APPLICATION NOTE

Circulators and Isolators, unique passive devices

AN98035

Philips
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0. Contents

1. Introduction

Circulators and isolators are passive devices used in modern rf and microwave equipment since some decades. By using them the stability, performance, and reliability of the systems can be improved, and often better and cheaper solutions are possible. In addition, in certain applications, e.g. one-port-amplifiers, the use of circulators is a must.
This booklet will help you to understand these important devices and give you some hints to use them effectively.

2. Definitions

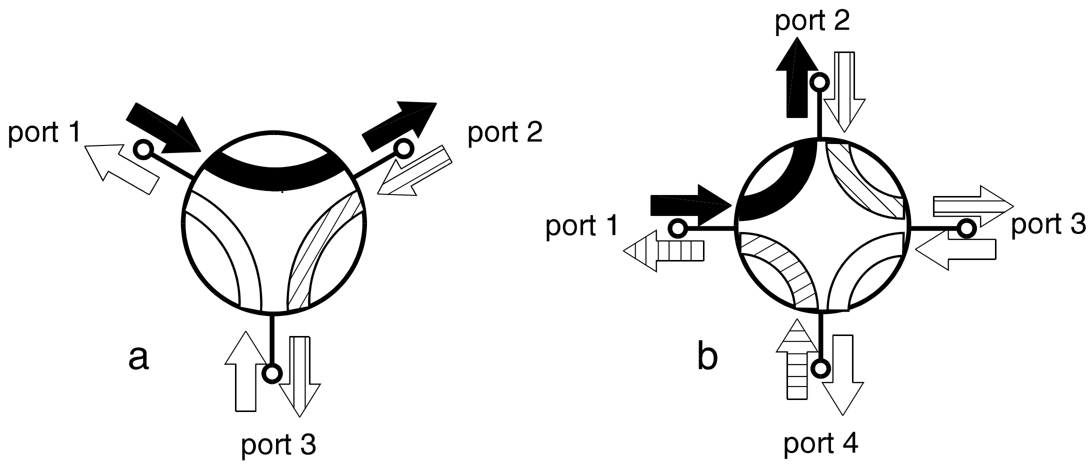


Fig.1: Energy flow in a. a 3-port-circulator
b. a 4-port-circulator

The circulator is defined as a passive device with 3 or more ports, where power is transferred from one port to the next in a prescribed order. That means for a 3-port-circulator (see fig.1a): power entering port 1 leaves port 2, port 3 is decoupled; power entering port 2 leaves port 3, port 1 is decoupled; and power entering port 3 leaves port 1, port 2 is decoupled. For a 4-port-circulator it is similar (see fig.1b): power entering port 1 leaves port 2, port 3 and 4 are decoupled etc.

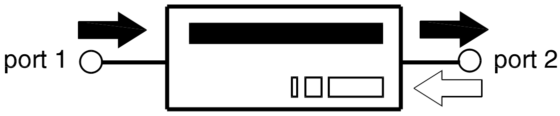


Fig.2: Energy flow in an isolator

The isolator is defined as a passive two-port, where power is transmitted in one direction and absorbed in the other direction. That means power entering port 1 leaves port 2, but power entering port 2 is absorbed (see fig.2).
An isolator can be a specially developed item. But we get also an isolator if we connect a matched load to port 3 of a 3-port-circulator.
Figure 3 gives the symbols used for circulators and isolators in circuit drawings.
By these definitions circulators and isolators are non-reciprocal devices, that means, their behaviour in one direction is very different from that in the other direction.

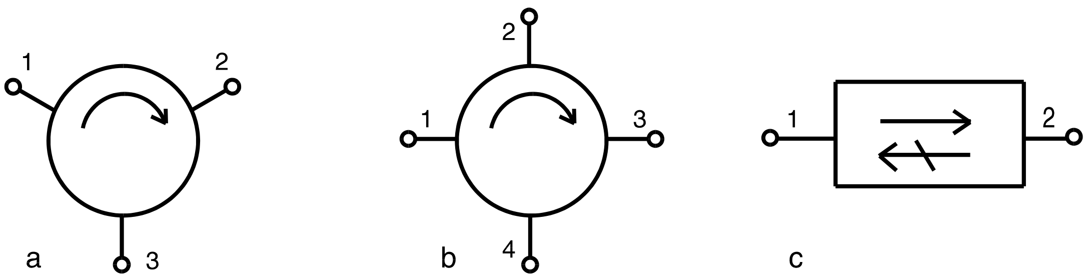


Fig.3: Symbols for a. 3-port-circulator
b. 4-port-circulator
c. isolator

3. Behaviour of ferrites

The way of operation of circulators and isolators is based on the unique properties of microwave ferrites. Therefore we will have a look on the behavior of ferrites under static and alternating fields at first.
Ferrites are magnetic material with very high ohmic resistance. Therefore they have nearly no eddy currents and are suitable for the operation at rf and microwave frequencies.
Like ferromagnetic material

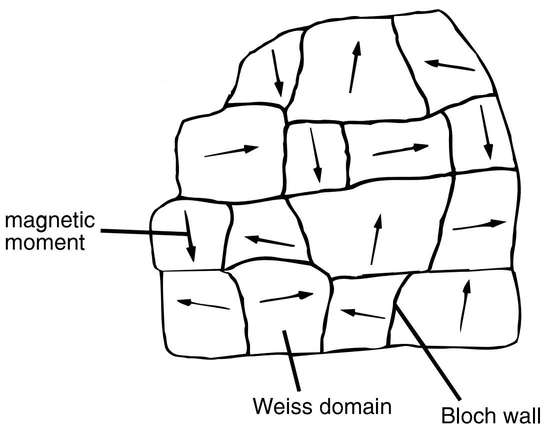


Fig.4: Planar model of Weiss domains

they consist of magnetic domains called Weiss domains, for Pierre Weiss discovered them 1908. The individual domains with dimensions of 1 to 100 µm are inherently magnetized by mutual exchange effects between adjacent electron spins. They are separated from each other by Bloch walls, named after their discoverer Felix Bloch. If there is no external magnetic field, the individual Weiss domains are oriented randomly. Therefore the resulting magnetization is zero (see fig.4).

If we apply an external magnetic field of sufficient strength, the magnetic moments of the individual Weiss domains are oriented in the direction of the external field and Bloch walls are displaced, resulting in an increase of the domains aligned with the external field. During this alignment the spinning electrons whose direction is changed makes a damped processional motion around the direction of the magnetic field as we know it in the mechanics from a gyro. If the procession has stopped, all magnetic moments are in the direction of the external magnetic field and the ferrite has its saturation magnetization.

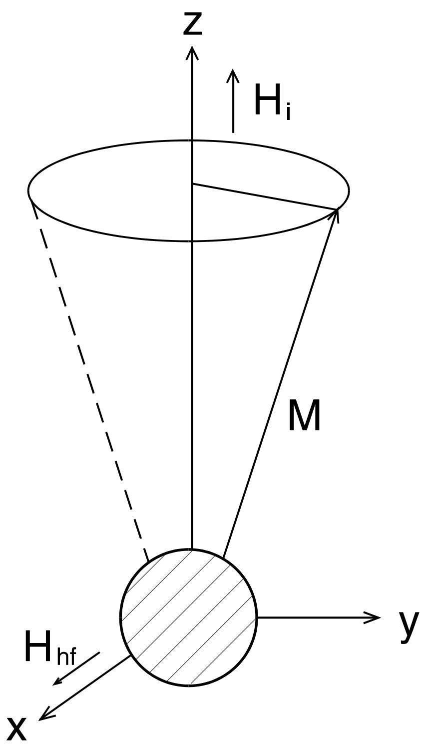


Fig.5: Precession of the spinning electron

If a small alternating rf field of a suitable frequency is applied perpendicular to the direction z of the strong static magnetic field H_i, e.g in the x-direction as shown in figure 5, the magnetic Moment M processes around the direction of H_i. Therefore there is not only a component of the magnetic moment in the x-direction but also one in the y-direction. Now the µ in the relationship between induction B and magnetic field H is no longer scalar but a tensor, known as the Polder tensor [1]. And we can write the relationship between B and H as follows:

$$\begin{aligned} B_x &= myH_x - j\kappa H_y \\ B_y &= j\kappa H_x + myH_y \\ B_z &= my_0 H_z \end{aligned} \qquad (3.1)$$

or expressed as a tensor

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \begin{pmatrix} my & -j\kappa & 0 \\ j\kappa & my & 0 \\ 0 & 0 & my_0 \end{pmatrix} \begin{pmatrix} H_x \\ H_y \\ H_z \end{pmatrix} \qquad (3.2)$$

The value of the induction component perpendicular to the magnetic rf field is determined by the value of κ. The values of $\mu = \mu' - j\mu''$ and $\kappa = \kappa' - j\kappa''$ are complex and depend on the static magnetic field, the frequency, and the material properties of the ferrite.

If the magnetic plane of an electromagnetic wave is parallel to H_i, the relative permeability is $\mu_{eff\parallel} = \mu_0$, for the ferrite is saturated. The propagation speed is

$$\gamma_{\parallel} = j\omega\sqrt{\epsilon my_0} \qquad (3.3)$$

The ferrite has no gyromagnetic effect on the wave.

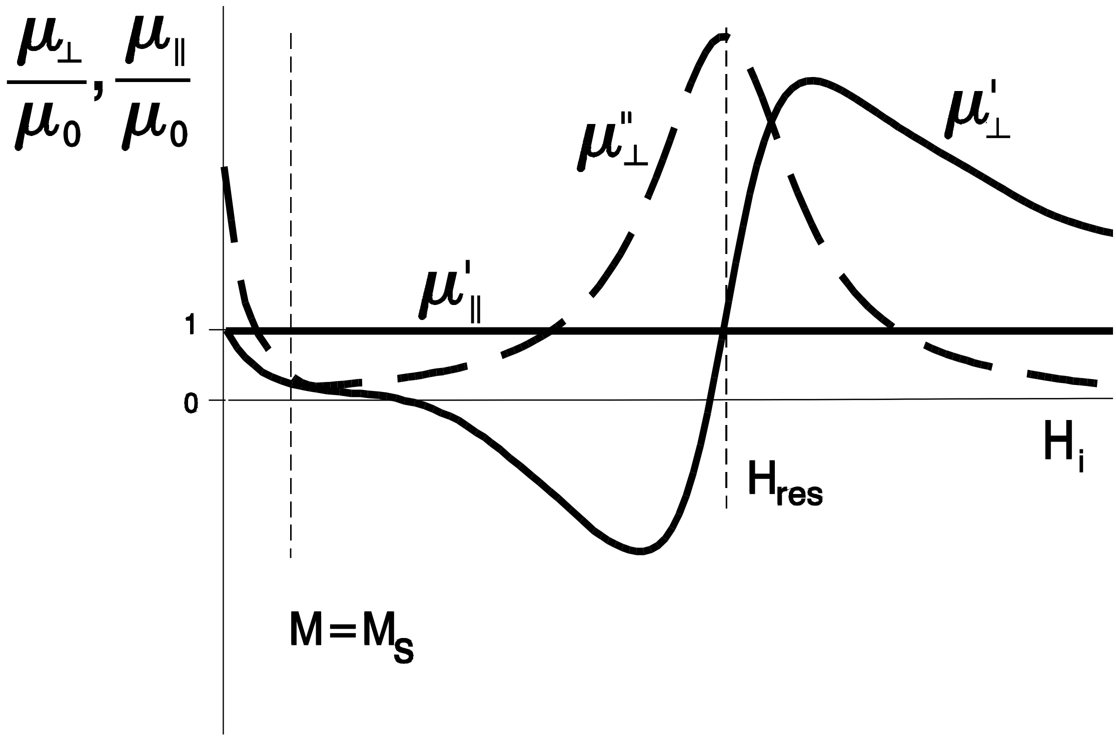


Fig.6: $\mu_{eff\parallel}$ and $\mu_{eff\perp}$ of a microwave ferrite as a function of the static magnetic field H_i

If the magnetic plane of the electromagnetic wave is perpendicular to H_i, the relative permeability is

$$my_{eff\perp} = \frac{my^2 - \kappa^2}{my} \qquad (3.4)$$

and the propagation constant

$$\gamma_{\perp} = j\omega\sqrt{\epsilon my_{eff\perp}} \qquad (3.5)$$

Figure 6 shows the real and imaginary parts of $\mu_{eff\parallel}$ and $\mu_{eff\perp}$ as a function of H_i. In the vicinity of the resonant value H_{res} of the static magnetic field the losses in the ferrite, represented by $\mu''_{eff\perp}$, rise steeply, for the precessional motions of the electron spins are generated by the components perpendicular to the static field.
If a circular polarized wave with a plane perpendicular to the direction of the magnetic field is polarized clockwise (+), the interaction with the electron spins results in a permeability of $\mu_+=\mu-\kappa$. The corresponding propagation speed is

$$\gamma_+ = j\omega\sqrt{\epsilon m y_+} \qquad (3.6)$$

The Ferrite has no gyromagnetic effect on the wave.

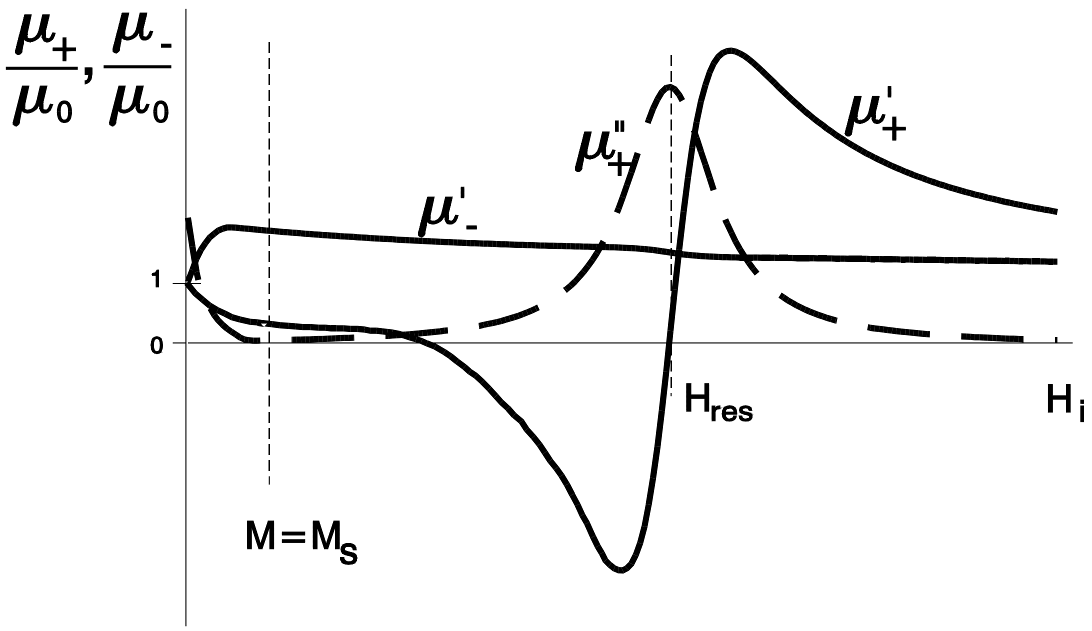


Fig.7: μ_+ and μ_- of a microwave ferrite as a function of the static magnetic field H_i

If the polarization of the wave is anti-clockwise (-), the interaction with the electron spins give the permeability $\mu_-=\mu+\kappa$, and the propagation speed is

$$\gamma_- = j\omega\sqrt{\epsilon m y_-} \qquad (3.7)$$

Figure 7 gives μ_+ and μ_- as a function of the magnetic field. μ_+, which rotates in the same direction as the electron spins, shows a resonance, for it causes them to precess, μ_- counteracts the precession, and therefore there is no resonance.

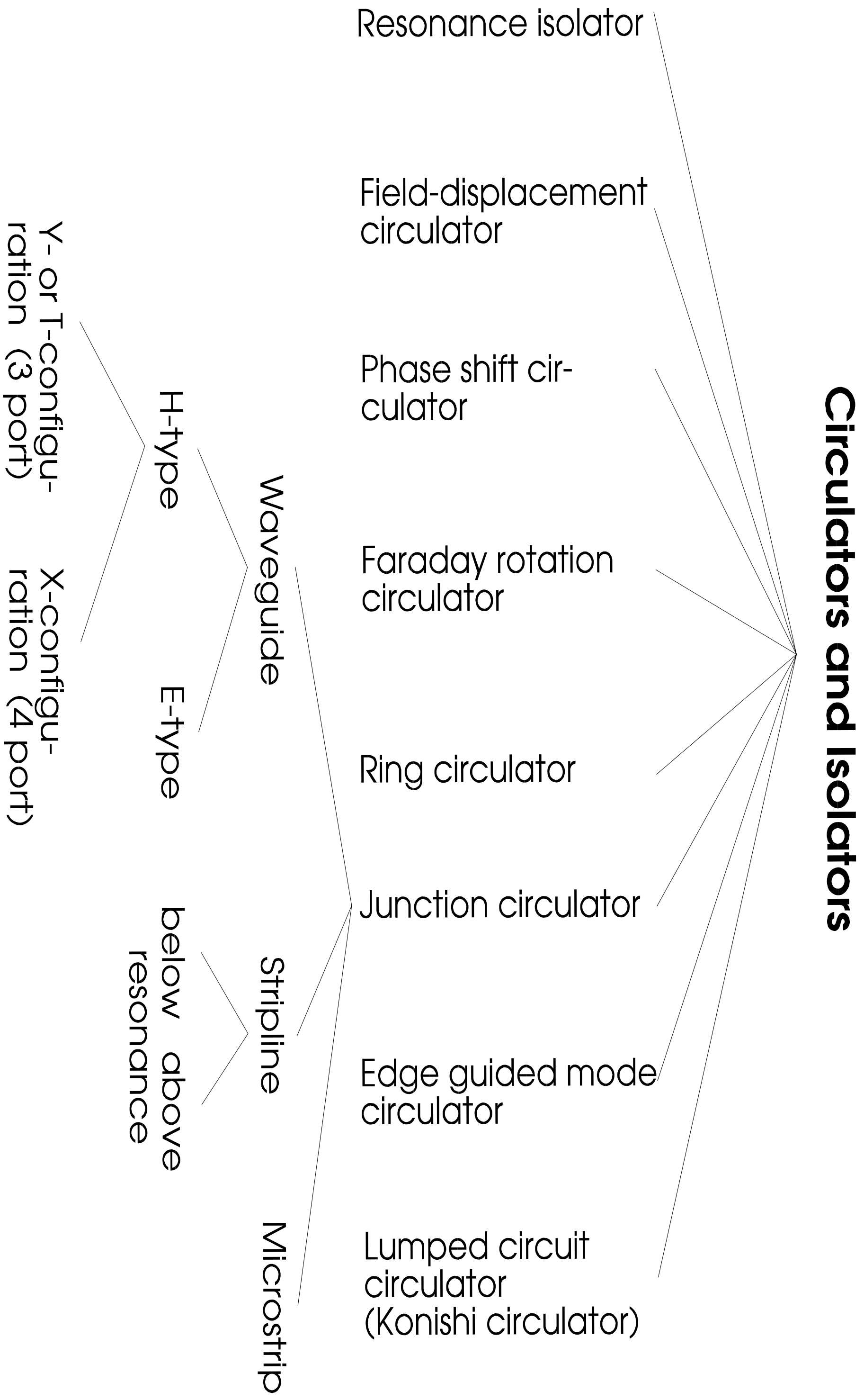

Circulators and Isolators
Resonance isolator
Field-displacement circulator
Phase shift cir-
culator
Faraday rotation circulator
Ring circulator
Junction circulator
Edge guided mode circulator
Lumped circuit circulator (Konishi circulator)
Waveguide
Stripline
Microstrip
H-type
E-type
below resonance
above resonance
Y- or T-configu-
ration (3 port)
X-configu-
ration (4 port)

Figure 8

4. Principles of operation and construction

The behavior of ferrites described in chapter 3 is the basis for different modes of operation for circulators and isolators. Figure 8 gives a survey.

4.1 Resonance isolator

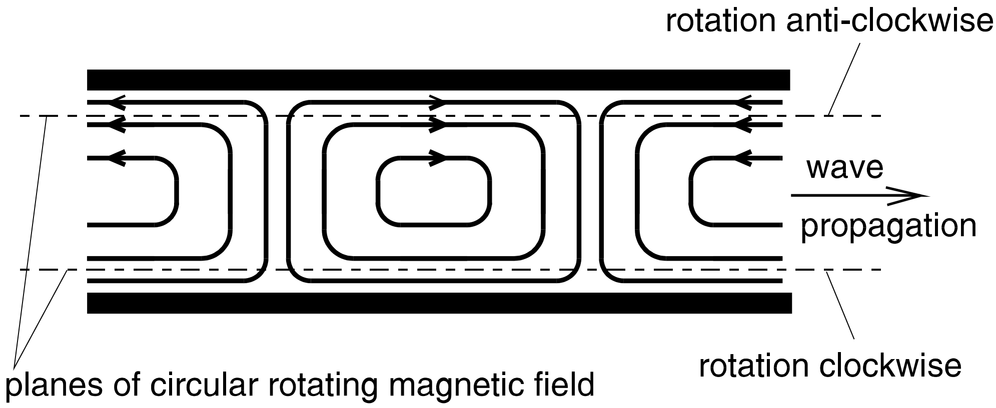


Fig.9: Rectangular waveguide with H_{10}-mode

Resonance isolators are constructed in rectangular waveguides carrying the fundamental mode H_{10}. In two planes parallel to the small sides of the waveguide the magnetic field of the wave is circular rotating, in one direction of the wave propagation clockwise, in the opposite direction of the wave propagation anti-clockwise (see figure 9). The position of these planes is frequency dependant.

If we put ferrite slabs in these planes and magnetize them to the resonance field H_{res} as shown in figure 6, we get an isolator: the wave with μ_- has low losses in the ferrite, the opposite travelling wave with μ_+ has high losses and is damped.

Figure 10 shows the principle construction of such an isolator. The ferrites are in contact with the waveguide walls to transfer the heat generated in the ferrite to the waveguide. In principle the isolator is a small band device, for the resonance peak giving the isolation is not broad. But if we shape the static magnetic field we can make it broader.

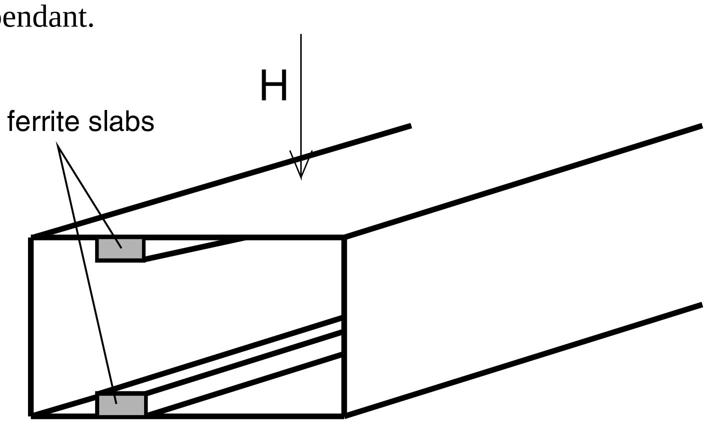


Fig.10: Principle construction of a resonance isolator

These devices are heavier compared with others and are not often used nowadays.

4.2 Field displacement circulator

Also the field displacement circulator [2] is built in rectangular waveguide with the H_{10}-mode and uses the planes of circular rotating magnetic rf fields. But the static magnetic field is not adjusted to the resonance but much lower.
A ferrite slab extending from one broad side to the other will influence the H_{10}-mode in such a way, that for a wave travelling in one direction the electrical field is taken into the ferrite giving a high value on one side of the slab, and pushing it out if the wave travels in the opposite direction giving a very low value on that side of the slab (see fig.11).

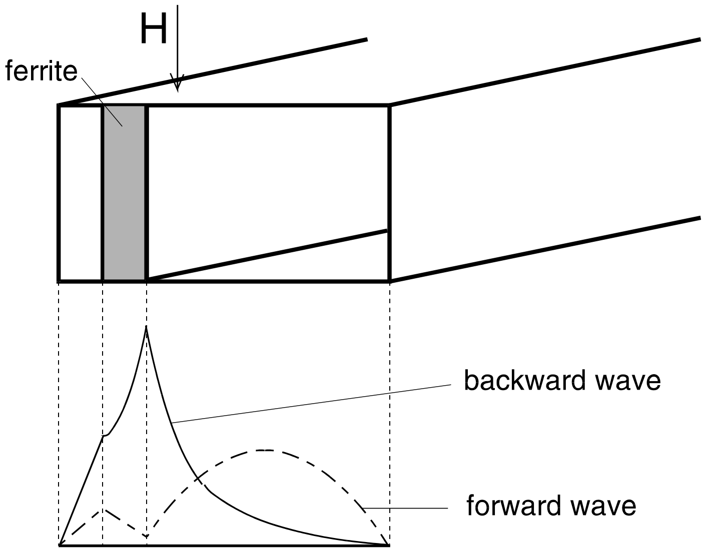


Fig.11: Electrical field of a field displacement circulator with a ferrite extending from one broad side to the other

Although it is possible to make circulators with this phenomenon, the practical devices are isolators. Figure 12 shows the common construction.
A ferrite slab smaller than the small side of the waveguide is situated in one of the planes of circular rotating rf fields. On the inner side of the slab a resistive layer is put, often in thick film techniques. In the forward direction of the isolator the electric rf field in this plane is a minimum, resulting in low insertion loss. In the backward direction the rf field in this plane is high and the wave is damped by the resistive layer, giving high isolation. The value of this isolation can be increased by increasing the length of the isolator. A ceramic slab clad to the ferrite is used to increase the bandwidth of the isolator by fixing the minimum and the maximum of the rf fields in the plane of the resistive layer.

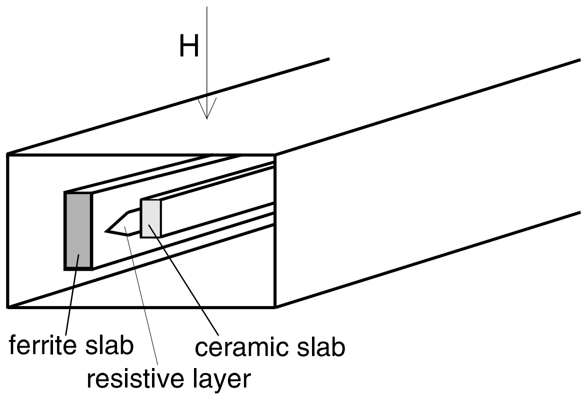


Fig.12: Principle construction of a field displacement isolator

4.3 Phase shift circulator

The phase shift circulator is built in rectangular waveguide with the H_{10}-mode. It uses three elements:

- a folded magic tee
- a non-reciprocal phase shifter
- a 3dB-coupler

see figure 13.

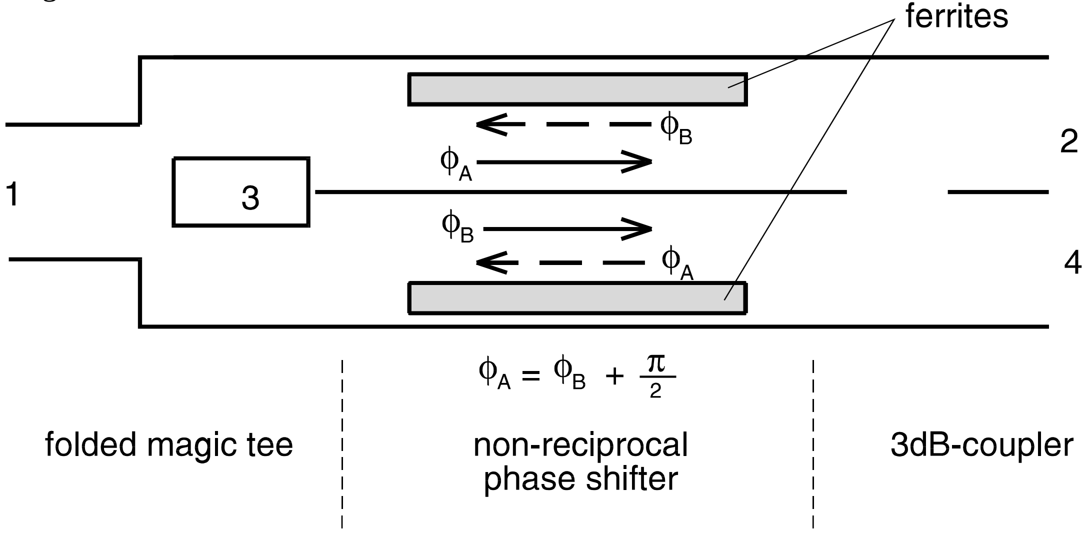


Fig.13: Principle construction of a phase shift circulator

A wave entering port 1 of the magic tee is split into 2 waves of equal energy and equal phase, which enter the non-reciprocal phase shifter. The first wave will be shifted by the non-reciprocal phase shifter by ϕ_A, the second wave by ϕ_B, where $\phi_A = \phi_B + 90$ degrees. In the 3dB-coupler the two waves are split again into two equal parts, but the wave going to the other guide is delayed by 90 degrees. Therefore the waves add at port 2 and cancel each other at port 4.

A wave entering port 2 is split in the 3dB-coupler into 2 waves with equal amplitude but 90 degrees phase difference. The first one will be shifted by ϕ_B, the second by ϕ_A. In the magic tee both waves combine and cancel each other at port 1, but add at port 3, and so on.

The principle construction of the non-reciprocal phase shifter is the same as the resonance isolator. But the permanent magnetic field is lower than for resonance. The interaction of the rf wave with the spinning electrons give a delay in one direction and no effect in the other. Thickness and length of the ferrite slabs, and the permanent magnetic field are chosen to give a phase difference of 90 degrees.

The phase shift circulator is used for high power handling. The construction is bulky, especially for high cw power (e.g. 1.5 MW_{cw} at 500 MHz).

4.4 Faraday rotation circulator

The Faraday rotation circulator [3] is based on the rotation of the polarization plane of an rf wave by the magnetic moments of the ferrite.
A H_{10}-wave in a rectangular waveguide traverses via a transition into a round waveguide and forms the linear polarized H_{11}-wave. In the middle of the linear waveguide there is a round ferrite rod magnetized in the direction of the rod.

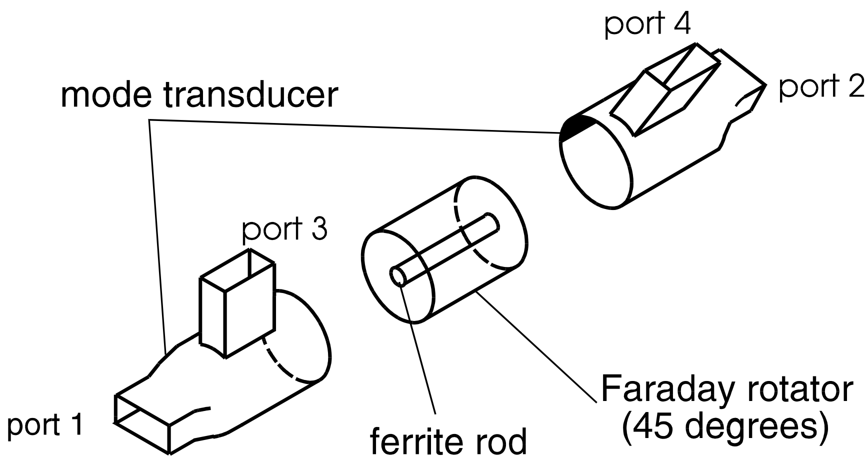


Fig.14: Principle construction of a Faraday rotation circulator

We can split a linear wave into two circular rotating waves, one rotating clockwise, the other anti-clockwise when looking in the direction of propagation. These two waves interact with the electron spins of the ferrite rod and have the propagation speed μ_+ and μ_- which differ from each other. If we combine the two rotating waves after they have travelled some distance, we get a linear wave again, but rotated some degrees.
The length of the ferrite rod and the magnetic field are chosen for a rotation of 45 degrees. Another transition from round waveguide to rectangular waveguide finishes the circulator (see figure 14). A H_{10}-wave entering port 1 is transformed to the round waveguide. The ferrite rotates the wave clockwise by 45 degrees. The second transition transforms it to the rectangular waveguide which has also an angle of 45 degrees with respect to the first rectangular waveguide, and the wave leaves the circulator at port 2. A wave entering port 2 travels in the opposite direction and is also rotated clockwise by 45 degrees. Now it is perpendicular to the waveguide of port 1, but can leave the circulator at port 3, etc.
Most of the devices using the Faraday rotation are not circulators but isolators. They have only the input and output ports 1 and 2 and absorb the waves perpendicular to them by resistive sheets.
Faraday rotation isolators are built for very high frequencies and nowadays for optical isolators for fibre cables.

4.5 Ring circulator

The ring circulator is a circulator discussed in theory, but not really used in practice. It is formed out of three junctions and three nonreciprocal phase shifters (see figure 15). A wave entering port 1 is split into one going clockwise around and another going anticlockwise around the circulator ring. The phase shift of the nonreciprocal phase shifters is adjusted so, that they cancel each other at port 3 and add up at port 2 and leave the circulator.

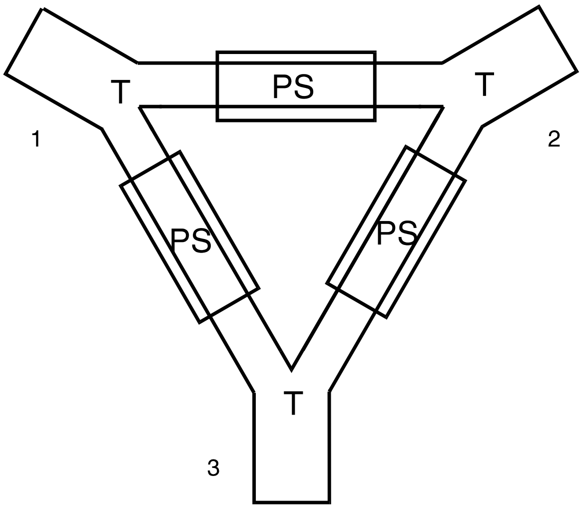


Fig.15: Principle construction of a ring circulator
T reciprocal T-junction
PS non-reciprocal phase shifter

4.6 Junction circulator

The junction circulator is the most common circulator. It is done in waveguide, in tri-plate mostly with coaxial connectors, and in microstrip.
Let us start with a tri-plate circulator. The principle construction is given in figure 16: between two outer conductors are two ferrite discs, and between them the inner conductor. This inner conductor forms a resonator and the matching networks to the ports. Two magnets out-side the outer conductors give the static magnetic field.

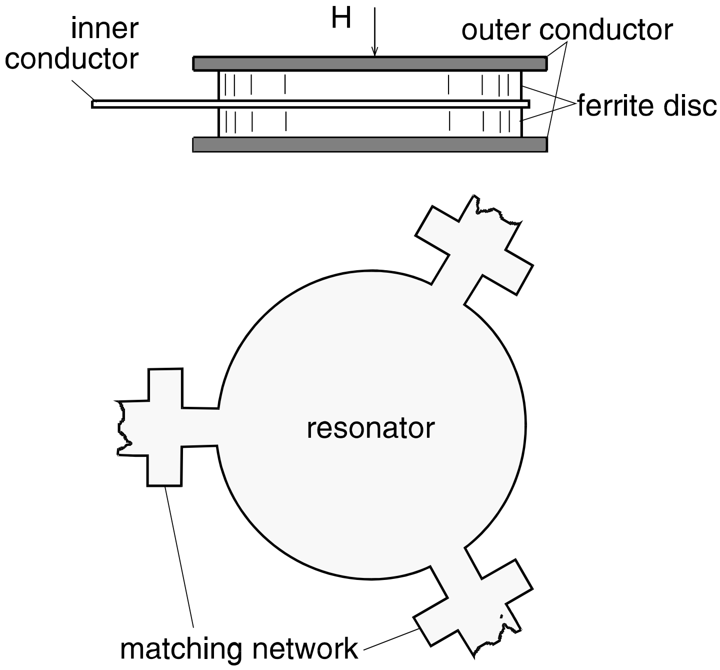


Fig.16: Principle construction of a tri-plate junction circulator

Fay and Comstock [4] explained the operation in the following way (see fig 17):
Without a permanent magnetic field a wave entering port 1 is split into two rotating waves with the same propagation speed, one rotating clockwise, the other anti-clockwise, giving a standing wave pattern in the resonator, which is coupled to port 2 and port 3. The incoming wave is divided and half of the power leaves port 2, the other half port 3 (figure 17a).

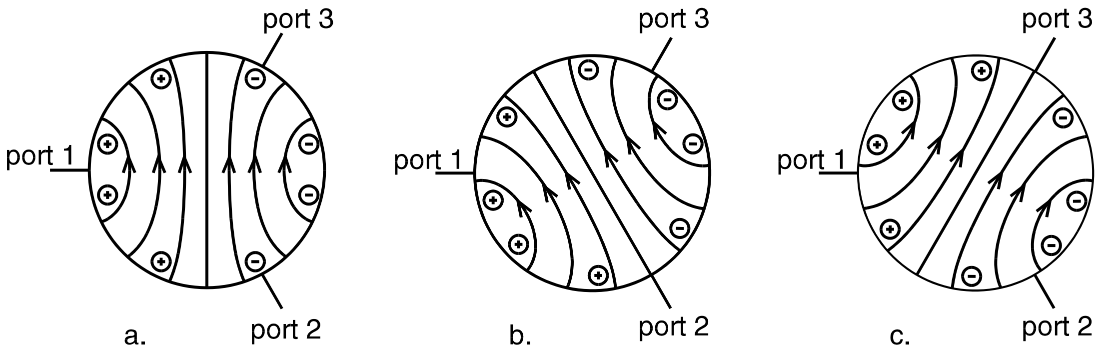


Fig.17: Standing wave pattern of a junction circulator
a. unmagnetized
b. magnetized below resonance
c. magnetized above resonance

With a permanent magnetic field supplied perpendicular to the ferrite discs, the propagation speed of the two rotating waves is no longer the same. The wave rotating clockwise has now the propagation speed γ_+, the wave rotating anti-clockwise the propagation speed γ_-. This results in a rotation of the standing wave pattern. By increasing the magnetic field the standing wave pattern rotates anti-clockwise. If the angle of rotation is 30 degrees, the device is a circulator (see figure 17b): Port 3 is decoupled and all energy passes from port 1 to port 2.
But there is also another magnetic field for circulator operation. If we use a much higher magnetic field and adjust it so, that the standing wave pattern is rotated 30 degrees clockwise, port 2 is decoupled and all energy passes from port 1 to port 3 (see figure 17c).
For the first mode of operation we need a static magnetic field lower than for putting the ferrite into resonance, therefore this mode is called below resonance, for the second mode of operation the magnetic field is higher than for resonance, therefore we call this mode above resonance.
Tri-plate junction circulators are made as above resonance circulators in the frequency range 150 MHz to about 2 GHz and as below resonance circulators in the frequency range 1.5 to 20 GHz.

The operation of microstrip junction circulators is very similar as this of tri-plate circulators. They operate in the below resonance mode.
Also waveguide junction circulators operate below resonance. Figure 18 shows the principle construction. The operation can be explained in the same way as for the tri-plate circulator.

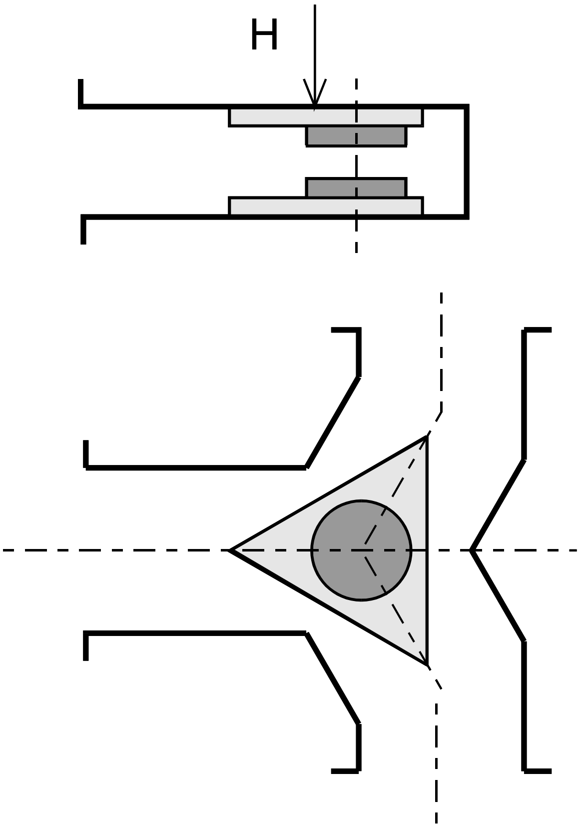


Fig. 18: Principle construction of a waveguide junction circulator

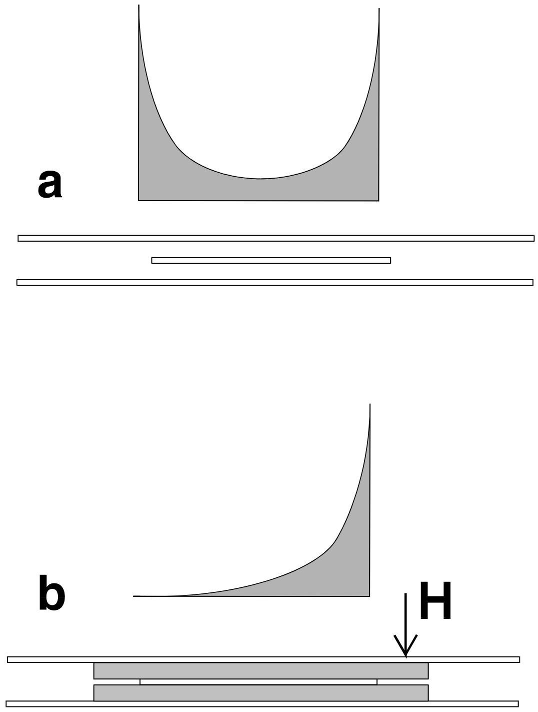


Fig.19: Current density in a broad inner conductor of a tri-plate line
a. normal line
b. line filled with ferrite and magnetized perpendicular

4.7 Edge guided mode circulator

In broad tri-plate or microstrip lines the rf currents run on the two edges of the inner conductor (see figure 19a). Is there a microwave ferrite between inner and outer conductor biased with a permanent magnetic field perpendicular to the line, then the rf current runs on one edge of the inner conductor only for the forward wave and on the other for the backward wave (see figure 19b).
This behaviour can be used for the construction of circulators, but normally very broadband isolators (broader than one octave) are made by this effect. In figure 20 such an isolator is shown schematically. The wave coming from the input passes at first a

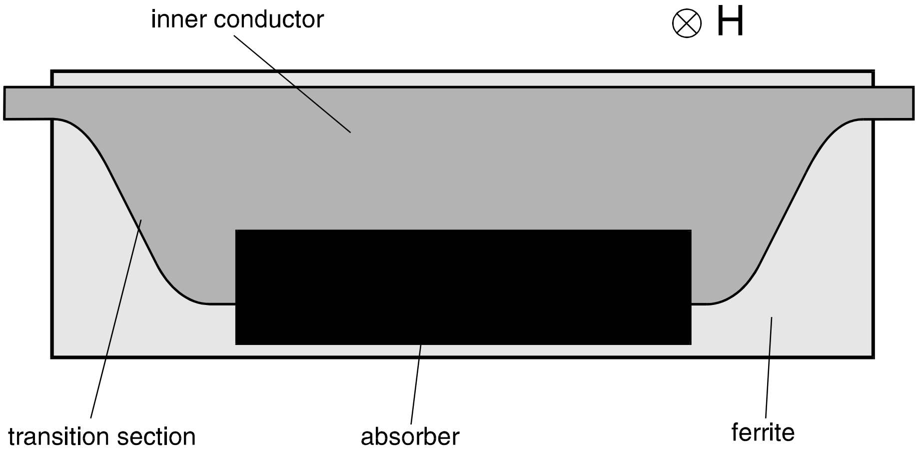
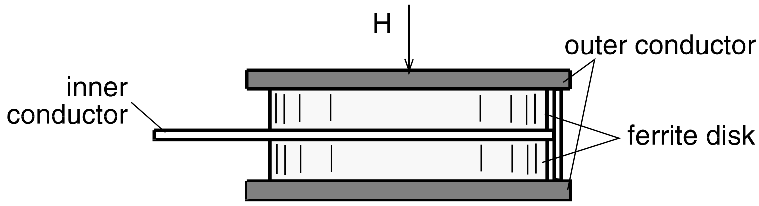


Fig. 20: Principle construction of an edge guided mode isolator

transition to the broad stripline. In the forward direction it runs nearly unattenuated on the left edge of the inner conductor of this line and reaches the second transistion and finally the output. The wave entering the isolator at the output passes the second transition to the broad stripline and runs on the right edge of the inner conductor. Here it comes to the damping material and will be attenuated.

The operation of the edge guided mode circulator is very similar to the operation of the field displacement circulator in the waveguide.



4.8 Lumped element circulator

For low frequencies the principles of operation described up till now give too big and too heavy constructions. This is the domain of the circulators built of lumped elements. The core of them is the non-reciprocal junction, often called isoductor.

Figure 21 shows the principle construction of such an

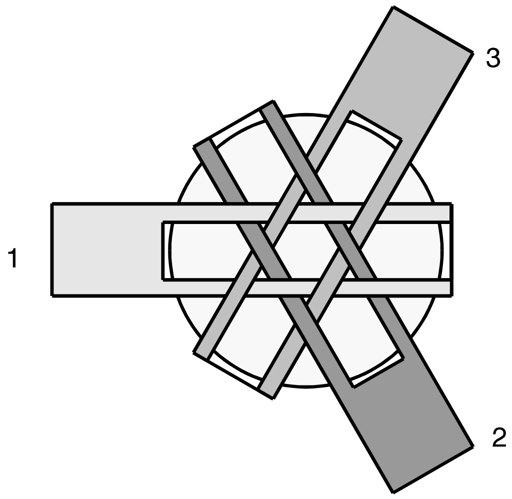


Fig. 21: Principle construction of an isoductor

isoductor: three inner conductors coming from the three ports cross under an angle of 120 degrees and are connected to the outer conductors at the other end. They are isolated from each other where they cross each other. Between the inner and outer conductors there are two ferrite disks, magnetized by a permanent magnetic field.
An rf current in inner conductor 1 generates in the ferrite disks an rf magnetic field perpendicular to the plane of the loops, which it makes together with the outer conductors. Due to the properties of the ferrite the rf magnetization is not in the same direction, as we can see in the Polder tensor page 3. The angle between the rf magnetic field and the rf magnetization depends on the frequency and the permanent magnetic field. If we adjust the permanent magnetic field so that the rf magnetization is parallel to the inner conductor 3, then loop 3 is not induced but only loop 2: an excitation of inner conductor 1 will be coupled to inner conductor 2 but not to inner conductor 3, inner conductor 3 is decoupled.
If we look from outside into one port of the isoductor, we see an inductance parallel to a resistor (see figure 22).
The simplest way to make a ciculator out of this isoductor is given in figure 23: We bring the inductance of the isoductor into resonance by a parallel capacitor and match the whole to the line by a series capacitor. With more complicated networks we can build broadband circulators with a band-width of up to one octave.

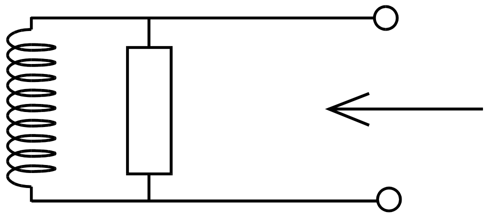


Fig.22: Equivalent circuit of an isoductor

Lumped element circulators can be made for frequencies between 30 MHz and about 2 GHz, but normally they are used between 50 and 500 MHz.

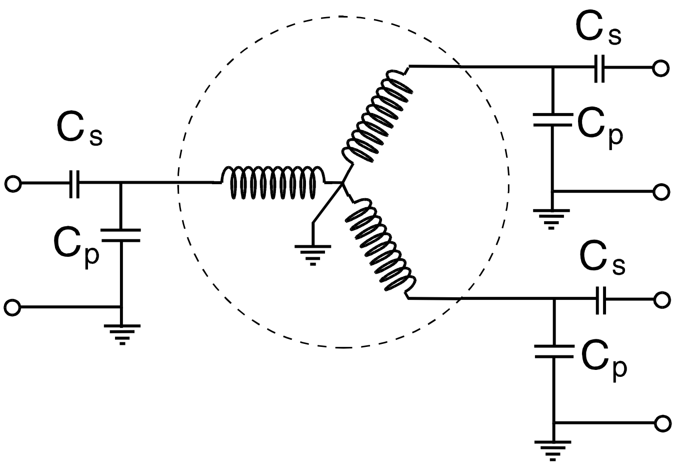


Fig. 23: Small band lumped element circulator

6. Correlation of parameters of a symmetrical 3-port-circulator

6.1 The lossless symmetrical 3-port- circulator

The relationship of the input waves a_n and the output waves b_n of a 3-port-circulator (see figure 24) can be written as

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} \cdot \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} \qquad (6.1)$$

or

$$b = S \cdot a \qquad (6.1a)$$

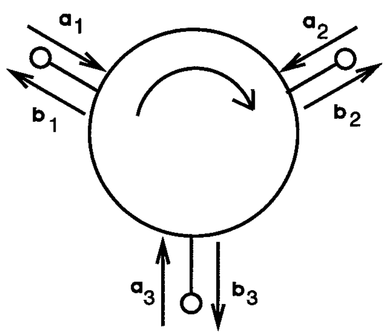


Fig. 24: Input and output waves

with S_{nm} the scattering parameters and S the scattering matrix respectively. The non-reciprocal behaviour of the circulator is reflected in the asymmetry of the scattering matrix:

$$\begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} \neq \begin{pmatrix} S_{11} & S_{21} & S_{31} \\ S_{12} & S_{22} & S_{32} \\ S_{13} & S_{23} & S_{33} \end{pmatrix} \qquad (6.2)$$

that means $S_{12} \neq S_{21}$, $S_{13} \neq S_{31}$, $S_{23} \neq S_{32}$. If we assume that the circulator is lossless, then the sum of the input powers is equal to the sum of the output powers, or in the expressed in the form of a matrix: the product of the scattering matrix S with the transposed and conjugate complex scattering matrix S'^{*} equals the unity matrix

$$\begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} \cdot \begin{pmatrix} S_{11}^* & S_{21}^* & S_{31}^* \\ S_{12}^* & S_{22}^* & S_{23}^* \\ S_{13}^* & S_{23}^* & S_{33}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (6.3)$$

or

$$S \cdot S^{|*} = E \qquad (6.3a)$$

If we assume,

that our circulator is cyclically symmetrical, then we can write

$$= S_{22} = S_{33} = S_1 \qquad \text{the input reflexion of the ports}$$
$$= S_{23} = S_{31} = S_2 \qquad \text{the isolation of the circulator} \qquad (6.4)$$
$$= S_{13} = S_{32} = S_3 \qquad \text{the insertion loss of the circula}$$

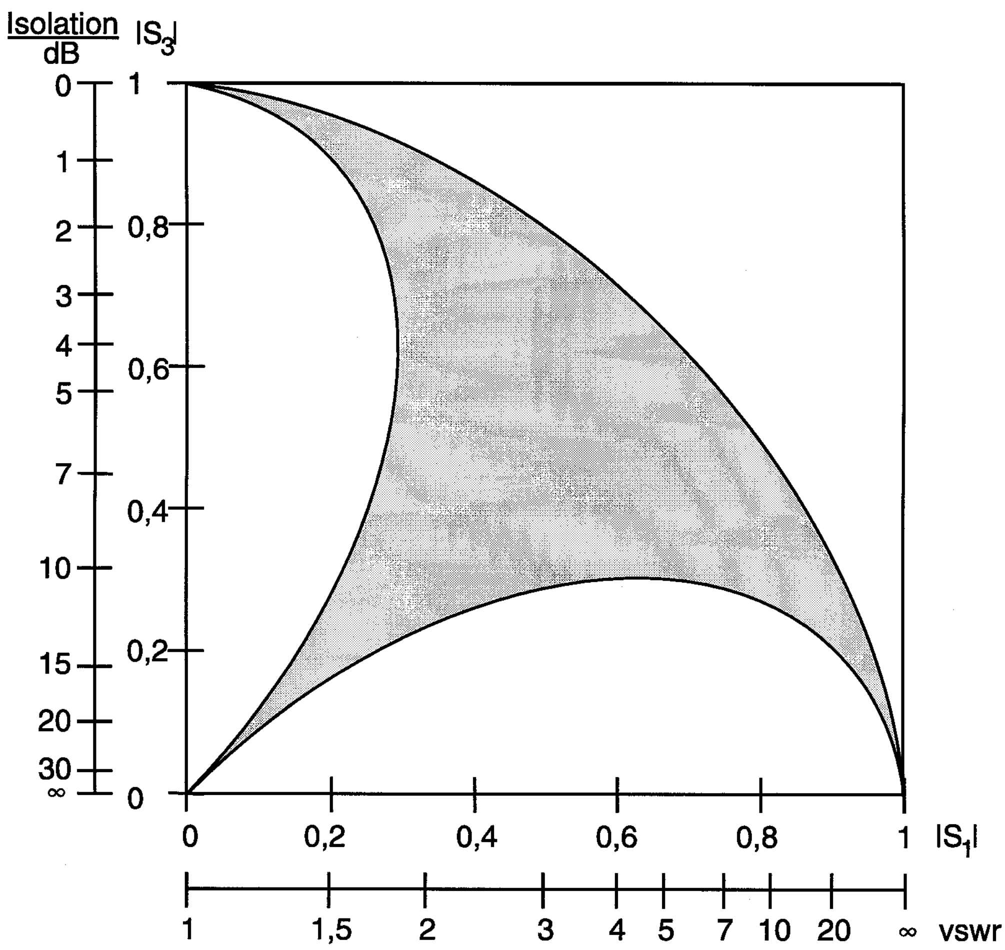


Fig. 25: Permissible area for $|S_1|$ and $|S_3|$

but for the reason of non-reciprocity $S_2 \neq S_3$. Now we can write the scattering matrix more simple:

$$S = \begin{pmatrix} S_1 & S_2 & S_3 \\ S_3 & S_1 & S_2 \\ S_2 & S_3 & S_1 \end{pmatrix} \qquad (6.5)$$

If we combine now the scattering matrix (6.5) and the matrix equation (6.3a), then we get

$$\begin{aligned} S_1^* S_1 + S_2^* S_2 + S_3^* S_3 = |S_1|^2 + |S_2|^2 + |S_3|^2 &= 1 \\ S_1^* S_2 + S_3^* S_1 + S_2^* S_3 &= 0 \\ S_1^* S_3 + S_3^* S_2 + S_2^* S_1 &= 0 \end{aligned} \qquad (6.6)$$

These relationships show us that not all combinations of S_1, S_2, and S_3 are possible for a lossless, cyclical symmetrical 3-port-circulator (see Butterweck [6]). The permissible combinations of e.g. $|S_1|$ and $|S_3|$ values can be given graphically as a curved triangle in the $|S_1|$,$|S_3|$-plane limited by elliptical curves as given in figure 25 as a shaded area.
In this figure we find for high isolation, that means low $|S_3|$, two permissible regions for the input vswr or $|S_1|$, one for low vswr ($|S_1| \approx 0$) and a second one, which is not of interest for circulators, for very high vswr ($|S_1| \approx 1$).

6.2 The lossy symmetrical 3-port-circulator

For a lossy 3-port equation (6.3) is not valid. We have to replace it by

$$(E - S^{|*} \cdot S) \quad \textit{positive semidefinite} \qquad (6.7)$$

That means for a lossy symmetrical 3-port-circulator that the permissible combinations of e.g. $|S_1|$ and $|S_3|$ values can lie also a bit outside of the curved triangle of figure 25, depending on the value of the loss. E.Schwartz and H.Bex calculated the new boundaries in [7]. Figure 26 presents the results for the region of high isolation (low $|S_1|$) and low vswr (low $|S_3|$ values).
From figure 26 we can see, that the permissible area for the vswr and isolation is not restricted to the small region of the lossless 3-port-circulator given in figure 25 but broadens with increasing insertion loss. For example for a vswr of 1.2 and an insertion loss of 0.2 dB in the isolation can lie between 19 and 24 dB while in the lossless case it is around 21 dB.
Figure 26 gives the theoretical limits of the relationships between vswr and isolation. In practice the values measured are closer to the lossless case.

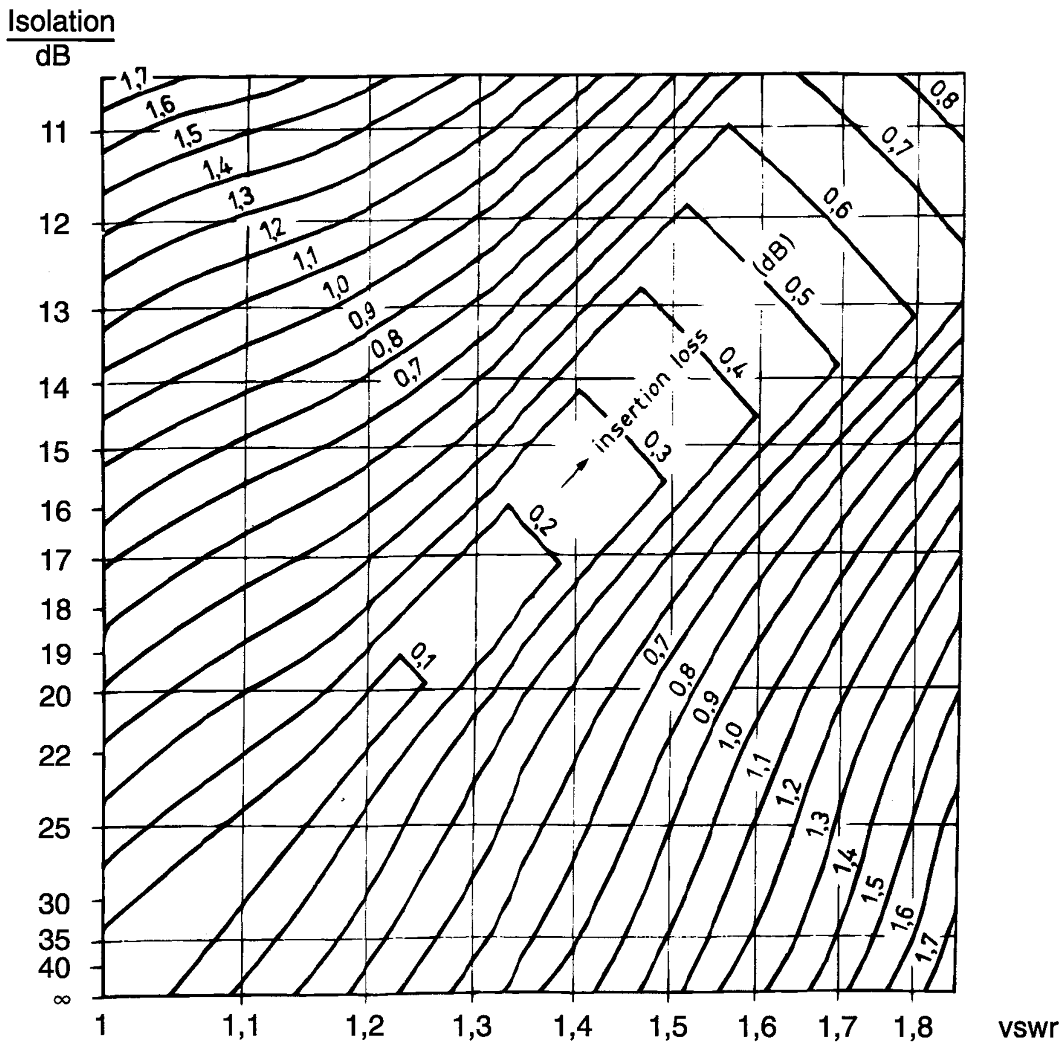


Fig. 26: Permissible combinations for a lossy symmetrical 3-port-circulator with low vswr and high isolation with the insertion loss as a parameter

7. Application

Circulators and isolators can be used

for

- ♢ decoupling - of generator and load of amplifier stages
- ♢ reducing
  - intermodulation caused by other transmitters
  - load return loss and vswr
- ♢ combining
  - two and more transmitters
  - transmitters and receivers on the same antenna
  - amplifier stages in solid state transmitters
- ♢ operating one-port-amplifiers
- ♢ duplexing
- ♢ locking and priming of oscillators

in

- broadcast and TV - transmitters
- radio links and navigation
- air traffic control
- radar systems
- military equipment
- car telephone systems
- measurement systems
- industrial microwave heating applications
- magnetic resonance tomography

7.1 Decoupling of generator and load

Generators are influenced by their loads resulting in frequency shift (pulling), instabilities, and, if a long line connects generator and load, even frequency jumping under certain conditions (long line effect). To avoid this we can put an attenuator of e.g. 10 dB between generator and load to attenuate the reflected signal by 20 dB (see figure 27a). This will result in high losses in this attenuator.

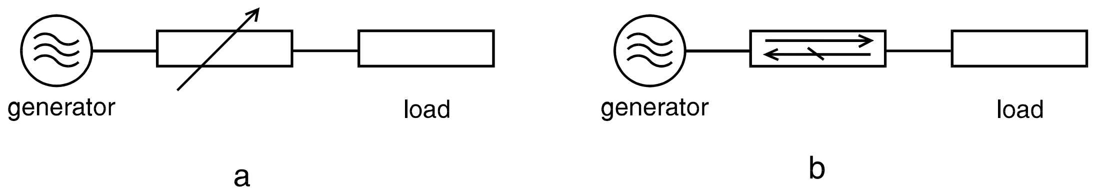


Fig. 27: Decoupling of generator and load
a. with a variable attenuator
b. with an isolator

An isolator of 20 dB isolation instead of the attenuator will do the same job (figure 27b). But the attenuation is now only the insertion loss of the isolator, normally less then 0.5 dB.

7.2 Decoupling of amplifier stages

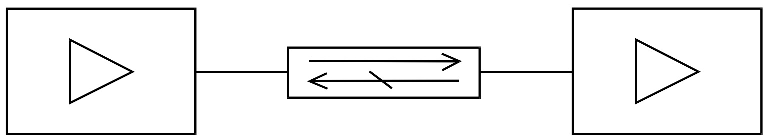


Fig. 28: Decoupling of amplifier stages

The different stages of an amplifier influence each other, especially if they are small-banded. If they are decoupled by isolators (see figure 28) each stage can be tuned and adjusted without affecting the others. And if one stage fails, the others will not be overloaded. Also the time interval for readjusting power transmitters can be extended very much in this way. Especially between the driver stages and klystrons or inductive output tubes (IOT's) as final amplifiers isolators are highly recommended for decoupling them.

7.3 Decoupling of a transmitter or receiver from its antenna

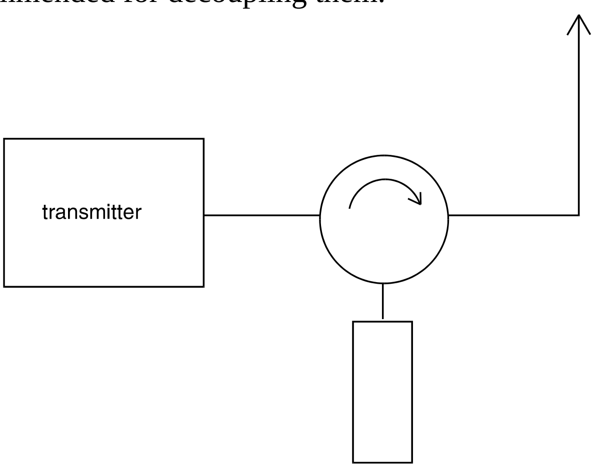


Fig. 29: Decoupling of a transmitter from its antenna

If a transmitter is connected to an antenna it may be influenced by impedance changes of the antenna caused e.g. by snow or near-by obstacles. This can be avoided by an isolator with an isolation of about 20 dB (figure 29).
Furthermore other antennas in the neighbourhood may couple signals into the antenna, which travel to the amplifier. The final stage operates in class B or C to

give high efficiency resulting in very non-linear behaviour. Therefore the induced signal will mix with the signal of the amplifier giving intermodulation.
The intermodulation can be reduced by an isolator. But here often a normal isolator with an isolation of 20 dB is not sufficient. To reduce the level of the intermodulation products to the desired value normally double isolators with an isolation of about 50 dB are required.
The input stage of a receiver is often a low noise amplifier which input impedance is chosen to give a very low noise figure but no match to the antenna. An isolator between the antenna and the input of the receiver will get rid of this problem.

7.4 Transmitter and receiver on the same antenna

If we operate one transmitter and one receiver on the same antenna tuned to different frequencies, normally we use two sharp and expensive filters to avoid interaction between them (see figure 30a). Using a circulator for branching, only one inexpensive filter is necessary at the input of the receiver, for the power of the transmitter at the input of the receiver branch is reduced by more than 10 dB by the circulator, depending on the impedance of the antenna (figure 30b).

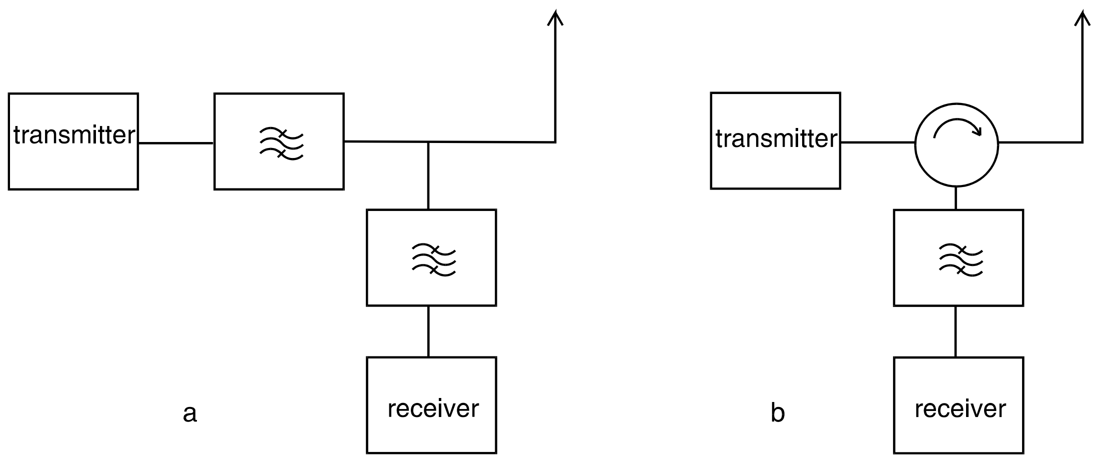


Fig. 30: Transmitter and receiver on the same antenna
a. conventional solution
b. solution with a circulator

7.5 Combiner for 2 or more transmitters in the VHF- and UHF-bands

Combining 2 or more transmitters e.g. for the operation on one antenna is done conventionally in the following way (see figure 31a): each 2 transmitters are connected to a 3-dB-hybrid. One output arm is terminated to a matched load, the other goes to the antenna, if we have to combine 2 transmitters only, or to the next 3-dB-hybrid. If we have to combine 4 transmitters as in figure 31, we have to use three 3-dB-hybrids, and the signal of each transmitter passes two of them. The losses in this coupling circuit are high: we have about 0.5 dB losses in the 3-dB-hybrid and convert half of the power in the matched load into heat. For our combiner for 4 transmitters this results in a loss of about 7 dB. If we have to combine more than 4 transmitters the losses are even higher. The frequency spacing of the transmitters is limited only by the bandwidth of the 3-dB-hybrids.

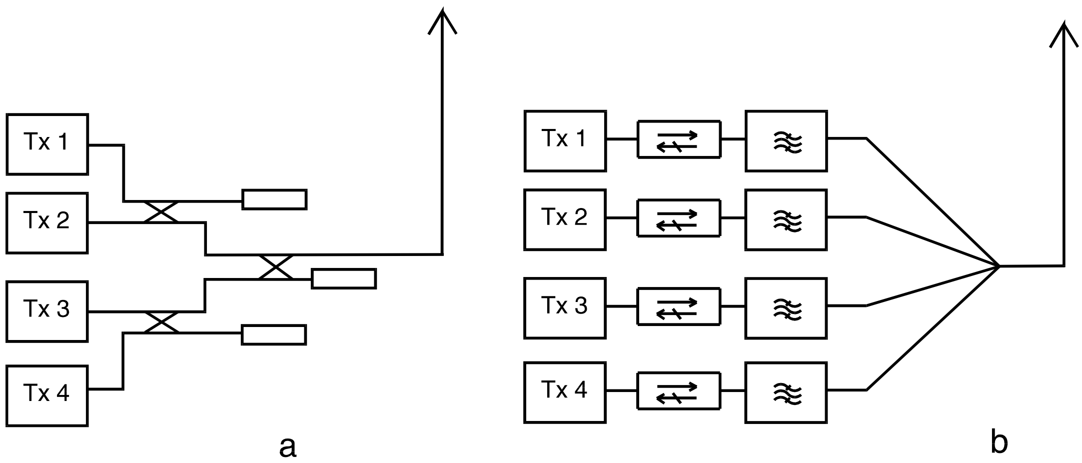


Fig. 31: Combiner for 4 transmitters in the VHF- or UHF-bands
a. conventional solution
b. solution with isolators

Using isolators we can build a completely different combiner (see figure 31b): the transmitter is connected to a cavity, which is tuned to its signal, via a double-isolator. Cables with a length of $\lambda/4$ or odd multiples of it or $\lambda/2$ or multiples of it, depending of the coupling of the cavity, connect the different cavities with a star point, which leads to the antenna.

The signal of transmitter 1 passes the isolator, which has an insertion loss of about 0.5 dB, and the cavitiy 1 and travels to the star point. The other transmitters are on different frequencies, therefore the cavities are tuned to different frequencies too, and the cables transform their impedances to a high impedance at the star point. This let the signal of the transmitter 1 travel to the antenna, attenuated about 1.5 dB by cavity 1 and losses in the cables and the other cavities. The losses in the other cavities depend on the frequency spacing, the coupling and the Q-factors of the cavities. The total loss of the signal in the combining network for the 4 transmitters of our example is typically 2 dB and does not increase significantly if we increase the number of transmitters. Up to 18 transmitters are combined in this way in the UHF-band.

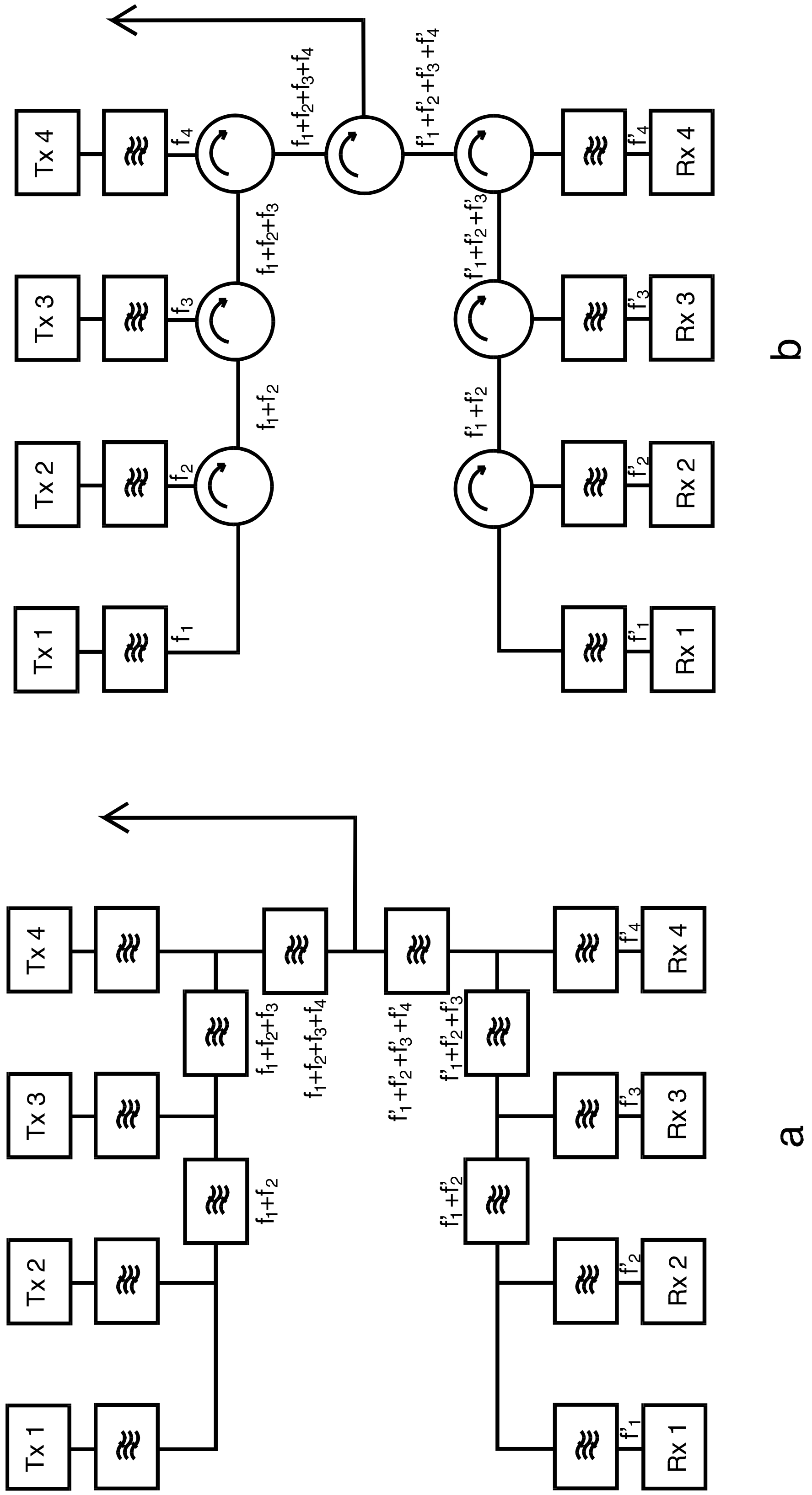


Fig. 32: Combining networks for radio links

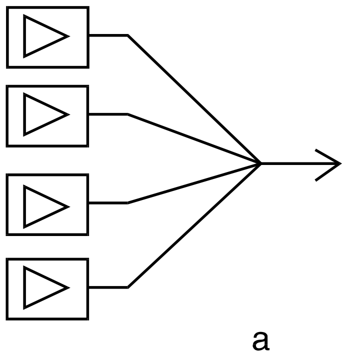
We need the double-isolators to attenuate the signals of the other transmitters leaking through the cavities. Otherwise we would run into intermodulation problems caused by the non-linearity of the final stages of the transmitters.

7.6 Combiner for radio links

For radio links operating at 2 GHz and higher the combining technique of chapter 6.5 is difficult to realize, for the line length will be very short. Here we find other solutions.
Conventionally an array of sharp filters form the combiner for a station of e.g. 4 transmitters and 4 receivers (see figure 32a), resulting in relatively high losses especially for transmitter 1 and receiver 1. Unfortunately tuning of one filter influences the neighbouring ones, making tuning a difficult task.
If we replace some of the filters by circulators (see figure 32b) we can reduce the losses and avoid influencing other filters by tuning. The circulator combining the transmitter branch and the receiver branch has to fulfill stringent requirements for intermodulation. Therefore we should use it only in waveguide systems. In coaxial systems filters are preferred in this stage.

7.7 Combining amplifier stages in a solid-state transmitter

In solid-state transmitters for high power output several transistor amplifiers operate



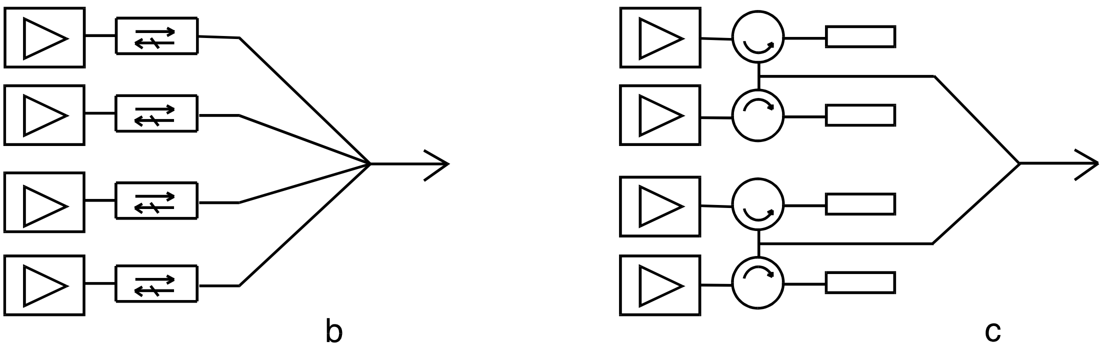


Fig. 33: Combining amplifier stages in solid state transmitters
a. by a simple star combiner
b. by using isolators
c. by combining isolators

in parallel and have to be combined. To do this with a minimum of losses often star point combiners are used, see figure 33a. But also 3-dB-hybrids can be chosen. In normal operation the transistors see the right load and work well.
But if one of the transistor amplifiers fails a big reflection is transformed to the other amplifiers. If they cannot tolerate this, they will fail too. To avoid this we can use isolators at each amplifier output, see figure 33b.
Another solution is the use of special combining isolators as given in figure 33c. Such a combining isolator consists of two isolators. The amplifiers being combined are connected to the inputs which have an impedance of 50Ω. The output of each isolator has an impedance of 100Ω, and they are connected in parallel. Therefore the output of the combiner has 50Ω again.
For proper operation of all of these combining networks the insertion phase of the amplifiers and isolators or circulators must be equal within ±5 degrees.

7.8 Operation of one-port-amplifiers

If we want to use a one-port-amplifier e.g. varactors, Gunn-amplifiers, masers, we have to construct an input and an output port for the signal being amplified. The only possibility to do it is to use a circulator as given in figure 34. The isolation of the circulator must be higher than the amplification of the amplifier to give stable operation. An isolator between circulator and receiver avoids detoriation by the input impedance of the receiver.

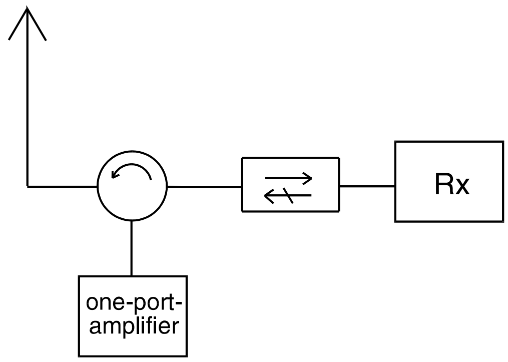


Fig. 34: Operation of a one-port-amplifier

7.9 Locking and priming of oscillators

Oscillators e.g. magnetrons can be stabilized in frequency by a circuit as in figure 35. The signal of a small master oscillator goes through two circulators to the magnetron, and the output power of the magnetron travels through the second circulator to the load or antenna.

For injection locking the frequency of the master oscillator is about the frequency of the magnetron and its power about 30 dB below the level of the magnetron output. The magnetron will lock at the frequency of the master oscillator and will follow it also in phase within certain limits. In case of a pulse magnetron the start up of the pulse is phase correlated to the master oscillator.

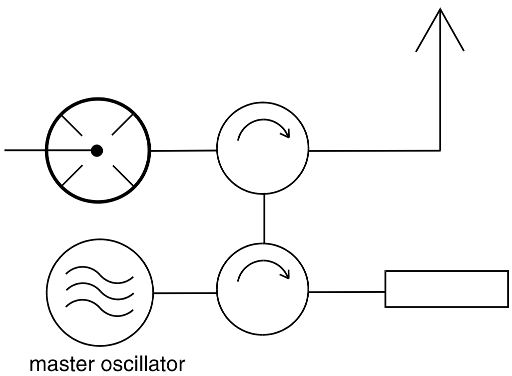


Fig. 35: Circuit for locking and priming of oscillators

Pulse magnetrons are very noisy when starting up at each pulse. We can improve this by "priming": Using the circuit of figure 35 the level of the signal of the master oscillator is about 60 dB below the magnetron output and a bit lower than the magnetron frequency, for magnetrons start up with a slightly lower frequency. This priming signal helps the magnetron to start the oscillation. Therefore the noise is reduced drastically and the shape of the hf pulse improved. For priming it is not necessary to operate the master oscillator in cw, a short pulse covering the leading edge of the magnetron pulse is sufficient.

7.10 Variable attenuator and phase shifter for laboratory use

For the adjustment of a signal to the right level normally we use variable attenuators. But if we do not have the right device in our lab we can use a circulator with a load on one port which can be short circuited by a stub partly or totally, see figure 36. Depending on the length of the stub more or less power is absorbed by the load, the rest travels to the output of the circulator.

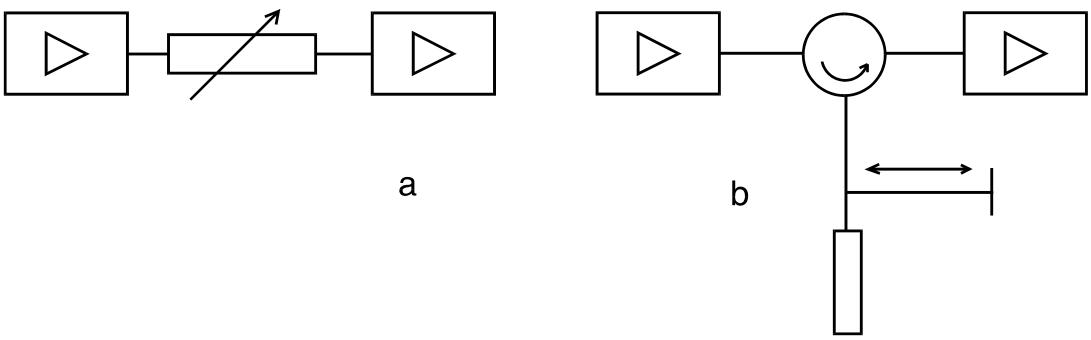


Fig. 36: Adjustment of the level of a signal
a. by a variable attenuator
b. by a circulator with load and stub

For adjusting the phase of a signal normally we use a line stretcher. Instead of that we can use a circulator with a stub on one port, see figure 37. With the length of this stub we can adjust the phase of the signal at the output of the circulator.

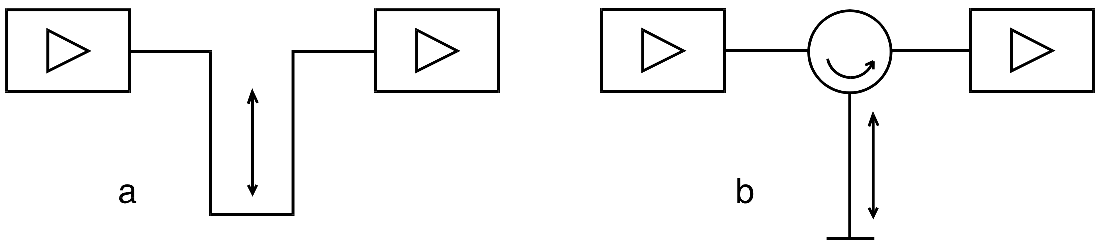


Fig. 37: Adjustment of the phase of a signal
a. by a line stretcher
b. by a circulator and a stub

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