A NEW 100 KW CW Y-JUNCTION STRIPLINE CIRCULATOR CONCEPT AND ITS REALIZATION IN THE 500 MHZ RANGE

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Abstract

This paper presents the design and performance of a new Y-junction stripline circulator. The design procedure of the circulator is based on a computer simulation of the ferrite disc resonator. The predicted s-parameters are compared to measurement results. Thermal and electrical conditions of the circulator in high power operation are discussed. The matching procedure of the stripline ferrite resonator is described. Finally an overview of high power measurements for various load conditions is given. A power handling capability of 100kW continuous wave (CW) with the circulator's output shorted at any phase can be achieved by this design.

Introduction

For a long period phase-shift circulators[1] were the only reasonable means to decouple high power klystrons and accelerator cavities. A typical power level for a phase-shift circulator is 2 MW/500 MHz. In recent years the first Y-junction waveguide circulator capable of handling power levels up to the MW-range was reported [4]. Now, the Y-junction stripline circulator intended for operation up to more than 100kW was developed. This new device is intended to operate in smaller accelerator and storage rings. Because of its compact size and smaller weight further applications may be found in industry.

Field theoretical simulation of the stripline ferrite disc resonator

The complete theoretical design of the Y-junction stripline circulator is accomplished in two steps:

- evaluation of the ferrite resonator radius
- computation of the s-parameter of the coupled resonator

Radius of the ferrite disc resonator

In a first step the radius of the ferrite disc resonator is determined with a computer program based on field theory. By means of this program [2,3] the Helmholtz equation of the 120°-cyclic symmetric problem is solved. Fig. 1 shows a top view of the resonator and the coupling lines.
Fig. 2 demonstrates the associated cross section of the Y-junction stripline ferrite resonator. The circulator function is mainly determined by the EH_{m11} modes with $m=-1,1$. These modes are the so-called "split resonances", to be observed in a loosely coupled ferrite resonator. The operational bandwidth of the circulator is determined by the frequency splitting of the named resonances [5,6].
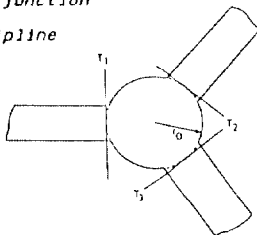

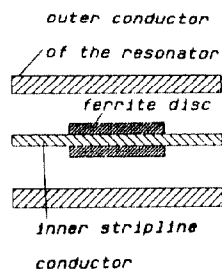Fig. 1 Top view of coupled resonator

Fig. 2 cross section of resonator

Therefore it is sufficient to consider only the split resonances of first order ($m=-1,1$). The resonances [5] occur at different frequencies depending on the magnetization of the ferrites. Each of these resonances is related to a resonance radius [3]. Without any magnetization the split resonances degenerate to a single resonance with a medium radius between both radii. The resonant modes can be looked at as circular polarized waves propagating clockwise and anticlockwise in the disc resonator with different phase velocities perpendicular to the applied static magnetic field. At an appropiate magnetization the field patterns of both circular polarized waves superpose on each other to effect rotation of the resulting pattern. In this way it is possible to couple RF energy from the circulator's input transmission line (port 1) to its output transmission line (port 2). The third port receives no RF energy from port 1 if all the ports of the circulator are perfectly matched to the characteristic impedance of the lines connected to the circulator.
The program mentioned computes the following radii: At 500 MHz the EH_{+111} mode is related to a radius $r=111$ mm, whereas the EH_{-111} mode is related to $r=97$ mm. A medium resonator radius of $r_0=105$ mm is now chosen for the further design procedure.

Scattering parameters of ferrite disc resonator

In the second step the s-parameters of the resulting cylindric ferrite resonator are computed. The resonator is tightly coupled to three striplines having angles of 120° (Fig. 1) to each other. Because of this symmetry, the circulator is described by only three s-parameters s_{11}, s_{21}, s_{31}; s_{11} is the input reflection coefficient, s_{21} the transmission loss and s_{31} the isolation loss.
The problem of the interchanging influence of these s-parameters is overcome with a corrected parameter s_{11}' [3, 4]. Thus s_{11}', the corrected input reflection coefficient of each coupling line at the resonator disc, is matched to the coaxial line used. When using s_{11}', matching of the resonator can be achieved in one step, because the effect of the other s-parameters on the input reflection coefficient is eliminated.
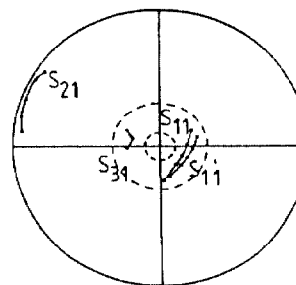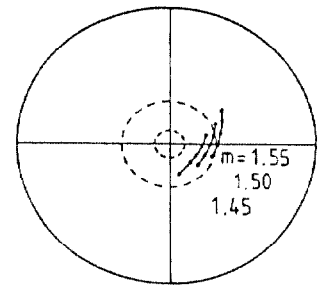

Fig. 3
Computed resonator s-parameters s_{11}, s_{21}, s_{31} and corrected input refl. s_{11}'

Fig. 4
Dependence of s_{11}' from magnetization m

Fig. 3 shows all s-parameters including the computed s_{11}' at a fixed operation point ($m=1.36$, see below). The magnetic induction B is measured with a gaussmeter in the air gap above the ferrites.

$$m = B / M_s \quad (m > 1) \qquad (1)$$

M_s is the saturation magnetization of the ferrites.

At this operation point the circulator works in the "above resonance" region. The corrected s-parameter s_{11}' depending on the operation point m is demonstrated in Fig. 4. These curves must not have any resonances within the desired frequency band. A small curve of s_{11}' allows broadband operation of the matched circulator. Because the value of m is proportional to the magnet volume required for operation and proportional to the achievable bandwidth, one always has to make a compromise between the bandwidth to be achieved and magnet volume.

The geometrical data underlying s_{11}' in Fig.3 are chosen to construct the Y-junction stripline resonator together with its three coupling lines. The problem of matching the Y-junction stripline resonator to the coaxial line EIA 6 1/8" is solved in a separate step.

Mechanical design of the stripline resonator

The inner surface of the case (1) provides the stripline ground planes as shown in Fig. 5. The Y-junction is formed by the stripline inner conductor (2) with its 120° symmetry carrying ferrites (3) on both sides. Thus the inner conductor of the stripline serves as ferrite carrier. The inner stripline conductor is fixed to the sidewall of the resonator case by three pipes (4), each of them opposing a stripline as can be seen from Fig.5. Cooling water flows through the pipes into the ferrite carrier to remove the energy dissipated inside the ferrites. At each of the three striplines there is a transition to coaxial line EIA 6 1/8" (5). Since the resonator does not yet include any coaxial matching lines, its s-parameters can be measured by simply connecting transitions to a network analyzer's coaxial system. On top and bottom side of the resonator-case permanent magnets (6) with pole pieces (7) are surrounded by a closed magnetic yoke (8). Each magnet has an own coil for field correction (9).
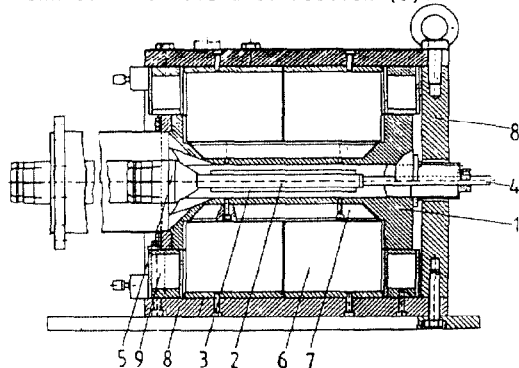

Fig. 5   Cross section of the mechanical design

High power design of the resonator

The resonator consists of layered dielectrics which can cause problems of voltage breakdown if the air gap above the ferrite disc is too small for the desired high power level. Earlier investigations [4] show that the electrical field rises at the periphery of the ferrite disc in the air gap. The air gap must be long enough to avoid sparking due to high voltage.
For example:
    input power: 100 kW
    characteristic impedance: 50 Ω
--> estimation of voltage in the air gap:

$$U = \sqrt{50 \cdot 10^5} \text{ V} = 2.23 \text{ kV} \qquad (2)$$

This is the worst case value, because the resonator impedance is normally below 50 Ω and voltage is divided between ferrites and air gap. The following data of the ferrite RG 4 (ANT mark) are important when discussing high power behaviour of the circulator.

saturation magnetization: M_s=80 kA/m
resonance linewidth: ΔH=1.8 kA/m
dielectric loss factor: $\tan\delta$=0.0002
dielectric constant: ϵ_r=14
Curie temperature: T_c=140°C

As can be seen, dielectric loss and resonance linewidth of the ferrites are very small, which will result in a low insertion loss of the resonator. Most of the power dissipated inside the ferrites is due to magnetic losses. This is due to the fact that the ferrite dimensons are small in parallel with the electrical field but large in the plane of the magnetic field. Therefore thermal considerations can be concentrated solely on magnetic loss of the ferrites. From earlier high power measurements about one percent of the input power dissipated in the ferrites is reported [4]. The water flow rate used for cooling should be large enough to avoid partial overheating of the ferrites. All conditions for operation at 100 kW are observed by the design of the resonator.

Measurement of stripline resonator and comparison to computer design

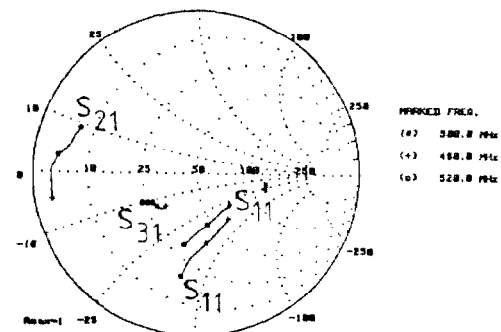Fig. 6 shows typical measurement results of a tightly coupled resonator.

Fig. 6: Measured s-parameters for m=1.36

A comparison to computer design values at the same reference plane (s. Fig. 3) shows significant differences. There are two possible ways accounting for these differences. First, the water pipes connected to the ferrite carrier could not be taken into account in computer design. Second, the magnetization of the ferrites is not constant over the whole area, which results in a slightly higher m. However, s_{11}' has similar frequency dependence as in computer design, thus agreeing with the estimated design-bandwidth.

Matching the resonator

As mentioned, matching of the circulator simply means matching of s_{11}' of each stripline being coupled to the resonator. The circulator design is finished, if all the ports of the resonator are matched. The matching procedure was done with SUPERCOMPACT, a microwave network analysis program.
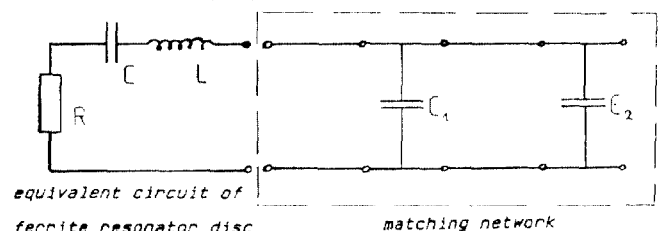

equivalent circuit of
ferrite resonator disc   *matching network*

Fig.7 Series resonant circuit of the resonator together with matching network

1: corrected reflection
   at resonator disc
2: coaxial line
   Z=50 ohms l=120 mm
3: capacitor in parallel
   C=27 pF
4: coaxial line
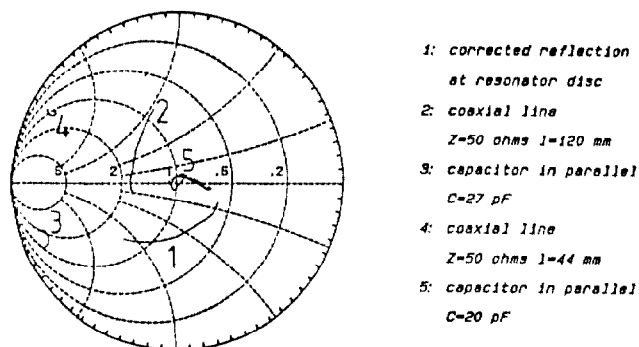   Z=50 ohms l=44 mm
5: capacitor in parallel
   C=20 pF

Fig.8 Transformation steps in Smith-diagram

Matching elements

Matching of the resonator is accomplished within the coaxial lines EIA 6 1/8", which are screwed to the resonator case. The matching elements are coaxial capacitive discs soldered to the inner conductor of the line. The edges of the capacitive discs are rounded to avoid sparking within the air gap between discs and outer conductors. Rounding of the edges was modeled and analyzed. With the discs produced as modeled the circulator's measured s-parameters show very good agreement with the computer design of Fig. 8.
The transmission loss s_{21} was 0.08 dB. The symmetry of the resulting circulator is obtained by applying equal matching circuits at each circulator port.
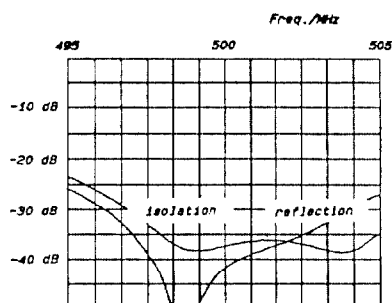Fig. 9 demonstrates the circulator performance after matching process.

Fig. 9: s-parameters of matched circulator

High power test of the circulator

The high power behaviour of the circulator was verified by three different tests:
- pulse power test for sparking limit
- forward power test CW
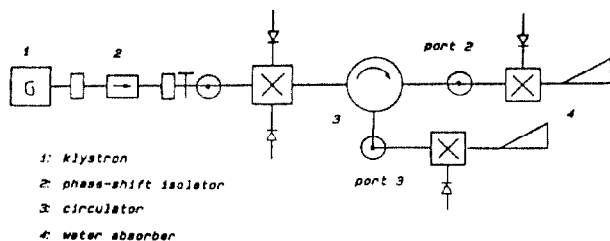- power test CW with shorted lines of different length at port 2

1: klystron
2: phase-shift isolator
3: circulator
4: water absorber

Fig. 10: Measurement setup for high power tests

Sparking limit
The test was performed with pulsed power. Pulse duration was 100 μs with a pulse repetition frequency of 50 Hz. Sparking happened at 600 kW.

Forward power test CW
During this test the circulator was loaded with water absorbers at port 2 and 3 (Fig. 10). The power dissipated inside the ferrites is removed by the water flowing through the carrier and is measured calorimetrically. The ferrites were biased to optimum s-parameters (s_{11}, s_{31} <-26 dB) by applying a DC current to the field correction coils.
Although the coaxial lines EIA 6 1/8" of the circulator are specified for 100 kW maximum power, the circulator was operated at a power level of 350 kW. When operating these lines above their specified power level, cooling of the inner conductor is necessary. The calorimetric measurements indicate a transmission loss of 0.03 dB (0.7% of the input power) caused by the ferrites. Transmission loss of the matching lines is not included here. This part of the total loss is derived from small signal measurements and amounts to 0.05 dB.

Power test CW with shorted lines of different length at port 2

This test was performed with a variable short mounted at port 2. The circulator can be operated with a power level of 100 kW for all positions of the short. In contrast with the forward power test, the power dissipated inside the ferrites is not constant for different short phases. It shows a sinusoidal behaviour depending on the location of the short. The maximum dissipated power was about three times the minimum [7]. Notice that an input power of 100 kW reversed at port 2 corresponds to a power level of 400 kW in forward power test.

Conclusion

The Y - junction stripline circulator presented here can be used as a decoupling device for high power sources, because of its low transmission loss and its high isolation loss. Reflections at input and output as well as isolation can be tuned to optimum values in operation. Possible industrial applications are: microwave heating, use of synchrotron light sources in lithography and medicine and in RF accelerating systems using superconductive cavities.

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