The cross directional coupler

Fundamentals

General properties of waveguide (directional) couplers

The cross directional coupler is a special type of directional coupler. Thus, it makes sense to follow with a general explanation applicable to the function of all types of waveguide couplers and their most important parameters. An (unconnected) waveguide coupler is a reciprocal four-port, which is also ideally loss-free. Fig. 10.1 illustrates the response of the ideal directional coupler. If a wave is fed exclusively into port 1, its effective power P_1 is distributed to port 2 (primary path) and port 4 (coupling path). If the power exiting port 4 amounts to k^2P_1, then the power must be $(1 - k^2)$ P_1 at port 2 because of the lossless property of waveguide port 2 (conservation of energy). Ideally there is no power exiting port 3, i.e. it is "decoupled" (isolation path). If, on the other hand, a wave is fed into port 2, port 4 is decoupled and the power fed is distributed to port 1 (primary path) and port 3 (coupling path). The magnitude of k (coupling coefficient) can vary in amplitude depending on the design of the directional coupler. The following:

$$a_k = -20 \log k \ \text{[dB]} \qquad (10.1)$$

is referred to as coupling loss. If you consider the definitions provided above and furthermore the relationships between the S-parameters resulting from the loss-free property of the waveguide (see Experiment 5 from MTS 7.4.5 or the bibliography provided there), we obtain the following scattering matrix for the ideal waveguide coupler.

$$(S) = e^{j\psi} \begin{bmatrix} 0 & \sqrt{1-k^2} & 0 & jke^{j\varphi} \\ \sqrt{1-k^2} & 0 & jke^{j\varphi} & 0 \\ 0 & jke^{j\varphi} & 0 & \sqrt{1-k^2} \\ jke^{j\varphi} & 0 & \sqrt{1-k^2} & 0 \end{bmatrix} \qquad (10.2)$$

Here, in addition to the coupling coefficient k, there are also the phase angles ψ and φ as parameters (ψ is the phase rotation in the primary guide and $\psi + \varphi$ are the phase rotations in the coupling guide). Fig. 10.2 shows one of the primary applications of waveguide couplers, namely the separate measurement in front of a one port (e.g. antenna) of the wave propagating to and reflected from the load.

The signal exiting at port 3 is only proportional to the wave $P_{2,in} = |r|^2 P_{2,out}$ reflected by the load (here the antenna), while a signal proportional to the wave propagating to the load appears at port 4. The following applies:

$$\frac{P_{3,out}}{P_{4,out}} = \frac{k^2 \cdot P_{2,in}}{k^2 \cdot P_{1,in}} = |\underline{r}|^2 (1-k^2) \qquad (10.3)$$

When the value of k^2 is known, the reflection coefficient $|r|$ can be derived from the relationship between $P_{3,out}$ and $P_{4,out}$. The configuration shown

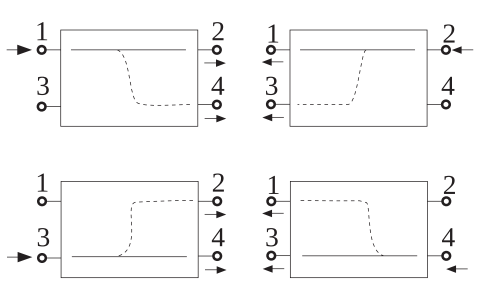

Fig. 10.1: Principal response of a directional coupler

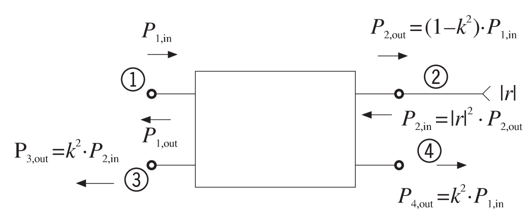

Fig. 10.2: Use of the directional coupler as a reflectometer

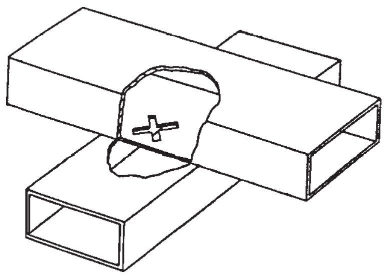

Fig. 10.3: Principal design of a waveguide (cross directional) coupler and including port numbering

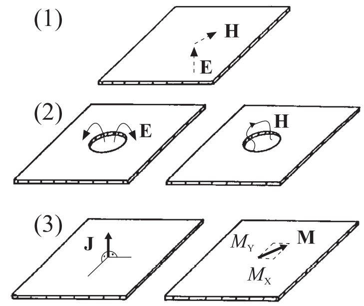

Fig. 10.4: Explanation of the hole coupling

in Fig. 10.2 is referred to as a reflectometer. In Experiment 11 the cross directional coupler is used as a reflectometer.

Contrary to the statements above, in real directional waveguide couplers decoupling via an isolation path (e.g. from port 1 to port 3 in Fig. 10.1) is not total. If a wave is only fed in at port 1, power is still obtained at port 3; $P_{3,out} > 0$. The ratio of undesired power at port 3 ($P_{3,out}$) to desired power at $P_{4,out}$ at port 4 is one of the ways of determining the quality of a waveguide coupler. This is called the directivity factor. The following applies for directivity:

When feeding at port 1

$$\frac{a_D}{dB} = -10 \cdot \log \frac{P_{4,out}}{P_{3,out}} \qquad (10.4)$$

When feeding at port 2

$$\frac{a_D}{dB} = -10 \cdot \log \frac{P_{4,out}}{P_{3,out}}$$

High quality directional couplers are expensive and can have a directivity of over 50 dB, whereas simple waveguide couplers average around 20 dB.

The cross directional waveguide coupler as a special form of directional waveguide coupler

Up until now the response of a directional waveguide coupler has only been dealt with as a kind of “black box”, i.e. only its operation within a circuit. However, nothing has been mentioned about the “physical effects” which are needed to exploit this behavior. There are directional couplers for all conventional transmission lines in microwave engineering (coaxial lines, microstrip lines, hollow waveguides). These couplers employ a wide variety of different principles to realize directivity (the separation of the incident and reflected wave). Examples for this include the directivity employed in coupling TEM lines running parallel and the interference of waves in hollow waveguides, which are coupled together via holes. In the following the principle of the cross directional coupler is studied in more detail. In accordance with Fig. 10.3 the cross directional coupler is made up of two hollow waveguides arranged at a 90° angle as specified in Fig. 10.3, so that they have a common wall (“overlapping square surface”). Coupling is carried out via one or two coupling holes in this common wall. For a closer examination of the theoretical aspects of this phenomena please refer to the literature specified in the bibliography. Only a few important findings are dealt with here.

Electric and magnetic coupling through a hole in a metal wall

In the upper part of Fig. 10.4 a cutaway section of a closed metal wall is shown, on whose underside an electrical (***E***) and a magnetic field (***H***) is found. This means that:

1. An electric and magnetic field exist on the underside of the closed metal wall.
2. Penetration of the electric and magnetic field through a coupling hole.
3. Description of the coupling via an electric (***J***) and a magnetic (***M***) dipole.

Fig. 10.5: gives a schematic depiction of the cross directional coupler with a cylindrical coupling hole. Where:

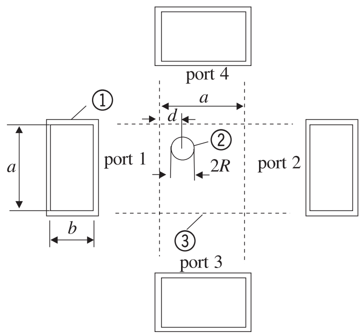

Fig. 10.5: Cross coupler with a circular coupling hole with a diameter of 2 R

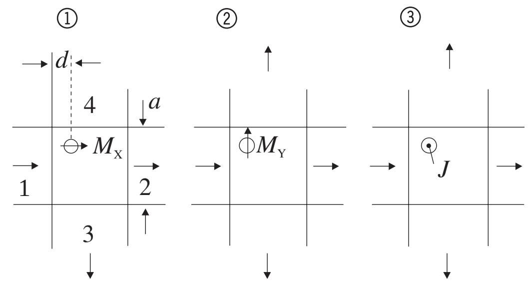

Fig. 10.6: Wave excitation when feeding wave into port 1

① Transversal hollow waveguide section
② Coupling hole
③ Reference planes (port 3) for the phases of the S-parameters

We are assuming that the TE_{10} wave propagates from port 1 to port 2. If you now consider separately the effect of the x- and y-components of the magnetic dipole and the effect of the electric dipole, see Fig. 10.6, you arrive at the following conclusions:

The partial magnetic waves at port 3 completely cancel each other out, while the magnetic waves at port 4 superposition each other constructively. Thus, if only magnetic coupling were present, the four-port would respond like an ideal directional coupler. However, there are still the partial waves excited by the electric dipole (“electric coupling”). Here, two partial waves of the same magnitude are formed for port 3 **and** port 4. The complete decoupling of port 3 thus fails due to the partial waves caused by the electric coupling.

Measures to increase directivity over that attained with a single round coupling hole

Deviation from this ideal directional coupler results when electric coupling is added. If an increase in directivity is desired, the electric coupling must be reduced. One suitable way of realizing this is by substituting the round coupling hole with the cross-shaped hole. Compared to round-shaped holes, in cross-shaped coupling holes (see Fig. 10.7 centre) the “magnetic penetration” predominates more than the “electric penetration”. As the experiment will show a substantial increase in directivity is achieved by exchanging the round coupling hole with the cross-shaped hole. An added improvement is achieved by using two cross-shaped holes instead of one (see Fig. 10.7, right). Due to the interaction between the two holes, the electric coupling is weakened.

The cross coupler included in the training system is comprised of several dismountable parts and there are various options between different alternative hole configurations for coupling. Therefore, the improvements attained when going from one round hole to one cross-shaped hole and from two round holes to two cross-shaped holes can be verified experimentally.

Required equipment

1 Basic unit	737 021
1 Gunn oscillator	737 01
1 Diaphragm with slots 2 x 15 mm, 90°	737 22
1 Variable attenuator	737 09
1 Cross directional coupler	737 18
1 Transition waveguide/coax	737 035
1 Coax detector	737 03
2 Waveguide terminations	737 14
1 Set of thumb screws (8 each)	737 399

Additionally required equipment

2 Coax cables with BNC/BNC plugs, 2 m	501 022
3 Standbases	301 21
3 Supports for waveguides	737 15
2 Stand rods 0.25 m	301 26

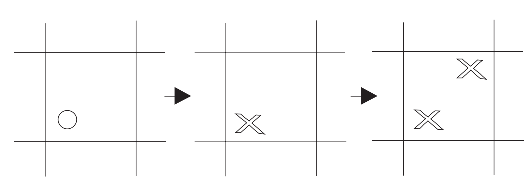

Fig. 10.7: Measures to increase directivity

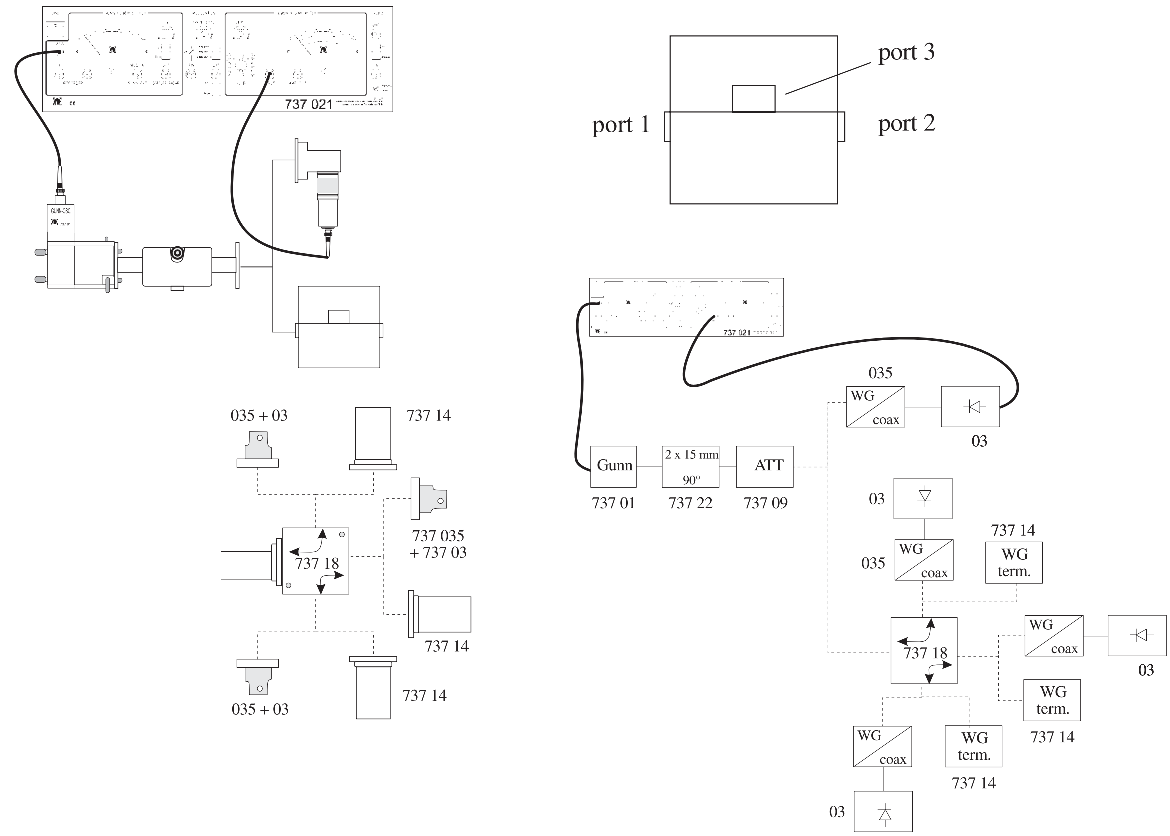

Fig. 10.8 Experiment setup

Recommended:

1 PIN modulator	737 05
1 Isolator	737 06

Experiment procedure

Note:

When using the isolator and PIN modulator modify the experiment setup in Fig. 10.8 according to the preface!

1. *Calibration of the experiment setup*

1.1 First set up the measuring system as specified in Fig. 10.8, above, without the cross directional coupler. Set “ZERO” to the far right, the gain level V/dB to approx. 10 dB (resp. 15 dB). With the aid of the variable attenuator calibrate the display of the SWR meter to 0 dB. This setting is no longer changed during the experiments.

2. *Measurement of some S-parameters of the cross directional coupler with 1 round coupling hole.*

2.1 Install the diaphragm with round hole into the cross coupler. Here it is important to focus on the installation direction (e.g. “4” to “4”) (see Fig. 10.9, above).

2.2 Connect port 1 of the cross coupler to the open end of the variable attenuator (instead of the measurement head in Fig. 10.8, above).

2.3 To measure the magnitude of the transmission coefficient ($|S_{21}|$) to port 2 you must equip ports 3 and 4 with a reflection-free waveguide termination and connect a measurement head (transition waveguide/coax with coax detector) to port 2. The display of the SWR meters supplies $|S_{21}|$ in dB. Enter the result in Table 10.1.

2.4 For the measurement of $|S_{31}|$ connect measurement head to port 3 and reflection-free terminations to ports 2 and 4. Enter result in Table 10.1.

2.5 For the measurement of $|S_{41}|$ connect measurement head to port 4 and reflection-free terminations to port 2 and port 3. Enter result into Table 10.1

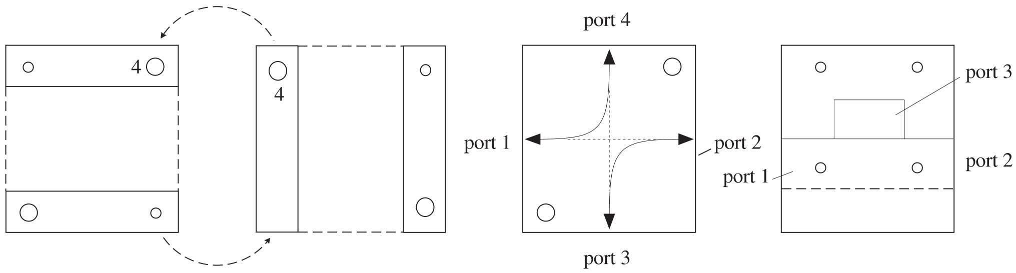

Fig. 10.9: On the numbering of the ports of the cross-coupler (here, for example, port 4 is marked)

2.6 Now make connections for wave feed via port 2, i.e. connect port 2 to the open end of the variable attenuator. The transmission coefficients $|S_{12}|$, $|S_{32}|$ and $|S_{42}|$ are determined as in 2.3 to 2.5. Enter the results in Table 10.1.

3. *Measurement of some S-parameters of the cross coupler with 1 cross-shaped hole.*

3.1 Exchange the diaphragm with round hole for the diaphragm with cross-shaped hole.

3.2 Measure the transmission coefficients $|S_{21}|$, $|S_{31}|$, $|S_{41}|$, $|S_{12}|$, $|S_{32}|$ and $|S_{42}|$ as in 2.3 to 2.6. Enter the values in Table 10.1

4. *Measurement of some S-parameters of the cross directional coupler with 2 round holes.*

4.1 Exchange the current diaphragm for the diaphragm with 2 round holes.

4.2 Measure the transmission coefficients as set forth under 2.3 to 2.6. Enter the results in Table 10.1

5. *Measurement of some S-parameters of the cross directional coupler with 2 cross-shaped holes.*

5.1 Exchange the current diaphragm for the diaphragm with 2 cross-shaped holes.

5.2 Measure the transmission coefficients as in 2.3 to 2.6. Enter the results in Table 10.1

Exercises

1. In Fig. 10.2 the coupling loss attenuation of the directional coupler is assumed to be 20 dB ("20 dB-coupler") and the power fed into the port is $P_{1,\text{in}} = 1$ W.
   Specify the values for $P_{1,\text{out}}$, $P_{3,\text{out}}$ and $P_{4,\text{out}}$ as well as $P_{3,\text{out}} / P_{4,\text{out}}$, if
   α) $|r| = 0.0$
   ß) $|r| = 0.5$.
2. Determine the directivity for the 4 different configurations of the cross directional coupler and enter these into Table 10.1.

Note

- Directivity:
  When feeding from port 1

$$a_\text{D} = -20 \cdot \log\left(\frac{|\underline{S}_{31}|}{|\underline{S}_{41}|}\right)$$

  or when feeding from port 2

$$a_\text{D} = -20 \cdot \log\left(\frac{|\underline{S}_{42}|}{|\underline{S}_{32}|}\right)$$

  Here the *S*-parameters are not to be used logarithmically.
- If when determining the S-paramters of the isolation path you reach the limits of the measurement amplifier, then try to enhance the modulated signal by varying the Gunn voltage (see Experiment 2. But take care: Monomode operation must be maintained). Otherwise, we would highly recommed using a PIN modulator (with isolator).

Table 10.1

		1 Round hole	1 Cross-shaped hole	2 Round holes	2 Cross-shaped holes
Feed	$\lvert S_{21}\rvert$ / dB				
via	$\lvert S_{31}\rvert$ / dB				
port 1	$\lvert S_{41}\rvert$ / dB				
Feed	$\lvert S_{12}\rvert$ / dB				
via	$\lvert S_{32}\rvert$ / dB				
port 2	$\lvert S_{42}\rvert$ / dB				
Port 1 :	$\lvert a_D\rvert$ / dB				
Port 2 :	$\lvert a_D\rvert$ / dB				