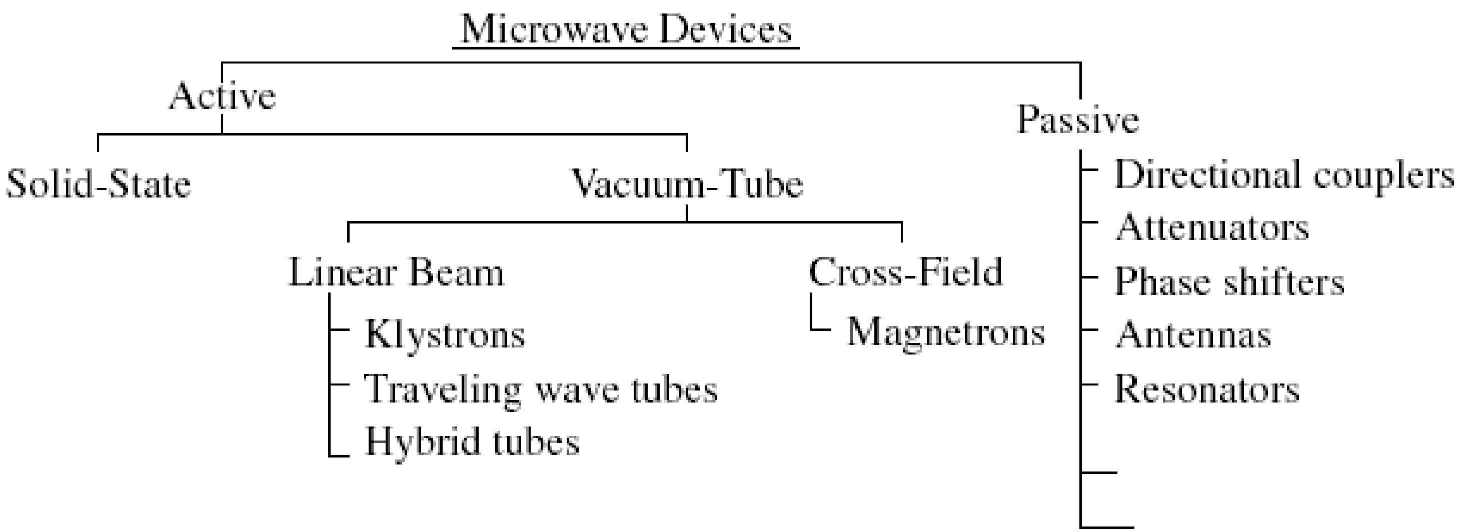
第7章 功率分配器和定向耦合器

- 7.1 分配器和耦合器的基本特征
- 7.2 T型结功率分配器
- 混合网络

本章作业

- 7.2

Microwave Devices



- 微波系统＝微波传输线＋微波元器件（对信号进行处理和变换）
- 微波元器件＝无源微波元件＋有源微波器件
- 微波元器件：线性互易元件（阻抗匹配器（可调）、阻抗变换器（不可调）、衰减器、移相器、功分器、定向耦合器、滤波器、微波电桥等）＋线性非互易元件（线性各向异性介质：区别沿不同方向传输的导行电磁波。如：隔离器、环形器等）＋非线性元件与器件（微波信号的频率或频谱变换。如：调制器、检波器、混频器、倍频器等）＋有源器件（产生微波能量或对微波信号进行放大。如：振荡器、放大器、微波管等）

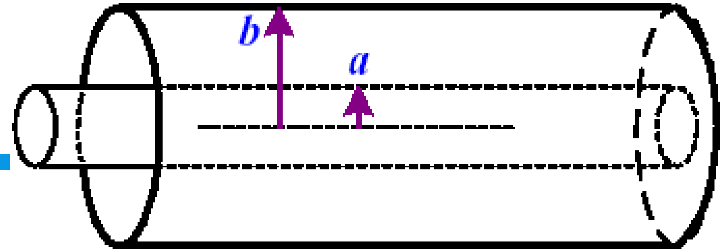
无源器件

描述:

- 用部分同轴线、波导、微带线设计成
- 可以看成单端口或多端口网络
- 用驻波比**VSWR**、反射系数、各种损耗描述
- 用于:实验室、微波通信、雷达系统
- 常用于: 连接器、终端、衰减器、位相转换器、耦合器、 **T**型连接器等 ...

无源器件
(同轴、波导、适配器、隔离器、环形器、耦合器、...)

同轴

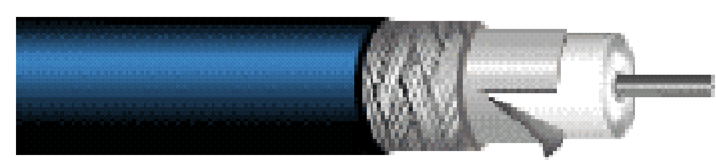


$$Z_0=\sqrt{\frac{L_0}{C_0}}=\sqrt{\frac{\frac{\mu_0}{2\pi}\ln\left(\frac{b}{a}\right)}{2\pi\varepsilon\frac{1}{\ln\left(\frac{b}{a}\right)}}}=\frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon}}\ln\left(\frac{b}{a}\right)$$

最小损耗: $\frac{b}{a}\approx 3.6$ Z_0近似75ohm

最大耐压: $\frac{b}{a}\approx 1.65$ $Z_0=30\quad(\Omega)$

折中: $\frac{b}{a}=2.3$ $Z_0=50\quad(\Omega)$



Connectors and Adapters(适配器)

PT-4000-006
SMA

PT-4000-012
SMA

BNC

TNC

F

Attenuators

Attenuators are passive devices used to control power levels in a microwave system by partially absorbing the transmitted signal wave. Both fixed and variable attenuators are designed using resistive films.

- 吸收式衰减器：镀有金属粉末的金属性介质片（电阻性材料—高损耗吸收材料，吸收微波功率），两端呈尖劈状；
- 截止式衰减器：根据波导中截止电磁波场强沿传播方向按指数规律衰减，配合隔离器、环形器使用，抑止反射干扰；
- 旋转偏振式衰减器：通过调整微波吸收介质片相对于电场的角度来改变衰减量。

Phase Shifters

A phase shifter is a two-port passive device that produces a variable change in phase of the wave transmitted through it.

$$S=\begin{pmatrix} 0 & e^{j\beta l} \\ e^{-j\beta l} & 0 \end{pmatrix}$$

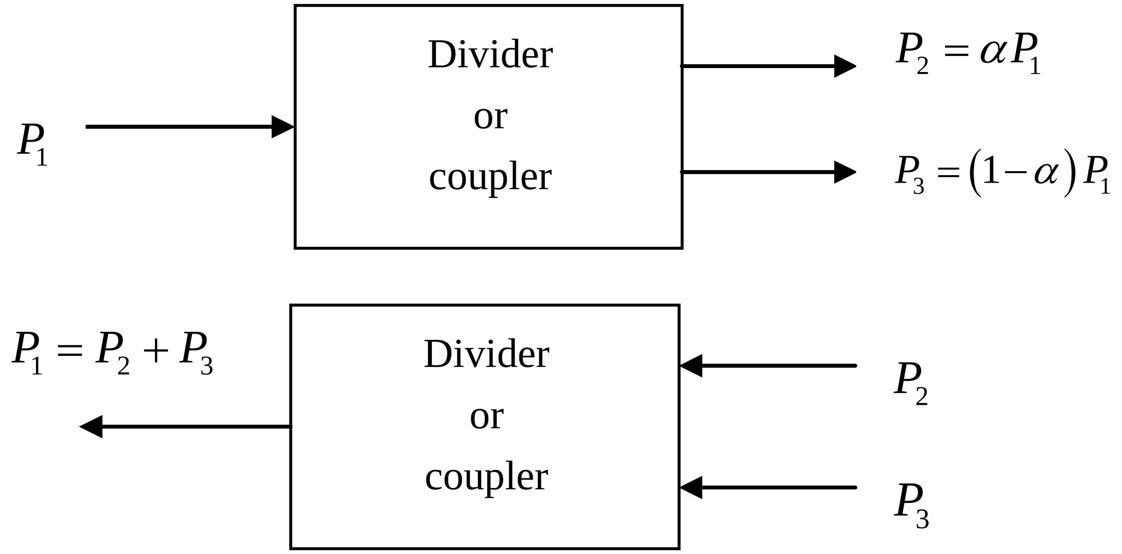
- 调整移相器的实际长度或改变行波在移相器内实际通过的距离；
- 调整移相器内填充介质的物理参数或几何参数，如用低损耗、高介电常数的材料，通过改变其在移相器内体积和位置；
- 调整波导宽边尺寸，传播常数与截止波长（宽边尺寸）相关。

Power Dividers and Combiners

A power divider is a device to split the input power into a number of smaller amounts of power at multiple ports (N) to feed N number of branching circuits with isolation between the output ports.

- Waveguide tees are three-port components used to connect a branch or section of the waveguide in series or parallel with the main waveguide transmission line for providing means of splitting, and also of combining power in a waveguide system.
- Directional couplers are four-port passive devices used for <u>coupling a known fraction of the microwave powers to a port (coupled port) in the auxiliary line</u> while <u>flowing from input port to output port in the main line</u>. The remaining port is ideally isolated port and matched terminated.

Three-Port Networks (T-Junction)



The scattering matrix of an arbitrary three-port network has nine independent elements:

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

Three-Port Networks (T-Junction)

- 所有端口匹配：Sii=0
- 各向同性媒质：互易矩阵—对称阵
- 网络无损：能量守恒，么正特性

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix}$$

互易网络与无耗网络

互易网络的[S]矩阵是对称的

即[S]矩阵与[S]矩阵的转置矩阵相等

$$[S] = [S]^t$$

$$\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$$

无耗网络的[S]矩阵是幺正的

$$[S]^* = \left\{[S]^t\right\}^{-1}$$

写成累加形式为:

$$\sum_{k=1}^{N} S_{ki} S_{kj}^* = \delta_{ij}$$

行　列

$i = j$

$$\sum_{k=1}^{N} S_{ki} S_{ki}^* = 1$$

$i \neq j$

$$\sum_{k=1}^{N} S_{ki} S_{kj}^* = 0, \quad i \neq j$$

正交

Three-Port Networks (T-Junction)

- 所有端口匹配：Sii=0
- 各向同性媒质：互易矩阵—对称阵
- 网络无损：能量守恒，么正特性

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix}$$

$$\boxed{\sum_{k=1}^{N} S_{ki}S_{kj}^{*}=\delta_{ij}}$$

$$\sum_{k=1}^{N} S_{ki}S_{kj}^{*}=\delta_{ij} \quad \begin{matrix} i=j \\ i\neq j \end{matrix}$$

$$\sum_{k=1}^{N} S_{ki}S_{ki}^{*}=1$$

$$\sum_{k=1}^{N} S_{ki}S_{kj}^{*}=0,\quad i\neq j$$

i=j=1 $|S_{12}|^2+|S_{13}|^2=1$ **i=j=2** $|S_{12}|^2+|S_{23}|^2=1$ **i=j=3** $|S_{13}|^2+|S_{23}|^2=1$

i=1, j=2 $S_{13}S_{23}^{*}=0$ **i=1, j=3** $S_{23}^{*}S_{12}=0$ **i=3, j=2** $S_{12}^{*}S_{13}=0$

由下面三个式子看出三个参量至少有两个为0

与前面三个式子不符

同时满足三个条件不成立

降低条件

Three-Port Networks (Circulator)

- 所有端口匹配：Sii=0
- 各向异性媒质：非互易（非对称）矩阵
- 网络无损：能量守恒，幺正特性

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{21} & 0 & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix}$$

$$\sum_{k=1}^{N} S_{ki}S_{kj}^{*} = \delta_{ij}$$

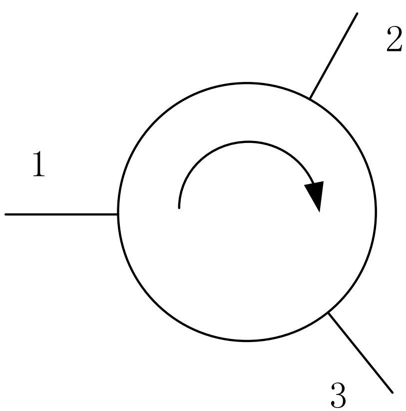
$$S_{31}^{*}S_{32}=0 \qquad S_{21}^{*}S_{23}=0 \qquad S_{12}^{*}S_{13}=0$$

$$|S_{21}|^2+|S_{31}|^2=1 \qquad |S_{12}|^2+|S_{32}|^2=1 \qquad |S_{13}|^2+|S_{23}|^2=1$$

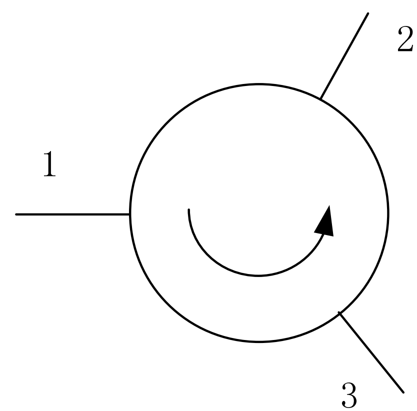
$$S_{12}=S_{23}=S_{31}=0 \qquad S_{21}=S_{32}=S_{13}=0$$

$$|S_{21}|=|S_{32}|=|S_{13}|=1 \qquad |S_{12}|=|S_{23}|=|S_{31}|=1$$

$$[S]=\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$



$$[S]=\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$



Three-Port Networks (T-Junction)

- 两个端口匹配：S33≠0
- 各向同性媒质：互易（对称）矩阵
- 网络无损：能量守恒，么正特性

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix}$$

$$\sum_{k=1}^{N} S_{ki}S_{kj}^{*} = \delta_{ij}$$

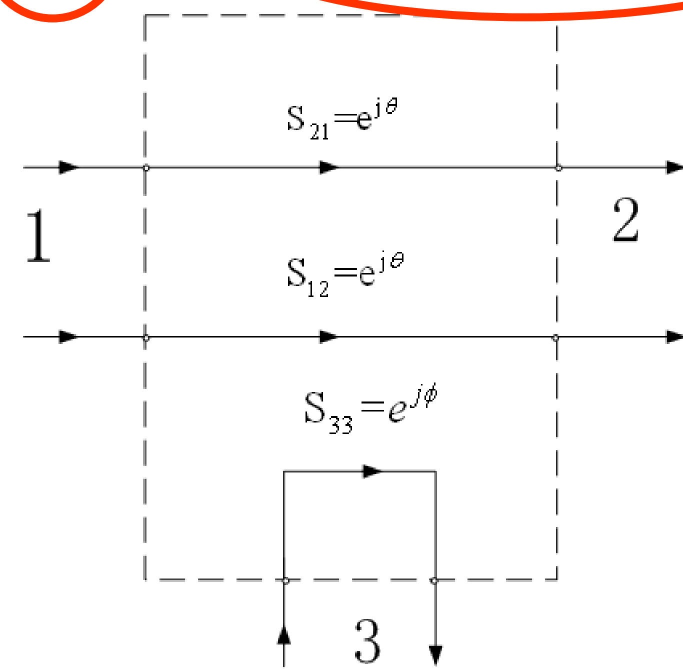
$$S_{13}^{*}S_{23}=0 \qquad S_{12}^{*}S_{13}+S_{23}^{*}S_{33}=0 \qquad S_{23}^{*}S_{12}+S_{33}^{*}S_{13}=0$$

$$|S_{12}|^2+|S_{13}|^2=1 \qquad |S_{12}|^2+|S_{23}|^2=1 \qquad |S_{13}|^2+|S_{23}|^2+|S_{33}|^2=1$$

$$|S_{13}|=|S_{23}|$$

$$S_{13}=S_{23}=0 \qquad [S]=\begin{bmatrix} 0 & e^{j\theta} & 0 \\ e^{j\theta} & 0 & 0 \\ 0 & 0 & e^{j\phi} \end{bmatrix}$$

$$|S_{12}|=|S_{33}|=1$$



Four-Port Networks (Directional Couplers)

$$\sum_{k=1}^{N} S_{ki} S_{kj}^{*} = \delta_{ij}$$

- 所有端口匹配：Sii=0
- 各向同性媒质：互易矩阵—对称阵
- 网络无损：能量守恒，幺正特性

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{12} & 0 & S_{23} & S_{24} \\ S_{13} & S_{23} & 0 & S_{34} \\ S_{14} & S_{24} & S_{34} & 0 \end{bmatrix}$$

$$S_{13}^{*} S_{23} + S_{14}^{*} S_{24} = 0 \qquad S_{14}^{*} S_{13} + S_{24}^{*} S_{23} = 0$$

S_{24}^{*} S_{13}^{*}

$$\Rightarrow S_{14}^{*}\left(|S_{13}|^2 - |S_{24}|^2\right) = 0$$

$$S_{12}^{*} S_{23} + S_{14}^{*} S_{34} = 0 \qquad S_{14}^{*} S_{12} + S_{34}^{*} S_{23} = 0$$

S_{12} S_{34}

$$\Rightarrow S_{23}\left(|S_{12}|^2 - |S_{34}|^2\right) = 0$$

$\Rightarrow$

$S_{14} = S_{23} = 0$

Directional Couplers

$|S_{13}| = |S_{24}|$ $|S_{12}| = |S_{34}|$ ×

Two Decoupled two-port netwrks (1&4, 2&3)

去耦

$S_{14} = S_{23} = 0$ 定向耦合器

$$\begin{cases} |S_{12}|^2 + |S_{13}|^2 = 1 & |S_{12}|^2 + |S_{24}|^2 = 1 \\ |S_{13}|^2 + |S_{34}|^2 = 1 & |S_{24}|^2 + |S_{34}|^2 = 1 \end{cases}$$

$\Rightarrow$ $|S_{12}| = |S_{34}|$ $|S_{13}| = |S_{24}|$

Four-Port Networks (Directional Couplers)

$$\sum_{k=1}^{N} S_{ki} S_{kj}^{*} = \delta_{ij}$$

$$\begin{cases} |S_{12}|^2 + |S_{13}|^2 = 1 \\ |S_{13}|^2 + |S_{34}|^2 = 1 \end{cases} \qquad |S_{12}|^2 + |S_{24}|^2 = 1 \qquad |S_{24}|^2 + |S_{34}|^2 = 1$$

$$\Rightarrow \quad \boxed{|S_{13}| = |S_{24}|} \quad \boxed{|S_{12}| = |S_{34}|}$$

选择三个端口相位参考点简化

选择 $S_{12} = S_{34} = \alpha \qquad S_{13} = \beta e^{j\theta} \qquad S_{24} = \beta e^{j\phi}$

$$S_{12}^{*} S_{13} + S_{24}^{*} S_{34} = 0 \Rightarrow \boxed{\theta + \phi = \pi \pm \cancel{2n\pi}} \qquad \boxed{\alpha^2 + \beta^2 = 1}$$

The Symmetrical Coupler

$$\theta = \phi = \pi / 2$$

$$[S] = \begin{bmatrix} 0 & \alpha & j\beta & 0 \\ \alpha & 0 & 0 & j\beta \\ j\beta & 0 & 0 & \alpha \\ 0 & j\beta & \alpha & 0 \end{bmatrix}$$

The Antisymmetrical Coupler

$$\theta = 0, \phi = \pi$$

$$[S] = \begin{bmatrix} 0 & \alpha & \beta & 0 \\ \alpha & 0 & 0 & -\beta \\ \beta & 0 & 0 & \alpha \\ 0 & -\beta & \alpha & 0 \end{bmatrix}$$

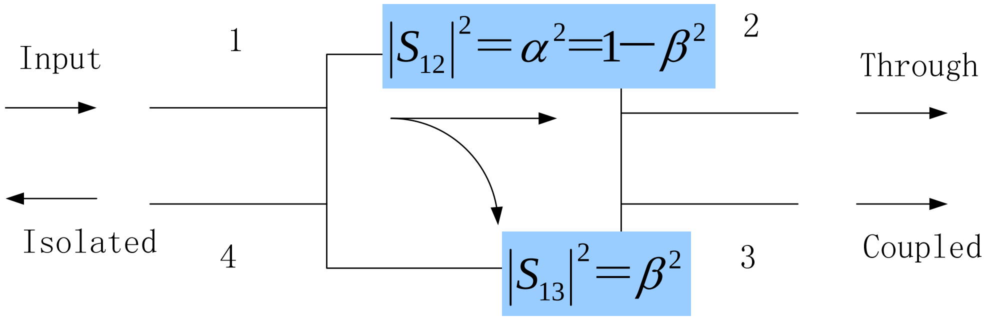
$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{12} & 0 & S_{23} & S_{24} \\ S_{13} & S_{23} & 0 & S_{34} \\ S_{14} & S_{24} & S_{34} & 0 \end{bmatrix}$$

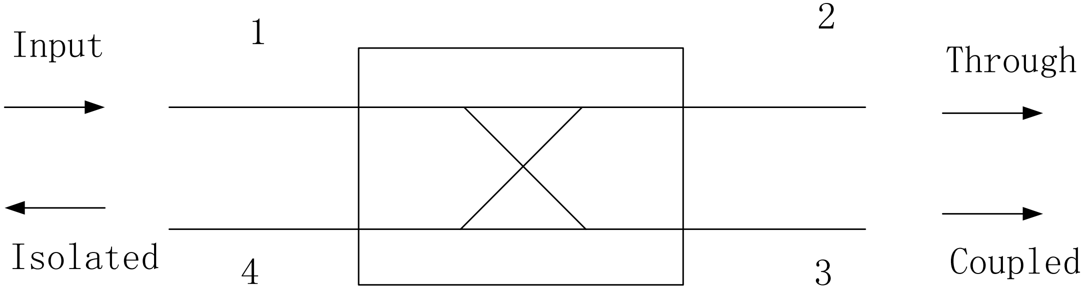
两种耦合器的差别在于参考面的选择。

除相位参考面外，一个理想的定向耦合器只有一个自由度。

任何互易、无耗、匹配的四端口网络是一定向耦合器

Directional Couplers





$$[S] = \begin{bmatrix} 0 & \alpha & j\beta & 0 \\ \alpha & 0 & 0 & j\beta \\ j\beta & 0 & 0 & \alpha \\ 0 & j\beta & \alpha & 0 \end{bmatrix}$$

耦合度 $\text{Coupling} = C = 10\log\frac{P_1}{P_3} = -20\log\beta \, dB$

隔离度 $\text{Isolation} = I = 10\log\frac{P_1}{P_4} = -20\log|S_{14}| \, dB$

方向性 $\text{Directivity} = D = 10\log\frac{P_3}{P_4} = 20\log\frac{\beta}{|S_{14}|} \, dB$

$$I = D + C$$

Hybrid Couplers 混合网络耦合器 是定向耦合器特例

The Symmetrical Coupler

$$\theta = \phi = \pi / 2$$

$$[S] = \begin{bmatrix} 0 & \alpha & j\beta & 0 \\ \alpha & 0 & 0 & j\beta \\ j\beta & 0 & 0 & \alpha \\ 0 & j\beta & \alpha & 0 \end{bmatrix}$$

The Antisymmetrical Coupler

$$\theta = 0, \phi = \pi$$

$$[S] = \begin{bmatrix} 0 & \alpha & \beta & 0 \\ \alpha & 0 & 0 & -\beta \\ \beta & 0 & 0 & \alpha \\ 0 & -\beta & \alpha & 0 \end{bmatrix}$$

$$\text{Coupling} = C = 10\log\frac{P_1}{P_3} = -20\log\beta\, dB$$

混合网络耦合器耦合因数

Coupler factor is 3dB $\alpha = \beta = 1/\sqrt{2}$

正交混合网络

$$[S] = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 1 & j & 0 \\ 1 & 0 & 0 & j \\ j & 0 & 0 & 1 \\ 0 & j & 1 & 0 \end{bmatrix}$$

Fed at port 1

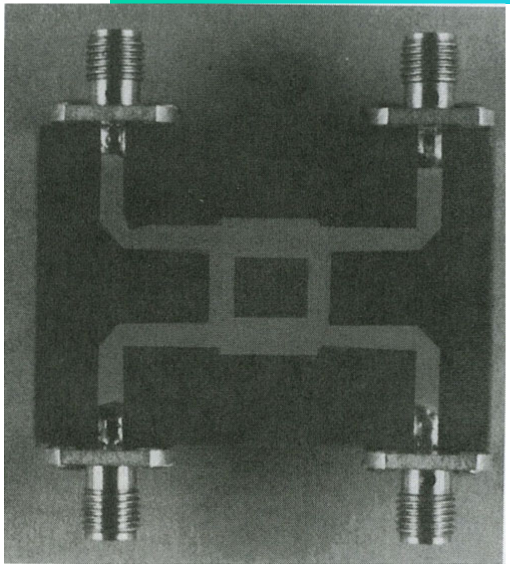
2/3端口有90° 相移

魔T混合网络或环型波导混合网络

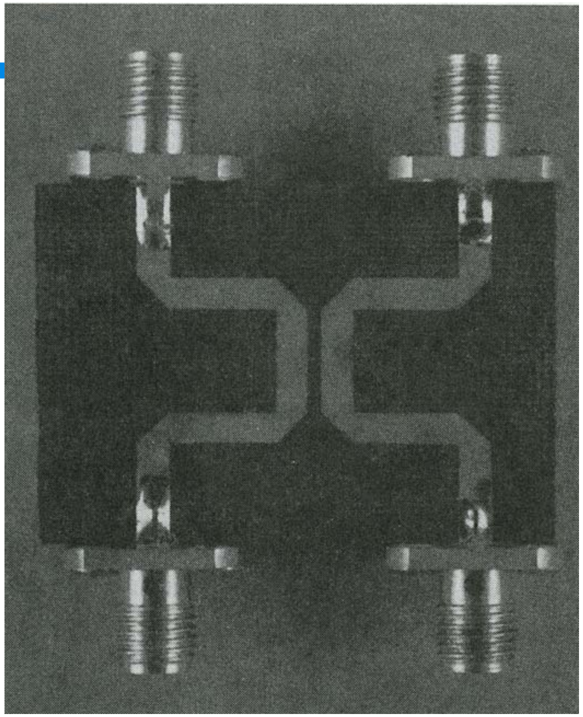
$$[S] = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix}$$

Fed at port 4

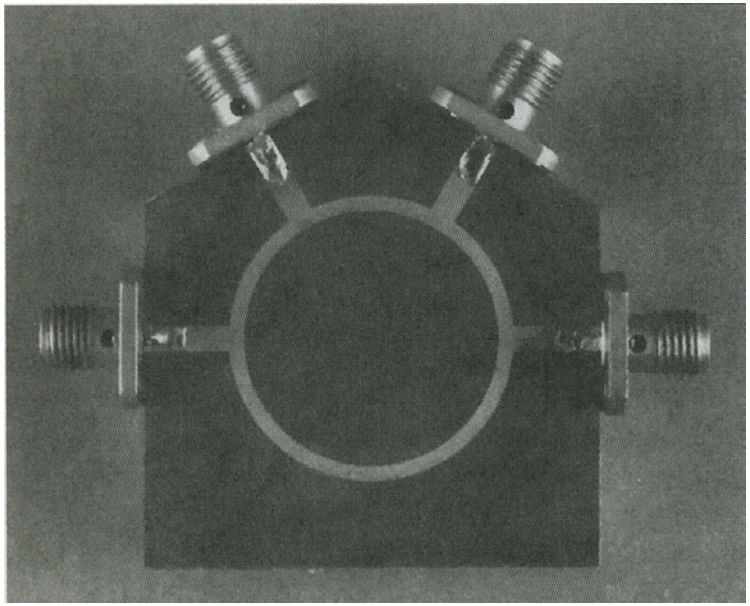
2/3端口有180° 相差



微带正交
混合网络



微带耦合器



微带环型
混合网络

T型结功率分配器

➢ 无耗分配器

为了使分配器与传输线匹配，有：

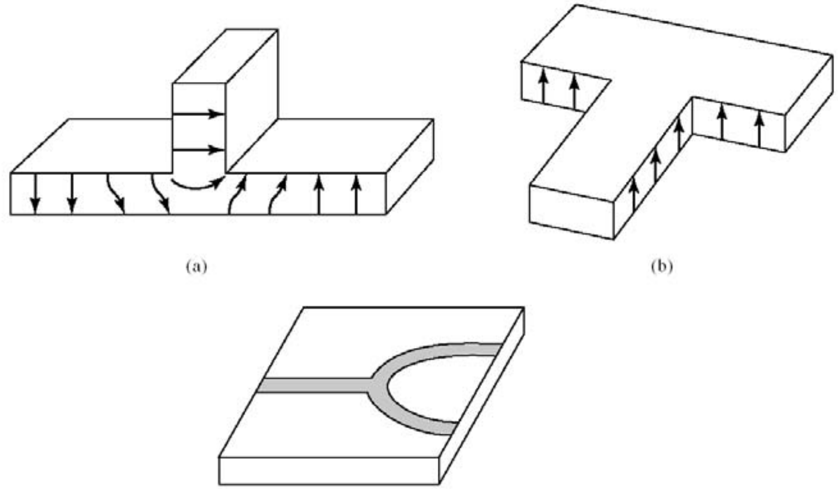
$$Y_{in}=jB+\frac{1}{Z_1}+\frac{1}{Z_2}=\frac{1}{Z_0}$$

设B=0，有：

$$\frac{1}{Z_1}+\frac{1}{Z_2}=\frac{1}{Z_0}$$

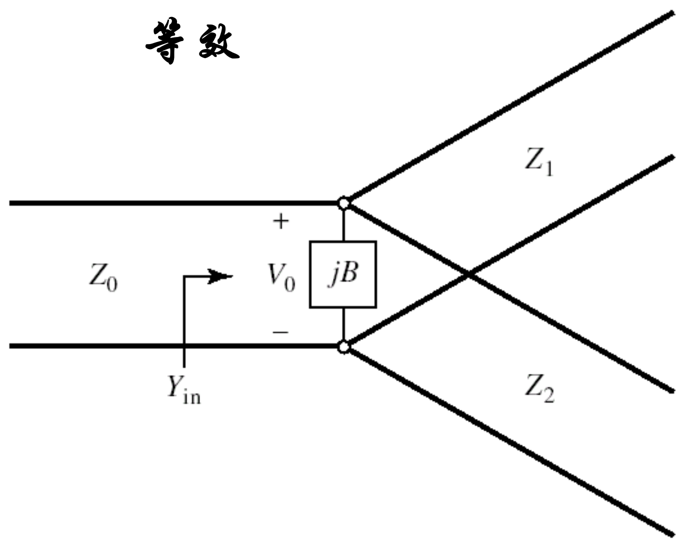
由结处电压相同，功率守恒

可以通过选择Z_1和Z_2，
提供不同功率分配比的功分器



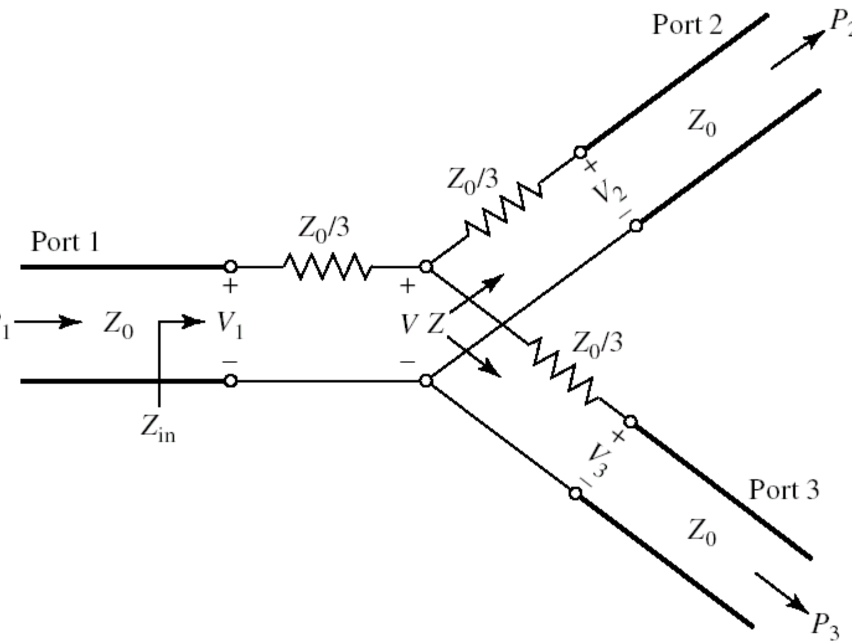
(a) (b) (c)

等效



T型结功率分配器

➢ 电阻性分配器



设所有端口接特性阻抗Z_0，向接传输线的电阻$Z_0/3$看，阻抗为：

$$Z = \frac{Z_0}{3} + Z_0 = \frac{4Z_0}{3}$$

分配器输入阻抗为：

$$Z_{in} = \frac{Z_0}{3} + \frac{2Z_0}{3} = Z_0$$

因此1端口匹配　　　由对称性有：　$S_{11}= S_{22}= S_{33}=0$

设端口1上的电压为V_1，则结中心分压为：　$V = \frac{2}{3}V_1$

端口2，3输出电压为：　$V_2 = V_3 = V\frac{Z_0}{Z_0 + Z_0/3} = \frac{3}{4}V = \frac{1}{2}V_1$

输入功率：

$$P_{in} = \frac{1}{2}\frac{V_1^2}{Z_0}$$

所以：　$S_{21}= S_{31}= S_{23}=1/2$

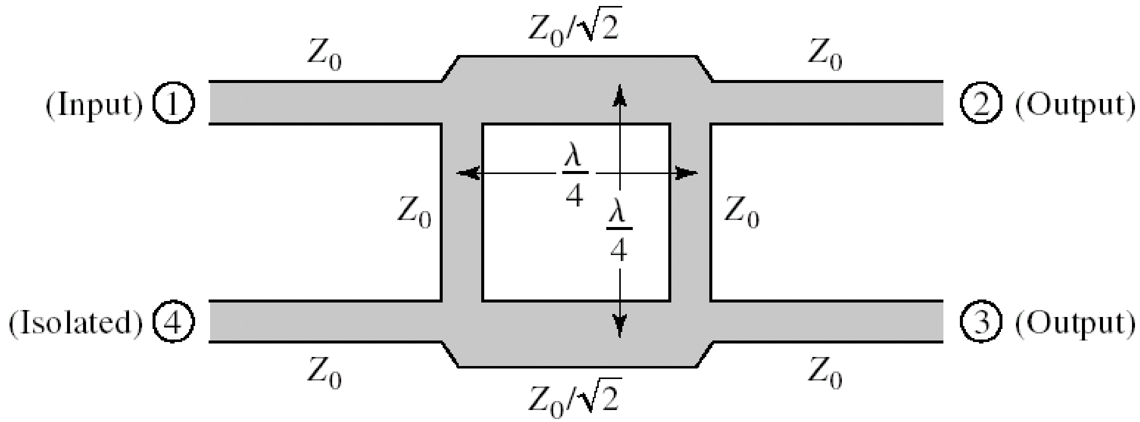
输出功率：

$$P_2 = P_3 = \frac{1}{2}\frac{(1/2V_1)^2}{Z_0} = \frac{1}{4}P_{in}$$

所以：　$[S] = \frac{1}{2}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$

The 90° Hybrid正交混合网络

- 3dB定向耦合器，直通和耦合臂输出间有90°相位差
- 所有端口都匹配，端口1入的功率分配给端口2、3，2、3端口间有90°相移。端口4隔离。

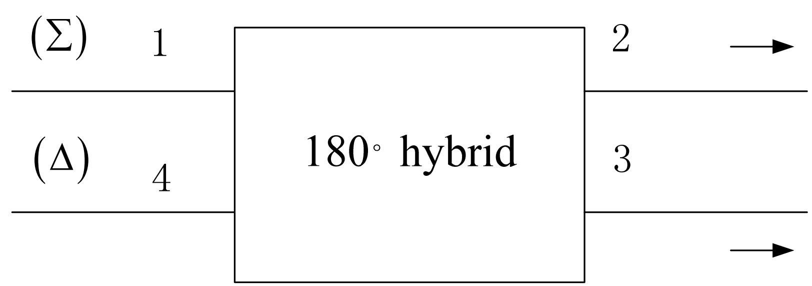


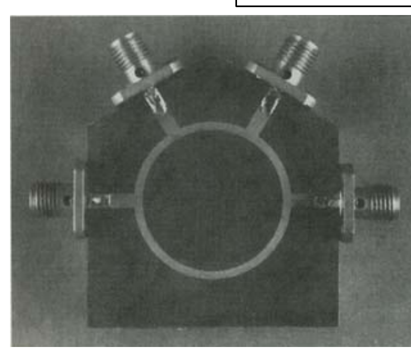
$$[S]=\frac{-1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

The 180° Hybrid混合网络

- A signal applied to port 1 will be evenly split into two in-phase components at ports 2 and 3, and port 4 will be isolated.
- A signal applied to port 4 will be evenly split into two components with a 180⁰ phase difference at ports 2 and 3, and port 1 will be isolated.
- When operated as a combine, with input signals applied at port 2 and 3, the sum of the inputs will be formed at port 1, while the difference will be formed at port 4. Hence, port 1 and 4 are referred to as the sum and difference ports, respectively.

$$[S]=\frac{-j}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix}$$

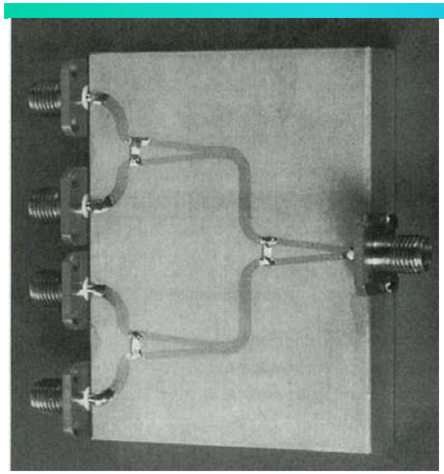
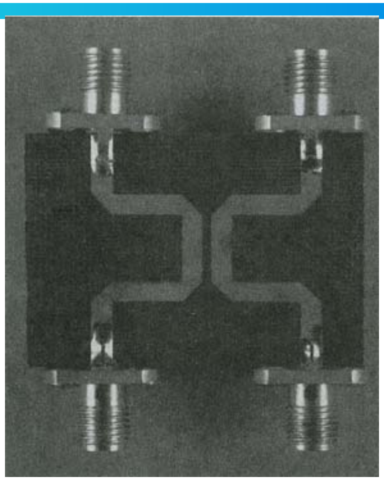
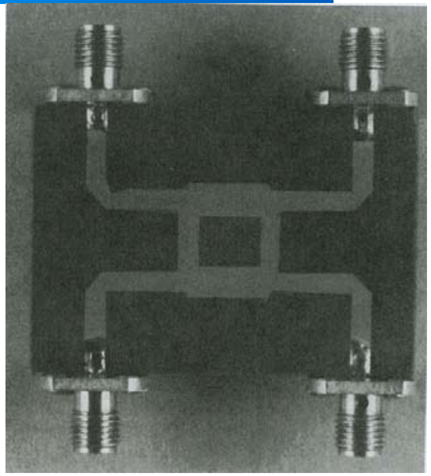
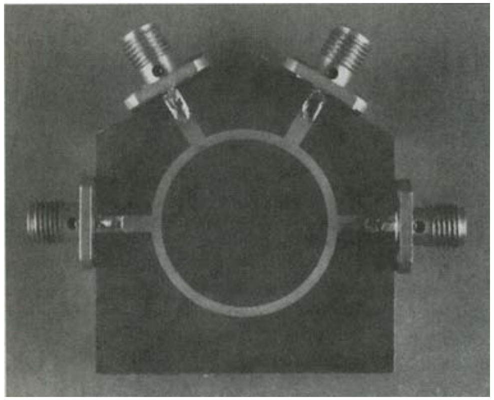
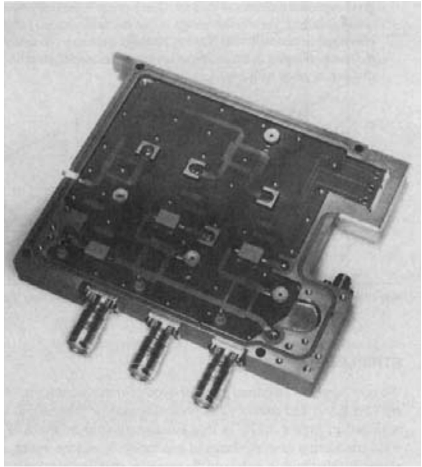
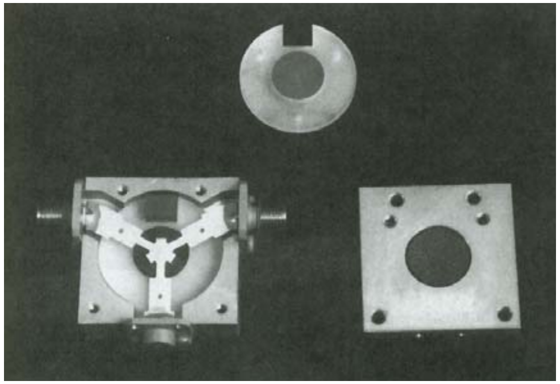




微带环型混合网络

Isolators隔离器 & Circulators环形器

- An isolator is a two-port non-reciprocal device which produces a minimum attenuation to wave propagation in one direction and very high attenuation in the opposite direction.
- Thus when inserted between a signal source and load almost all the signal power can be transmitted to the load and any reflected power from the load is not fed back to the generator output port.
- This eliminates variations of source power output and frequency pulling due to changing loads.
- A circulators is a multi-port junction in which the wave can travel from one port to next immediate port in one direction only.

Microwave Filters

(1) (微波)滤波器的基本原理、参数

(2) 滤波器分量元件的微波实现

(3) 滤波器设计

(4) 微波低通、高通、带通和带阻滤波器

What is the Microwave Filter ?

微波滤波器是一种二端口网络，在微波系统中用来控制频率响应，使信号在滤波器的通带内得以传输，阻带内则给出衰减。

典型的频响包括低通（Low-pass）、高通（High-pass）、带通（Band-pass）和带阻（Band-stop）特性。

- Microwave filters are two-port, reciprocal, passive, linear devices which attenuate heavily the unwanted signal frequencies which permitting transmission of wanted frequencies

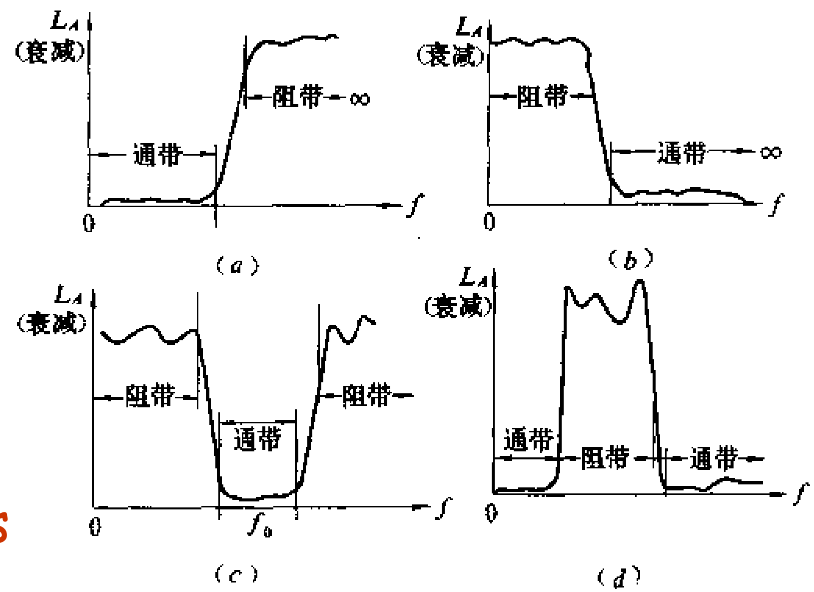
Filter Parameters

- Pass bandwidth
- Stop band attenuation and frequencies
- Input and output impedances
- Return loss
- Insertion loss
- Group delay

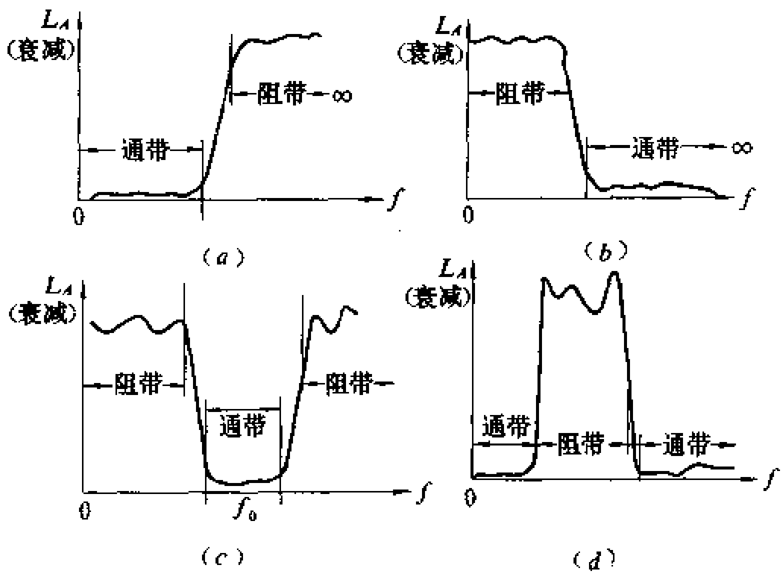
Amplitude Response

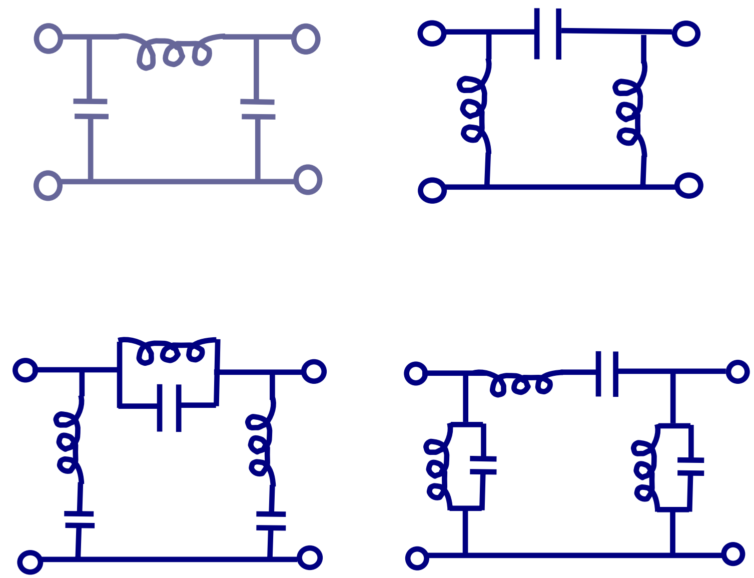
(Insertion Loss)

Vs Frequency Characteristics



Filter Design





原型设计→定标和变换→实现

Electrical equivalent circuits of filters

集中电路元件
用分布电路元件