APPLICATION NOTE

Behaviour of Circulators under practical conditions

AN98034

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0. Contents

1. Introduction

The data of circulators and isolators given in the data sheets or other publications assume, that all ports of the device are matched with the nominal impedances of the lines. When measuring the devices or in the application these impedances will deviate from the ideal matching, often very drastically. Therefore we will investigate what happens when we use not ideal loads and equipment to measure circulators and isolators, and how these devices behave in the practical environment.

2. Measuring circulator data

2.1 Isolation

When measuring the isolation of a 3-port-circulator we connect one port with the source, on the next port in the sense of circulation we put a matched load, and the third port is connected to a detecting device (Figure 1). This technique can be done with low signal level but also with high power. For

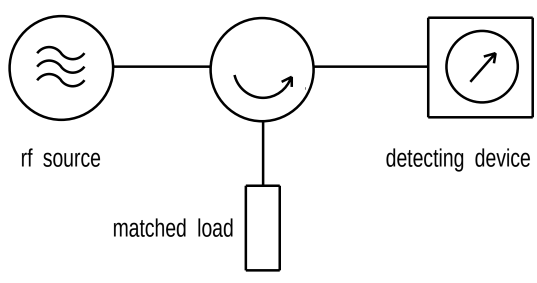

Fig.1: Measurement of isolation

low level measurements we can use also a network analyzer, connecting two ports to it and the remaining port gets a matched load.

The "matched load" used for terminating one port is not an ideal matching but has a small vswr s_{load}. This small reflection superimposes the signal caused by the not ideal isolation of the circulator. Therefore we measure a combination of the circulator isolation and the vswr of the connected load, the value of which depends on the phase between the two signals. The minimum value of isolation is measured when both signals add, the maximum when the signals subtract one from the other.

For the calculation we convert the isolation of the circulator D into an equivalent vswr s_D. Then we combine the vswr of the load s_{load} and s_D to the maximum and minimum vswr of both ($s_{meas\ max}$ and $s_{meas\ min}$) and convert these back to the extremes of the measured isolation $D_{meas\ max}$ and $D_{meas\ min}$:

$$s_D = \frac{1 + \frac{1}{10^{\frac{D}{20}}}}{1 - \frac{1}{10^{\frac{D}{20}}}}$$

$$s_{meas\ \min} = s_D \times s_{load}$$

$$s_{meas\ \max} = s_D / s_{load} \quad if\ s_D / s_{load} \geq 1$$

$$s_{meas\ \max} = s_{load} / s_D \quad if\ s_D / s_{load} < 1$$

$$D_{meas\ \max,\min} = 20\ lg \frac{s_{meas\ \max,\min} + 1}{s_{meas\ \max,\min} - 1}$$

These correlations between maximum and minimum measured isolation D_{meas}, the real isolation of the circulator D, and the vswr of the load s_{load} can be seen as a graph in figure 2. The measured isolation will lie between the upper and lower curve of the relevant load vswr.

If for example we use a load with a vswr of s_{load}=1,02 and the isolation of our circulator is 25 dB, our measurement can lie between 23,6 and 27,6 dB.

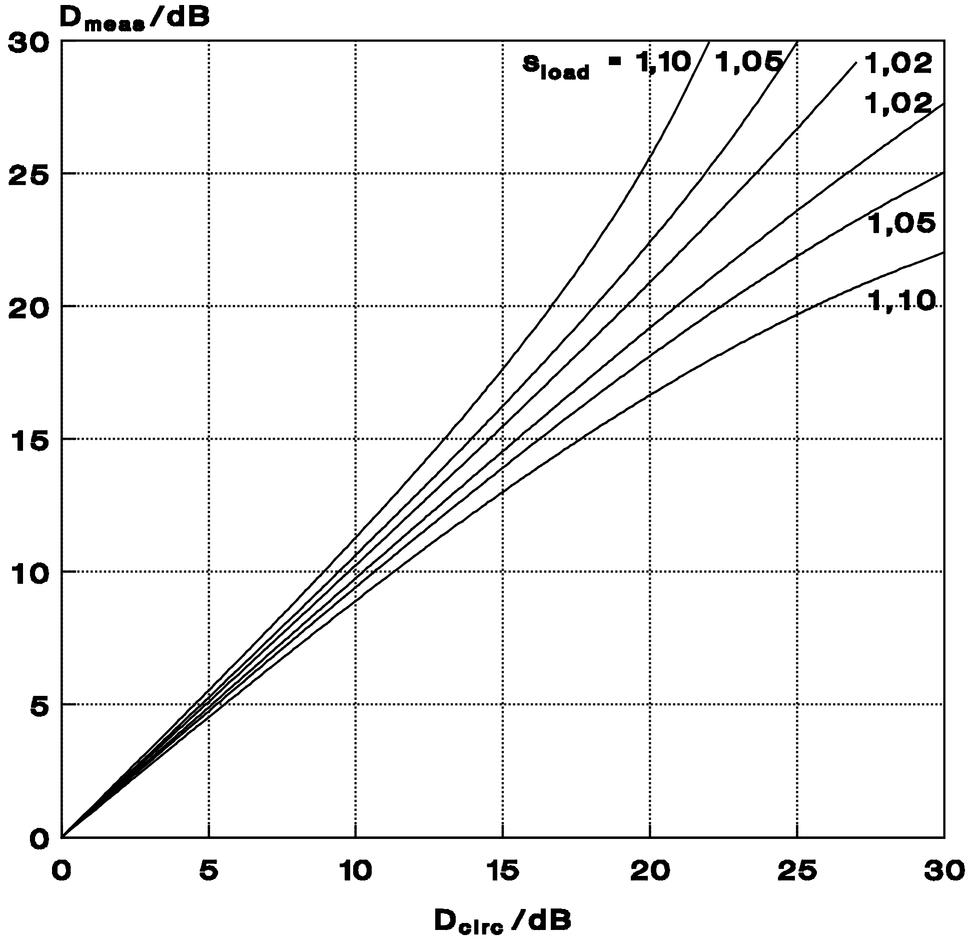

Fig.2: Measured maximum and minimum isolation as a function of the isolation of the circulator D_{circ} with the load vswr s_{load} as a parameter

To give a better idea how big the difference between the real isolation of the circulator and the measured isolation can be, figure 3 shows this difference as a function of the isolation of the circulator D_{circ} with the vswr of the load s_{load} as a parameter.

For example for a load with a vswr of s_{load}=1,05 and an isolation of the circulator of 20 dB the maximum difference of the measured isolation and the real isolation of the circulator is +2,4 dB and -1,9 dB.

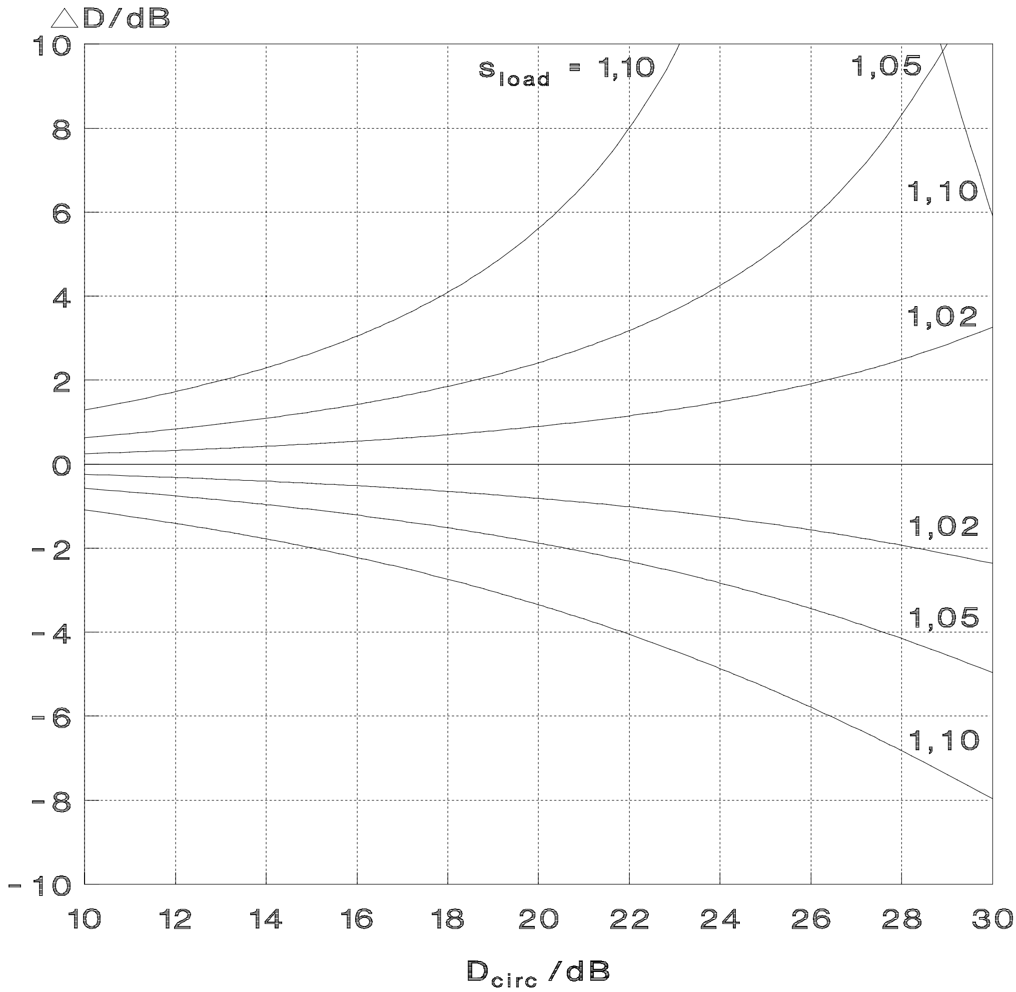

Fig.3: Maximum difference between the isolation of the circulator and the measured isolation as a function of the isolation of the circulator D_{circ} with the load vswr s_{load} as a parameter

2.2 Input reflection

The input reflection of the ports of a circulator is often measured by directional couplers. For low level measurements network analyzers, bridges, and slotted lines can be used too. On the ports not being measured we put matched loads, and the port being measured is connected to the directional coupler, bridge, slotted line or network analyzer. If the loads used have an input vswr lower than 1,1 we can neglect their influence on the measurement of the input reflection.

When using a directional coupler or bridge the main source of failures in this measurement is the directivity D_R of the directional coupler or bridge measured in dB. The signal resulting from the directivity combines with the signal returning from the circulator and we measure a vswr which lies between a maximum value $s_{meas\ max}$ when both signals add and a minimum value $s_{meas\ min}$ when the signals subtract one from the other. We can calculate these limits in the following way.

We transform the directivity D_R into the equivalent vswr s_D

$$s_D = \frac{1 + \frac{1}{10^{\frac{D_R}{20}}}}{1 - \frac{1}{10^{\frac{D_R}{20}}}}$$

and now we combine s_D with the vswr of the circulator port s to the extremes $s_{meas\ max}$ and $s_{meas\ min}$

$$s_{meas\ \max} = s_D \times s$$

$$s_{meas\ \min} = s_D / s \quad if \quad s_D / s \geq 1$$

$$s_{meas\ \min} = s / s_D \quad if \quad s_D / s < 1$$

This relationship is given in figure 4. In this diagram we can see, that a circulator with an input vswr of 1,25 will show figures between 1,22 and 1,28 if measured with a directional coupler or bridge having a directivity of 40 dB.

When using a slotted line the residual vswr of this line corresponds to the directivity of the bridge or directional coupler. If we transform the residual vswr s_D to the directivity

$$D_R = 20\ lg\frac{s_D + 1}{s_D - 1}$$

then we can use figure 4 for estimating the maximum failure.

When measuring the input reflection with modern network analyzers, the analyzer corrects the failure during calibration with the calibration kit. If there is no calibration kit for the line used and we have to use additional transitions, this results in measurement uncertainties.

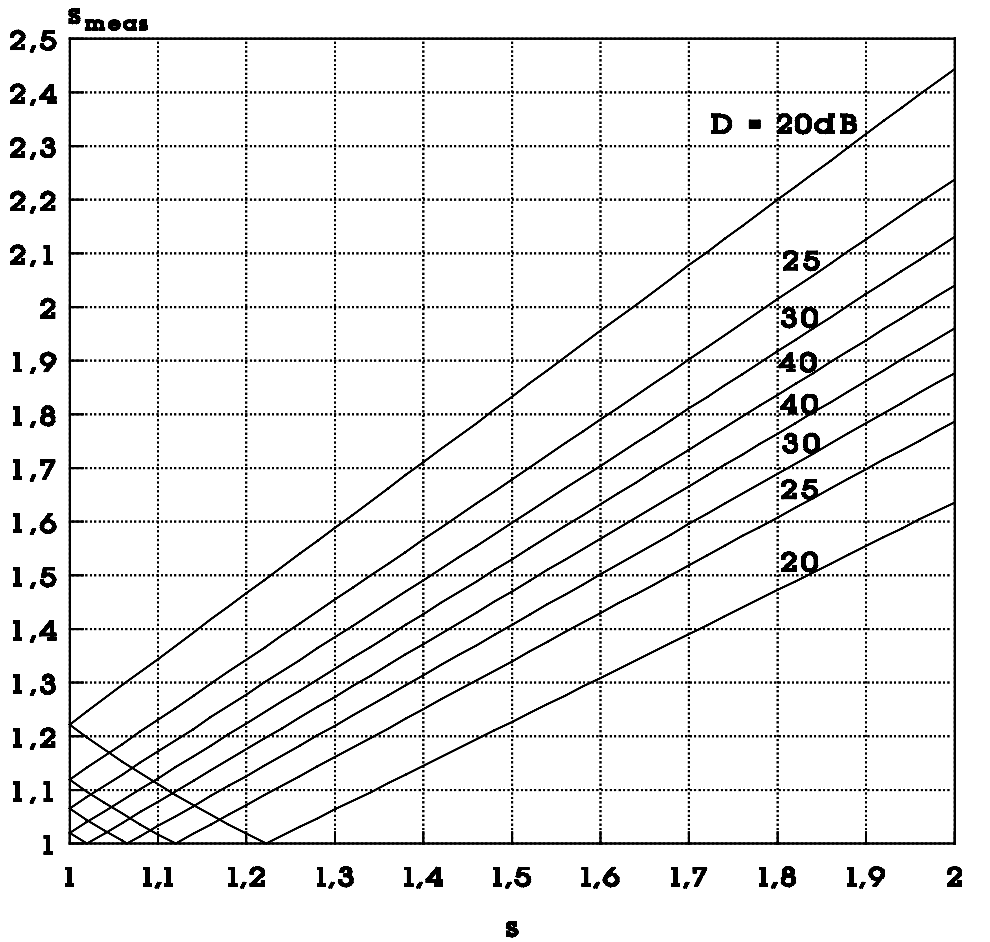

Fig.4: Measured maximum and minimum input vswr s_{meas} as a function of the input vswr of the circulator s with the directivity D of the directional coupler or bridge as a parameter

Up till now we assumed that we have a pure signal. If there are harmonics on our signal, which happens very often when measuring with power, we can get big failures. A normal circulator or isolator represents a more or less good match in its operating band, but reflects nearly all harmonics or other spurious frequencies far outside the operating band. Therefore these frequencies have to be removed by suitable filters.
To estimate the failures, which may happen, we can calculate in the following way.
If we have a harmonic x dB under our signal level and we measure with a power measuring device (e.g. a thermistor or baretter, or a diode in

the square-law-region), the harmonic power adds to the reflected power of the career:

reflected power of the career

$$P_r = P \times \left(\frac{s-1}{s+1}\right)^2$$

harmonic power, totally reflected

$$P_h = P \times 10^{-\frac{x}{10}}$$

$$s_{meas} = \frac{1+\sqrt{P_r+P_h}}{1-\sqrt{P_r+P_h}}$$

In figure 5 we see, that with a harmonic content of -20 dBc we will measure the vswr of a circulator to s_{meas}=1,31 instead of its real value of s_{circ}=1,20.

If we measure with an amplitude measuring device (e.g. a diode in the linear region) we have to calculate the areas between the time axis and the curve resulting from the reflected original signal and the totally reflected harmonics. We get the biggest deviation for the third harmonic, which is one of the most important too.

For small vswr's of the circulator the resulting curve cuts the time axis more often than for a normal sine wave, and we have to integrate the parts. There are two extremes for the phase of signal and harmonic: they are in phase or in antiphase.

With

$$r_{circ} = \frac{s_{circ} - 1}{s_{circ} + 1}$$

$$a_3 = 10^{-\frac{x}{20}}$$

we get the following equations for a third harmonic of x dBc:

a. time axis cut also within a half sine wave of the signal

$$\omega t_1 = \arcsin\sqrt{\frac{3}{4} \pm \frac{r_{circ}}{4a_3}}$$

$$r_{meas} = \left|r_{circ}(1 - \cos\omega t_1) \pm \frac{a_3}{3}(1 - \cos 3\omega t_1\right| +$$

$$+\left|r_{circ}\cos\omega t_1 \pm \frac{a_3}{3}\cos 3\omega t_1\right|$$

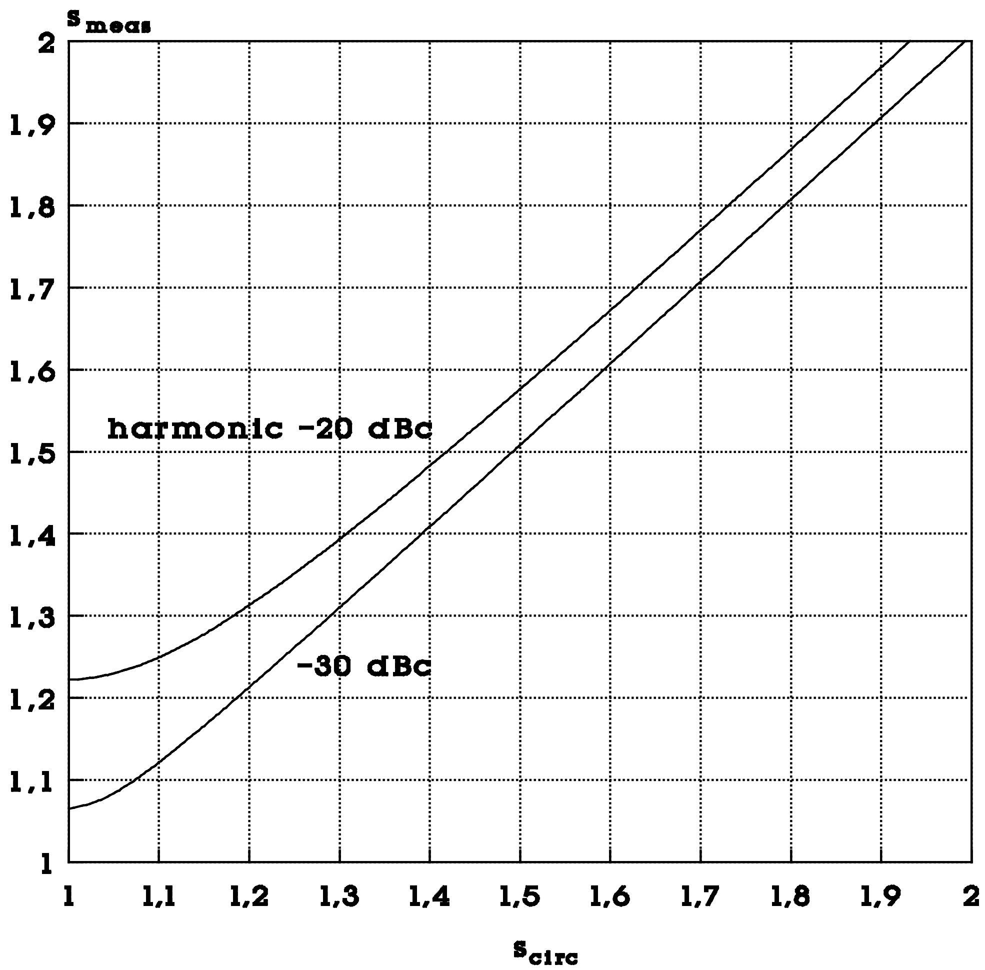

Fig.5: Measured input vswr s_{meas}, using a power measuring device, as a function of the vswr of the circulator s_{circ}, with the harmonic level as a parameter

b. time axis not cut within the half sine wave of the signal

$$r_{meas} = r_{circ} \pm \frac{a_3}{3}$$

and

$$s_{meas} = \frac{1 + r_{meas}}{1 - r_{meas}}$$

This relationship is given in the figures 6.

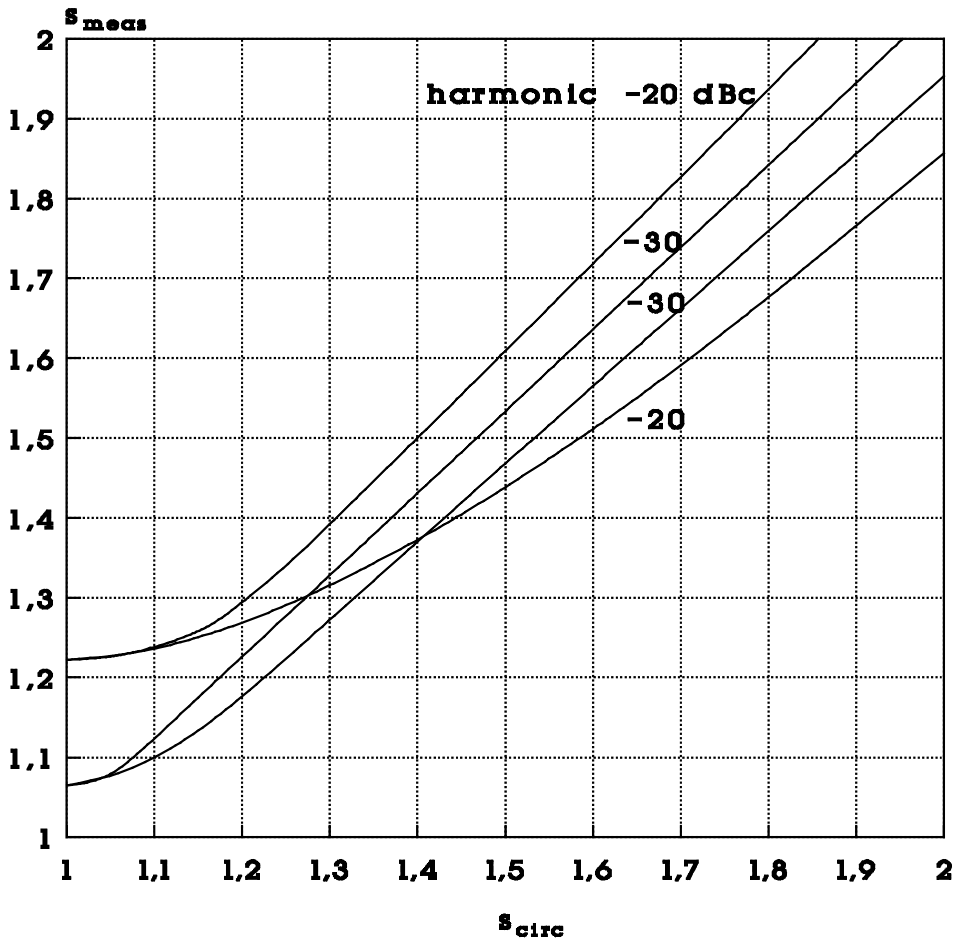

Fig.6: Measured maximum and minimum input vswr s_{meas}, using an amplitude measuring device, as a function of the vswr of the circulator s_{circ}, with the third harmonic level as a parameter

For a circulator with a vswr s_{circ}=1,20 and a third harmonic of -20 dBc the reading of an amplitude measuring device may lie between s_{meas}=1,31 and s_{meas}=1,27.

2.3 Insertion loss

At high power level the insertion loss of a circulator will be measured between isolators and directional couplers, similar to the measurement of the isolation, but with the circulator put in the forward direction, see figure 7. The value to be measured is very small, therefore we have to look for some sources of failure which could be neglected when we measured the isolation. On the other hand the loads on the ports not used in this measurement do not influence the result as long as they have a vswr lower than 1,1.

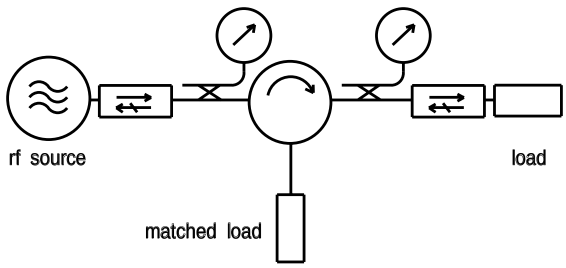

Fig.7: Measurement of the insertion loss

With s_i, the vswr of the isolators used, and s, the vswr of the circulator to be measured, we get a maximum reading of the input power $P_{in\ max}$ which deviates from the power of the generator due to the reflected waves

$$P_{in\ \max} = P\left(\frac{1}{1-rr_i}\right)^2$$

with

$$r = \frac{s-1}{s+1} \qquad r_i = \frac{s_i-1}{s_i+1}$$

and a minimum reading

$$P_{in\ \min} = P\left(\frac{1-2rr_i}{1-rr_i}\right)^2$$

For this calculation we assume that the vswr of the directional couplers is very low compared to the other reflections and can be neglected. For the output power we have a maximum reading with d, the real insertion loss of the circulator

$$P_{out\ \max} = P\left(\frac{1}{1-rr_i}\right)^2 10^{-\frac{d}{10}}\left(\frac{1}{1-rr_i}\right)^2$$

$$= P \times 10^{-\frac{d}{10}} \times \left(\frac{1}{1-rr_i}\right)^4$$

and a minimum reading

$$P_{out\,\min} = P\left(\frac{1-2rr_i}{1-rr_i}\right)^2 10^{-\frac{d}{10}}\left(\frac{1-2rr_i}{1-rr_i}\right)^2$$

$$= P \times 10^{-\frac{d}{10}} \times \left(\frac{1-2rr_i}{1-rr_i}\right)^4$$

The measured insertion loss lies now between

$$d_{meas\,\max} = \frac{P_{in\,\max}}{P_{out\,\min}} = d + 20\ lg\ \frac{1-rr_i}{(1-2rr_i)^2}$$

$$d_{meas\,\min} = \frac{P_{in\,\min}}{P_{out\,\max}} = d + 20\ lg\ [(1-rr_i)(1-2rr_i)]$$

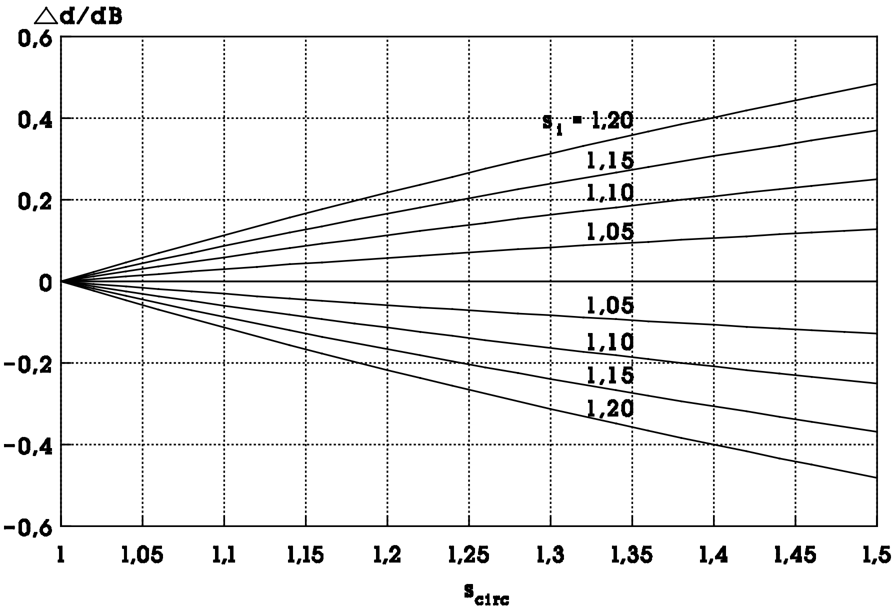

Fig.8: Max. diff. between the insertion loss of the circ. and the measured insertion loss as a function of the vswr of the circ. s_{circ} with the vswr s_i of the isolator of the measurement setup as a parameter

For small values of r and r_i we get the following deviation from the real value of the insertion loss

$$\Delta d_{meas} = 20\ lg\ (1 \pm 3rr_i)$$

The exact values of the deviation are presented in figure 8. It shows, that the measured insertion loss of a circulator with a vswr of s=1,25 measured between isolators with a vswr of s_i=1,10 may deviate from the real value by ±0,14 dB.
The same measurement setup can be used also at low power levels. Here we can use attenuators instead of isolators too.
But we can use also network analyzers. If we calibrate the network analyzer with the simple through calibration, then we get the same failures as discussed, taking s_i as the vswr of the ports. But using the 2-port-calibration the failure is reduced drastically by calculations.

There is also another method some times used, given in figure 9. It is very inaccurate and therefore not recommended. Here the measurement is done by connecting at first the signal source, which is decoupled by an isolator, directly to the detecting device, which is also decoupled by an isolator.

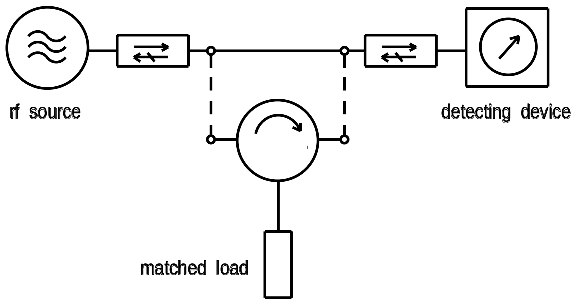

Fig.9: Another measurement setup for the insertion loss

For small signal measurements we can use attenuators instead of the isolators. Then the circulator to be measured is inserted. If the isolation of the isolators is higher than 20 dB or the attenuation of the attenuators is higher than 10 dB, the main sources of failure in the measurement of the insertion loss are the input and output reflections of the isolators or attenuators and the circulator being measured. During calibration the detected signal will lie between a maximum value A(1+r_i) and a minimum value A(1-r_i) caused by the vswr of the isolators or attenuators s_i, which multiply in the worst case.

$$r_i = \frac{s_i^2 - 1}{s_i^2 + 1}$$

If we now put the circulator with its vswr s in, then we get a maximum reading $A_1(1+r)$ and a minimum reading $A_1(1-r)$ with

$$r = 2\ \frac{ss_i - 1}{ss_i + 1}$$

The measured insertion loss lies now between

$$d_{meas\ \max} = 20\ lg\frac{A\ (1 + r_i)}{A_1\ (1 - r)} = d + 20\ lg\frac{1 + r_i}{1 - r}$$

and

$$d_{meas\ \min} = 20\ lg\frac{A\ (1 - r_i)}{A_i\ (1 + r)} = d + 20\ lg\frac{1 - r_i}{1 + r}$$

with d the real insertion loss of the circulator, or given as the deviation from the real value

$$\Delta d_{\max} = 20\ lg\frac{1 + r_i}{1 - r}$$

$$\Delta d_{\min} = 20\ lg\frac{1 - r_i}{1 + r}$$

and as an approximation for small values of r_i and r

$$\Delta d_{\max,\ \min} = 20\ lg[1 \pm (r_i + r)]$$

When measuring in this setup the measured insertion loss of a circulator with a vswr of s=1,20 measured between attenuators or isolators with a vswr of s_i=1,05 may deviate from the real value by +2,7 dB and -2,2 dB.

Also the measurement of the insertion loss is influenced by harmonics and other spurious signals for the same reason as under 2.2, and we have to remove them by filters.

3. Some applications

3.1 Reduction of the vswr or return loss of a load by using an isolator

Often the vswr of a load is high and fluctuating. For example the vswr of a gas filled chamber is very high, but after ignition this gas forms a plasma with high absorption. Or when curing rubber the impedance of the rubber changes with the progress of the process. Or the impedance of an antenna changes with obstacles in its neighbourhood. To reduce this vswr we can use isolators.

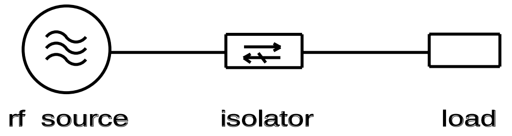

Fig.10: Reduction of the input vswr of a load by using an isolator

The resulting input vswr of the cascade load and isolator depends on the load vswr, the isolation of the isolator, the vswr of the isolator, and the phase between load and isolator. For the calculation of the resulting input vswr we use the signal flow diagram of a circulator as given in figure 11.

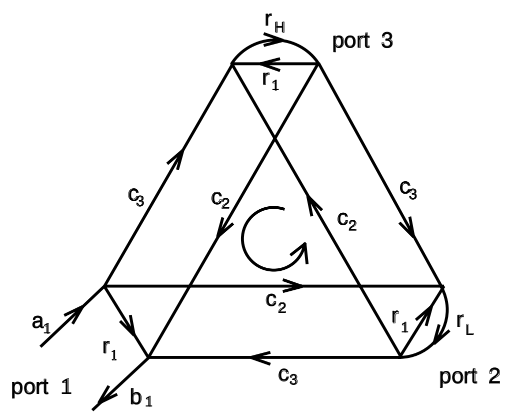

Fig.11: Signal flow diagram of a circulator

- port 1 — the input port, connected to the generator
- port 2 — the output port, connected to the fluctuating load with the reflection coefficient r_L
- port 3 — the internal port when using a circulator as an isolator, terminated with a matched load with the reflection coefficient r_H
- c_2 — the insertion loss of the circulator, given as a vector, $|c_2| = 10^{-d/20}$ with d = insertion loss in dB
- c_3 — the isolation of the circulator, given as a vector, $|c_3| = 10^{-D/20}$ with D = isolation in dB

Using the rules of the signal flow diagram, we get the reflection coefficient r at the input of the circulator

$$r = \frac{b_1}{a_1} =$$

$$= \frac{r_1(1 - r_1 r_H - r_1 r_L - c_2 c_3 r_L r_H + r_1^2 r_H r_L) + c_2 c_3 r_L(1 - r_1 r_H) + c_2 c_3 r_H(1 - r_1 r_L) + c_2^3 r_H r_L + c_3^3 r_H r_L}{1 - r_1 r_H - r_1 r_L - c_2 c_3 r_H r_L + r_1^2 r_H r_L}$$

This expression looks very complicated, but it simplifies, if we take the following assumptions of practical nature:

1. The isolation of the circulator terminated with matched loads is equivalent to the return loss of the input: $c_3=r_1$.
   In practice these values differ only slightly.
2. The insertion loss of the isolator is very small, and we can neglect it: $c_2=1$.
   In practice the small attenuation will improve the maximum vswr calculated a bit.
3. The third port has a perfectly matched load: $r_H=0$. Normally the loads used for terminating the third port are much better than the input reflection of the circulator, therefore the failure made by this assumption is negligible.

With these assumptions we get for the reflection factor

$$r = \frac{r_1(1 - r_1 r_L + r_L)}{1 - r_1 r_L} = r_1 + \frac{r_L}{1 - r_1 r_L}$$

where r, r_1, r_L are complex. Depending of the phase of the load reflection we will get different values for the input reflection of the isolator. In figure 12 the input vswr is calculated for an isolator with a vswr of 1,25 terminated with a phase varying load with a vswr of 5. As we can see the input vswr can lie between 1,47 and 1,09.
We get the maximum reflection factor, which is very interesting for the design of systems, from the last equation when taking the magnitude of the complex numbers and maximizing the whole expression:

$$r_{\max} = r_1 + \frac{r_L}{1 - r_1 r_L}$$

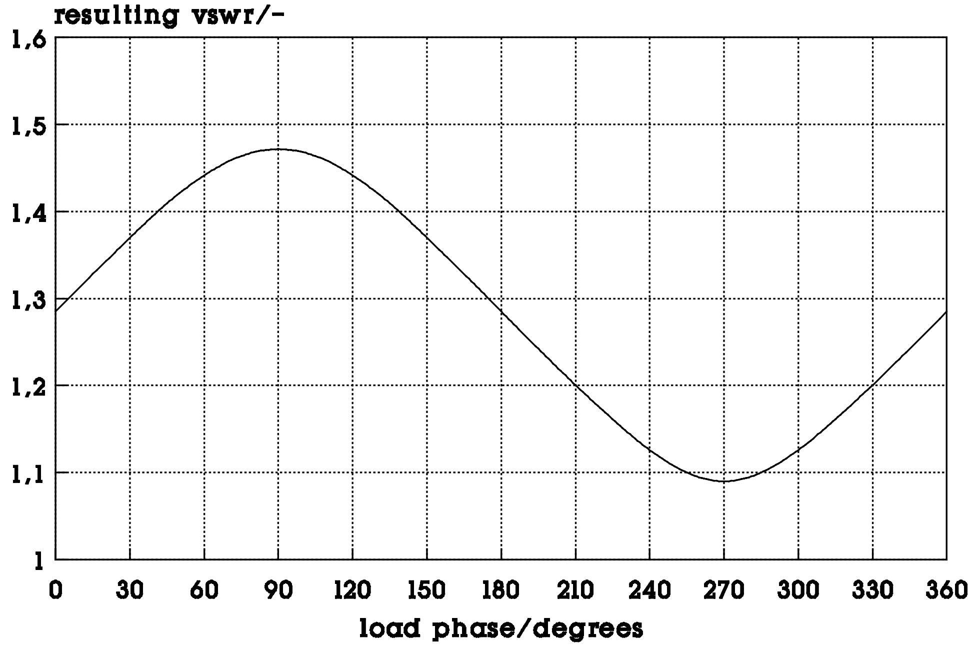

Fig.12: Resulting vswr at the input of an isolator with vswr of 1,25 terminated with a load of vswr=5 varying in phase

The maximum input vswr is then

$$s_{max} = \frac{1 + r_{max}}{1 - r_{max}}$$

In figure 13 the maximum vswr of the input of an isolator is given as a function of the load vswr with the vswr of the isolator as a parameter. For high load vswr's it is easier to look not at the vswr but at the return loss

$$r_{return\ loss} = -20\ lg(r)$$

Therefore in figure 14 the minimum input return loss of an isolator is given as a function of the return loss of the terminating load with the return loss of the isolator as a parameter. Here we can see, that the return loss of a load of 0 dB (vswr=∞, total reflection) is increased by an isolator with a return loss of 20 dB to a minimum return loss of 13,5 dB.

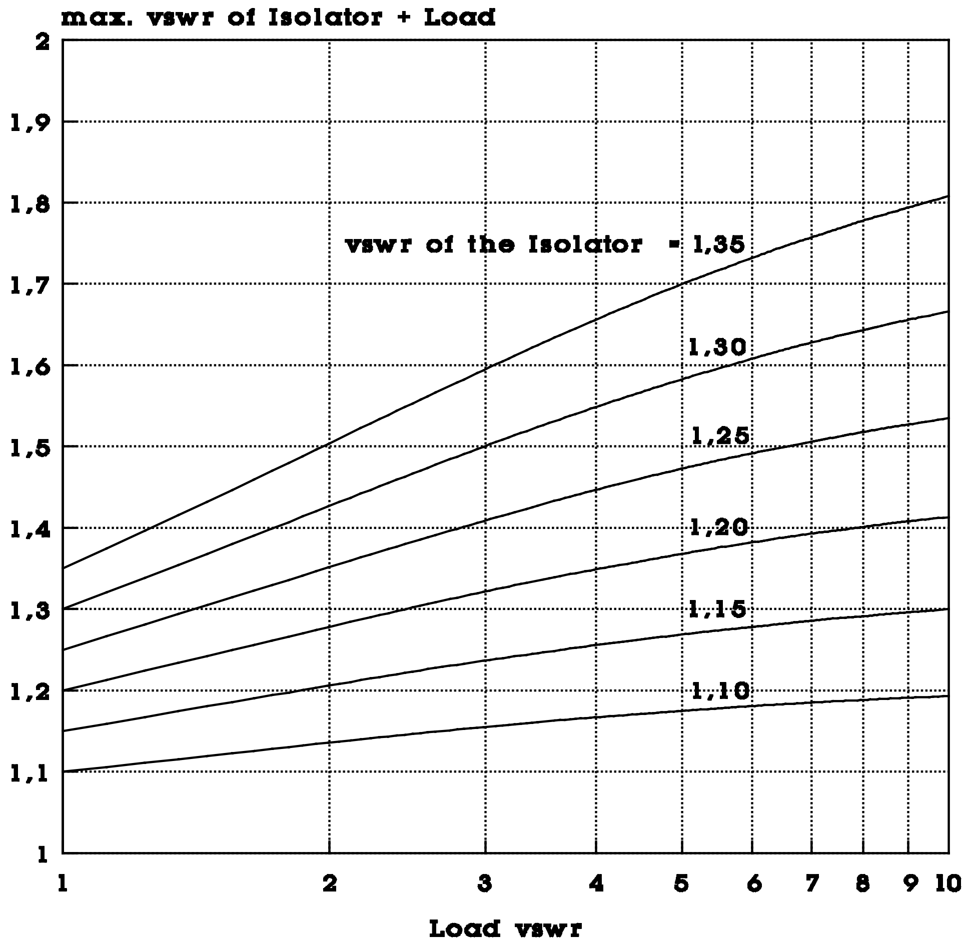

Fig.13: Reduction of the load vswr by an isolator. The maximum vswr of the cascade load plus isolator is given as a function of the load vswr with the vswr of the isolator

3.2 Behaviour of the input vswr or return loss of a circulator terminated with a filter

In applications with one transmitter and one receiver on one aerial or two or more transmitters or receivers on one aerial the circulator used is terminated with filters on two ports (see figure 15).
We assume that the transmitter and the receiver are reasonably matched at their ports. When looking into the filters from the circulator,

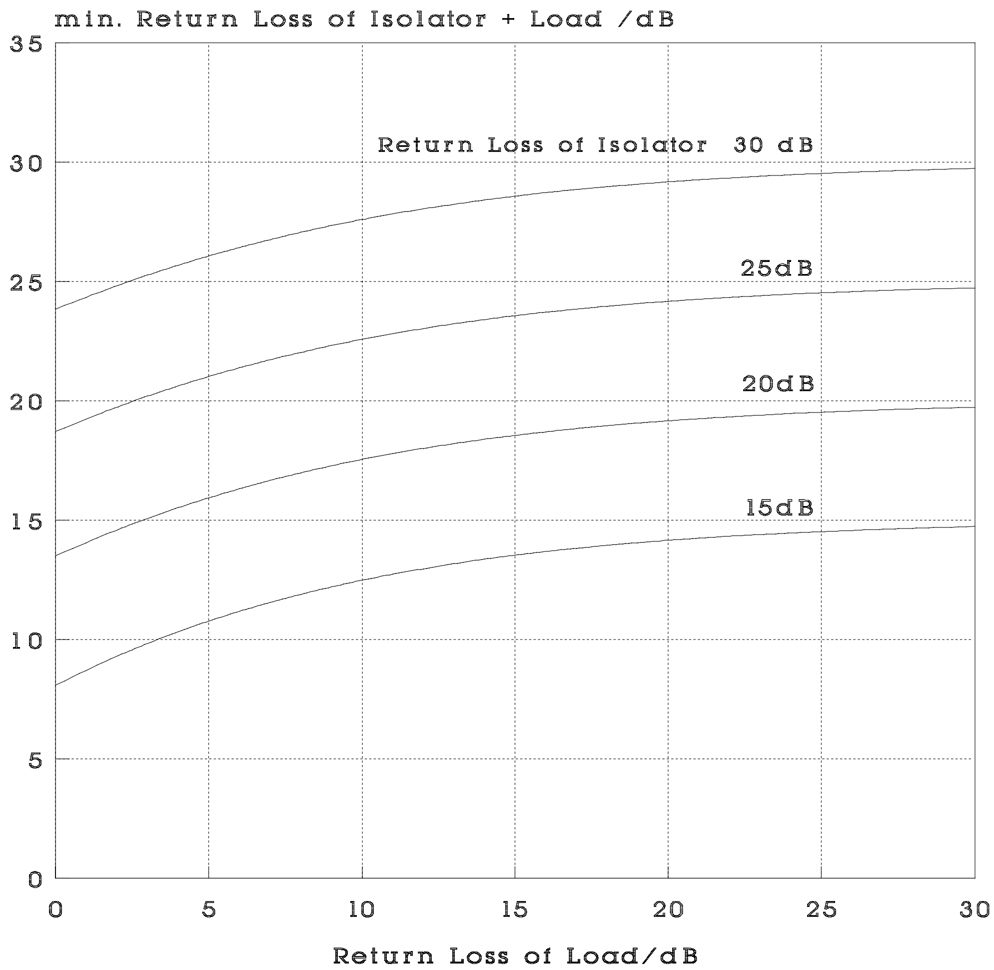

Fig.14: Increasing the load return loss by an isolator. The minimum return loss of the cascade load plus isolator is given as a function of the load return loss with the return loss of the isolator as a parameter

we see a reasonable match in the pass-band, but about total reflection in the stop-bands. These reflections influence the vswr s_a of the circulator at the antenna port.
We can calculate s_a by using the signal flow diagram of figure 11. As in the previous paragraph we can assume that

1. the isolation of the circulator terminated with matched loads is equivalent to the return loss of the input: $c_3=r_1$,
2. the insertion loss of the isolator is very small and can be neglected: $c_2=1$.

For the frequency bands of interest, receiving band and transmitting band, we have total reflection on one port (r_H=1) and a vswr s_L on the other port.
With these assumptions and the calculation of r_L out of s_L

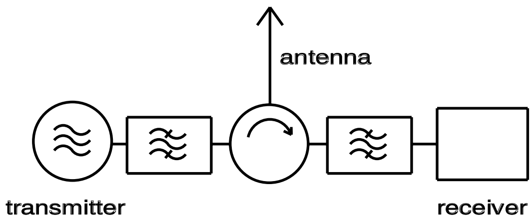

Fig.15: Transmitter and receiver on one antenna

$$r_L = \frac{s_L - 1}{s_L + 1}$$

we can simplify the complicated expression of page 15 to

$$r_a = \frac{r_1(2 - r_1 - 4r_1 r_L + 2r_1^2 r_L + r_L) + r_L}{1 - r_1 - 2r_1 r_L + r_1^2 r_L}$$

This approximation is valid for circulators with a vswr up to 1,30 and load vswr's up to 2. For higher values we have to take into account the insertion loss and the possible phases of r_1 and c_3.The maximum value of the reflection coefficient is

$$r_{a\,\max} = \frac{r_1(2 - r_1 - 4r_1 r_L + 2r_1^2 r_L + r_L) + r_L}{1 - r_1 - 2r_1 r_L + r_1^2 r_L}$$

or as a standing wave ratio

$$s_{a\,\max} = \frac{1 + r_{a\,\max}}{1 - r_{a\,\max}}$$

This is the worst vswr of the circulator at the antenna port when all the reflections add (see figure 16). But with variations in the line length between the filters and the circulator it can be improved drastically.

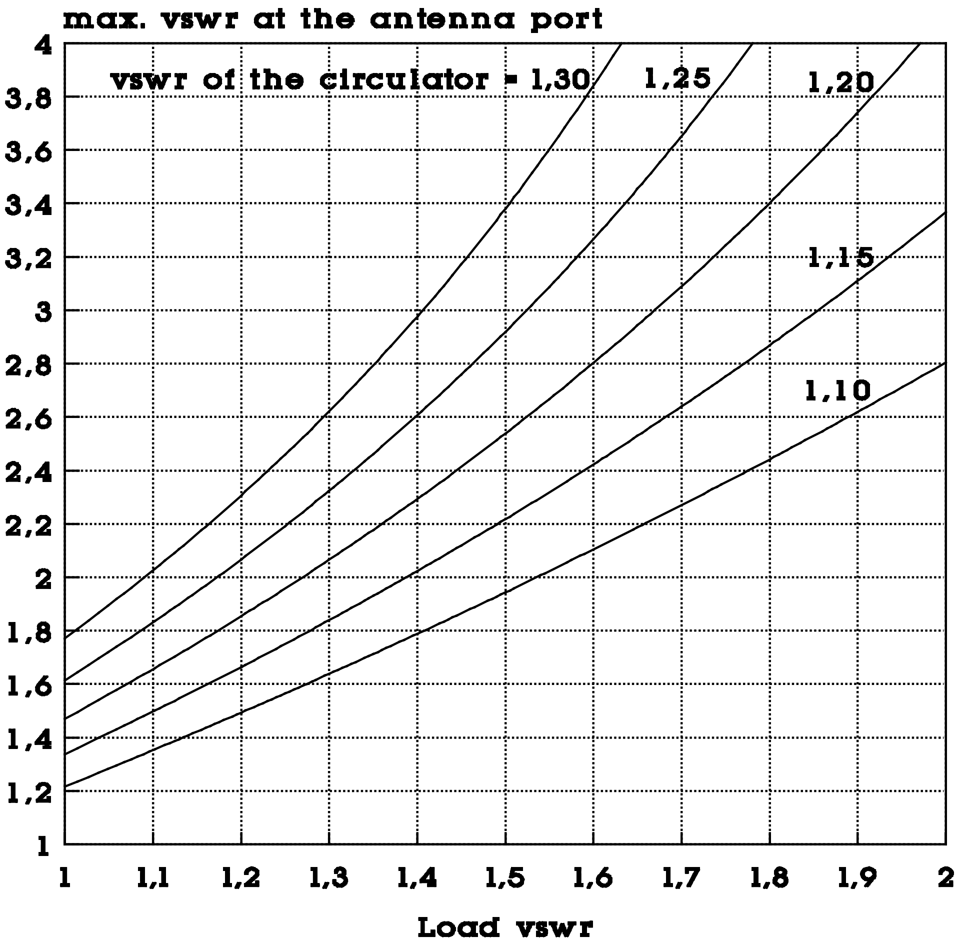

Fig.16: Worst vswr at the antenna port of a circulator terminated with a filter and a reflecting load

Literature:

1. Butterweck, H.J.: Der Y-Zirkulator, AEÜ 17(1963) S.163ff
2. Fiebig, A.: Lineare Signalflußdiagramme, AEÜ(1961), S.285ff

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