,波导 I,II 尺寸相同,即 $a_1 = a_2 = a = 22.86\text{mm}$, $b_1 = b_2 = b = 10.16\text{mm}$, 壁厚 $T = 1\text{mm}$ 时,我们对四种不同位置相对接的波导接头的缝隙耦合特性进行了数值计算和实际测试,得到的传输系数 $|S_{21}|$ 和电压驻波比 VSWR 随工作频率的变化规律绘于图 5—图 8 中。图 5 为波导 I,II 轴线重合,缝隙位置仅沿 x 向偏移, $x_1 = x_2 = x_0 = 0.46\text{mm}$, $y_1 = y_2 = y_0 = 0$, 槽尺寸 $L \times W = 15.1 \times 1.6\text{mm}^2$ 。图 6 是波导 I, II 轴线仅沿 x 向偏移的接头结果,二轴线沿 x 偏移 2mm ($x_1 = 1\text{mm}$, $x_2 = -1\text{mm}$), $y_1 = y_2 = y_0 = 0$, $L \times W = 16 \times 1.6\text{mm}^2$ 。图 7 是波导 I, II 轴线仅沿 y 轴偏 2mm 的接头结果, $y_1 = 1\text{mm}$, $y_2 = -1\text{mm}$, $x_1 = x_2 = x_0 = 0$, $L \times W = 16 \times 1.6\text{mm}^2$ 。图 8 是波导 I, II 轴线沿 x, y 轴分别偏移 2mm 的情况, $x_1 = 1\text{mm}$, $x_2 = -1\text{mm}$, $y_1 = 1\text{mm}$, $y_2 = -1\text{mm}$, $L \times W = 16 \times 1.6\text{mm}^2$ 。

由图 5—图 8 的结果可见,除传输系数的测试值出现波动外,计算与实验结果相吻合,特别是在缝隙的谐振频率附近二者吻合得相当好。

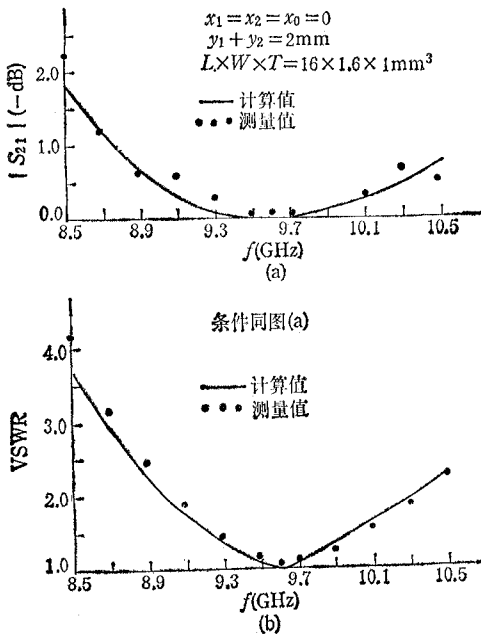


图 7 宽边错开波导接头的 $|S_{21}|$ 和 VSWR 随 f 的变化

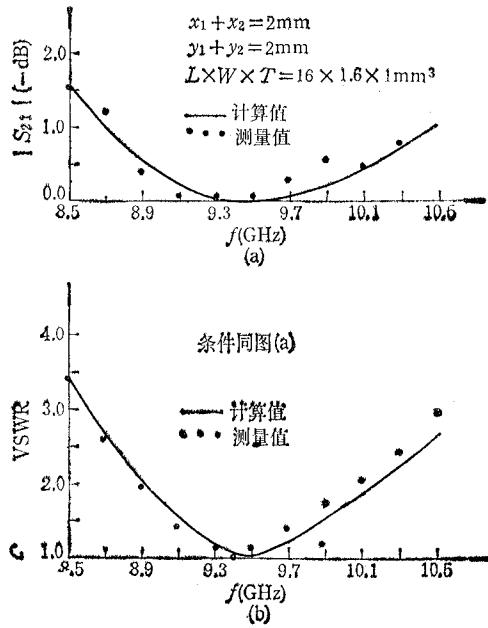


图 8 宽、窄边错开波导接头的 $|S_{21}|$ 和 VSWR 随 f 的变化

参 考 文 献

[1] 吕善伟,任济时,方榕,电子学报,1985年,第5期,第92—101页。
 [2] 张式洪,傅氏变换法求解磁流源激励场,中国电子学会1987年天线年会论文集,南京,第6-(I)-1-6-(I)-3页。

COUPLING PROPERTIES OF THE SLOT IN THE WAVEGUIDE JUNCTIONS

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Abstract The coupling properties of a transverse slot in the common wall between butting two rectangular waveguides are discussed. By means of Galerkin's method which takes into account the wall thickness, equivalent magnetic currents on the aperture surface of the slot are obtained, and then general formulas of scattering fields and of equivalent parameters are derived. The dimensions as well as seats of those two waveguides and the slot, and the thickness of the wall are arbitrary. For example, the transforming coefficients and the VSWRs of numerical calculation and experiments are given. The theoretical and experimental results are in good agreement.

Key words

Waveguide junction; Coupling; Slot; Moment method