RESONANT RING STRUCTURES FOR TESTING HIGH-POWER LOW-LOSS COMPONENTS

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Focusing primarily on the testing of a high power isolator for 100kW industrial processing systems, this paper will detail the design methodology employed for resonant ring construction. Additional information gained from testing using resonant rings will be included together with a discussion of the error margins associated with the measurements. Use of ring structures to extend test capability, and de-risk of component breakdown events is also discussed.

1 Introduction

Resonant Ring structures or travelling wave resonators have been used for some time to test the high power performance of microwave components. Advantages to this method include design margin capability investigations where use is in the same system as the available test source, and pre-testing components prior to inclusion in leading edge power generating systems.

Ring structures and gain characteristics are well documented [1], and summarised in Figure 1.

Use of resonant ring structures is documented for extreme power applications and frequently published, the novelty being on the powers generated. This paper attempts to demonstrate the ease of use, and significant benefits achieved by resonant ring testing as a device verification test, and as a common tool in the design margin testing of components. This is further demonstrated by results from testing of WG04 components for industrial processing systems.

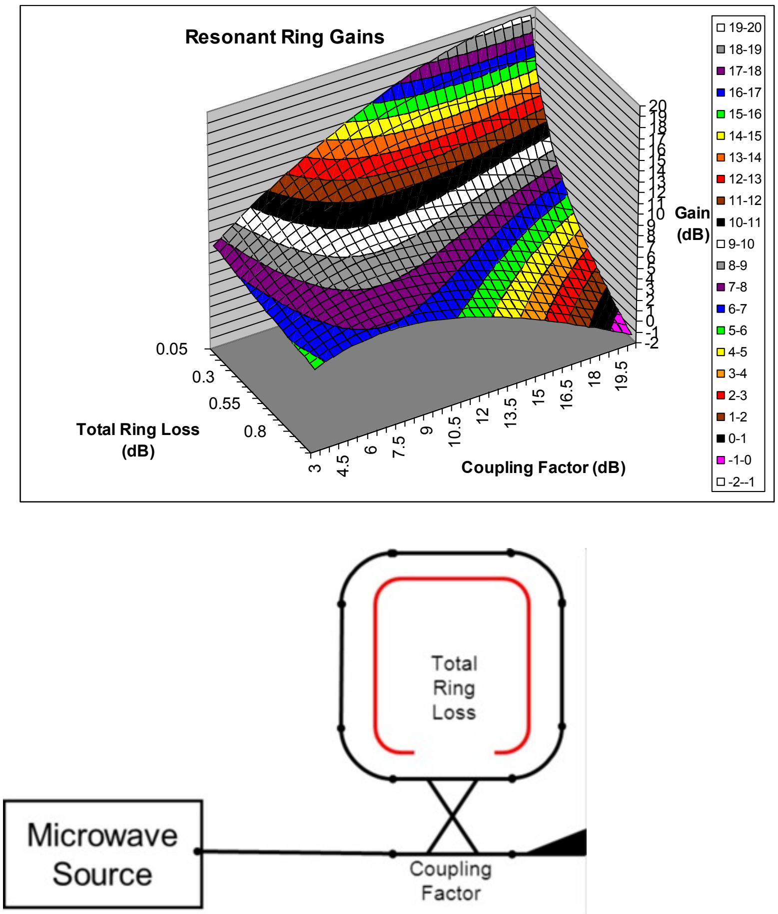


Figure 1 Resonant ring structure and gains achievable

2 Resonant Ring Structures

A resonant ring or travelling wave resonator is a structure where transmitted power is accumulated within a system. In a standard high power test arrangement, incident power and transmitted power is measured on a device with transmitted power being necessarily absorbed to avoid reflection back into the unit. Re-cycling the transmitted power within the device has a number of benefits detailed in the following sub-sections

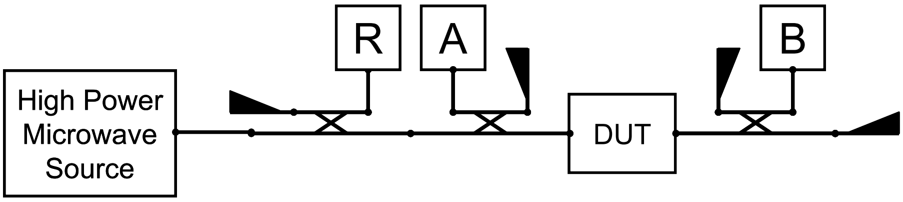


Figure 2: Standard High Power Test Arrangement

Typically coupling values are chosen to reduce the sampled power to a level compatible with the power measurement method.

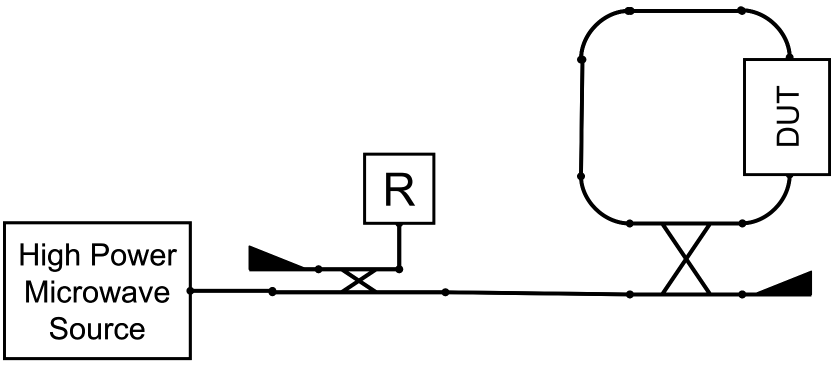


Figure 3 Resonant Ring Testing

Power is accumulated within the ring.

2.1 Power Amplification

Within a resonant ring structure the amplification is achieved through the phased addition of the power within the ring structure and cancellation in the termination. This is down to the fundamental properties of the coupler shown in Figure 4

By considering the reciprocal nature of these devices, a basic understanding of the resonant ring structure can be realised.

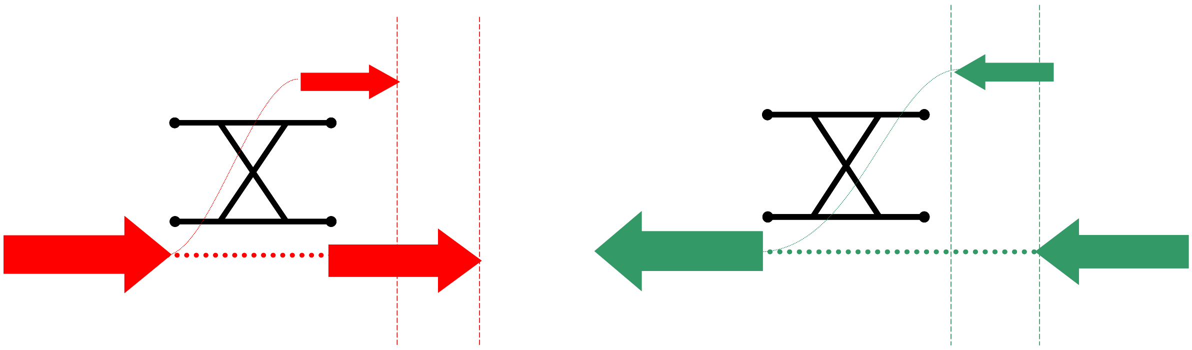


Figure 4 Reciprocal nature of a coupler

Power input at one port splits between the 2 output ports. By putting into the output ports with the correct phase relationship, the signals add in one port and cancel in the other.

$$G_p = \left(\frac{10^{\frac{-C}{20}}}{1 - \sqrt{\left(1 - 10^{\frac{-C}{10}}\right) \cdot 10^{\frac{-A}{20}}}} \right)^2$$

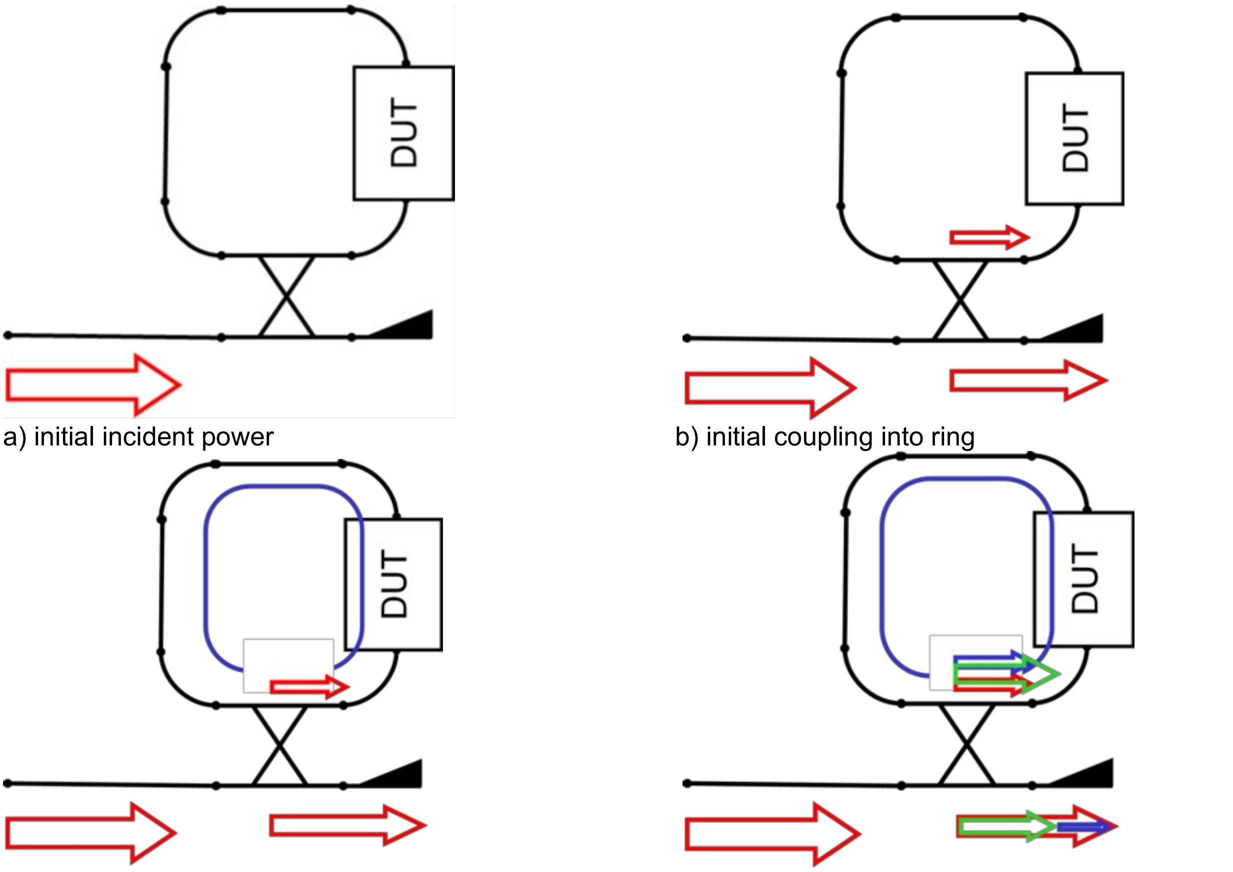
Equation 1 Power gain of a ring structure
Gp is power gain as a ratio
C is coupling factor of the main input ring coupler in dB
A is the loss around the ring.

2.2 Key Features of Resonant Rings

- Power gain is achieved when the phase around the ring is whole number of wavelengths, such that power in the ring adds with the input power from the coupler.
- Optimum gain is achieved when the power lost in the ring is equal to the input power.
- Increasing the loss in the ring decreases the gain.
- For optimum ring performance an increase in ring loss requires a reduction in the input coupler value.

2.3 Power Accumulation, Storage and Release

A number of ways of visualising the power build up in the ring exist, with the simple coupling and transit time round the ring being the easiest to visualise.



a) initial incident power
b) initial coupling into ring
c) Coupled power travels around the ring
d) Addition within the ring, cancelation into load

Figure 5 Resonant Ring Power Accumulation

Considering a 6dB ring coupler with a loss of 0.4dB (~10% loss) in the ring. The incident wave-front arriving on the ring coupler couples 25%power into the ring. This power travels round the ring, dropping to 22.5% and returning to the coupler. Now the interaction with the continuing input wave causes phase addition in the ring and cancellation in the through port. This process continues as power builds up in the ring, eventually reaching the steady state condition. [2]

The graph (Figure 6) shows the power flow changes described, the ring being over-coupled. The process is exactly the same as charging a cavity and the charging equations apply to the resonant ring structure.

2.3.1 Pulse Sharpening

The time taken to charge the ring is longer that the pulse rise time (10% to 90%), however the rate of rise of power can be greater in the ring, than on the incident pulse, particularly with a short over-coupled ring as discussed above. This is due to the amplified peak power achieved and the initial charging being below the 10% power in the ring.

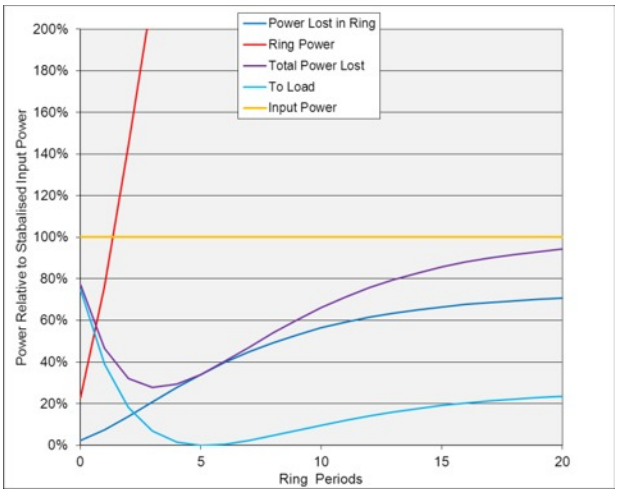


Figure 6 Power division as ring charges

2.3.2 Energy Storage

Stored energy within the ring at steady state is a function of the power level in the ring and the length of the ring. A large ring will take longer to reach steady state, and will store more energy, simply due to the length of the ring.

2.3.3 Energy release

At the end of a power test, either pulse or turn off of a CW signal the energy stored in the ring is then dissipated within the structure and also released to the external termination.

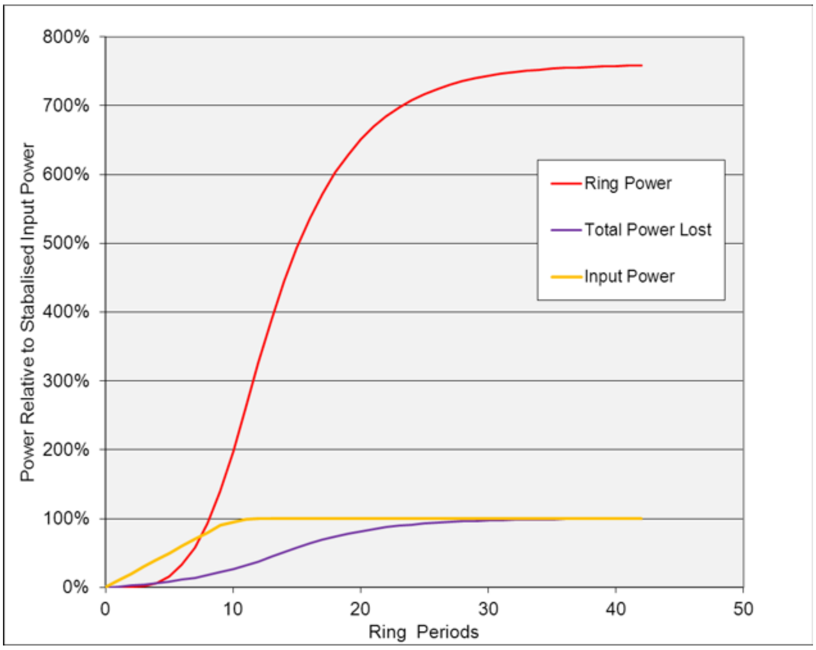


Figure 7: Showing rate of rise of Pulse can be greater within the ring for short over-coupled rings. Here, a pulse rise time of 10 ring lengths is shown.

2.3.4 Breakdown

Discharge events within the structure cause rapid changes from the steady state conditions and can present interesting and potentially useful effects. A column discharge in the centre of the broad wall (peak voltage) causes reflection and phase shift for the remaining signal, together with additional absorption within the discharge. This has a number of significant consequences on the resonant ring structure:

- The ring no longer resonates: this leads to a significant drop in power driving the discharge, potentially quenching the discharge. The power available to drive the discharge is reduced by nominally twice the coupling factor in that the gain reduces to a loss through the coupler.
- Significant reflected power (pulse) directed towards the source can be observed, at power levels greater than the input power.
- Significant power will be directed into the main load, potentially higher than the input power.

Decay periods will be nominally 4 ring lengths, (extremely short pulses) but highly dependent on the nature of the breakdown, and therefore not easily calculated.

2.3.5 Built in Breakdown Safety

What can be demonstrated is that the effects of breakdown can be less catastrophic than with an event with a CW signal where the microwave input power will continue to drive a discharge. Direct application of 100kW mean power to a unit, with a random breakdown event will cause a localised plasma heating effect dependent on the input power. With the device under test in a resonant ring structure, the input power is reduced by the gain of the ring. A breakdown event reduces the power level in the ring to the non-resonant coupled level. For the circulator tests performed, the power available to drive a potential arc is reduced from the test level of 100kW, initially to below 20kW (the power required to drive a ring structure at 100kW) and with a breakdown event collapsing the resonance to around 5kW, a reduction of 20 times the power or approximately 4.5 times the Electric field, potentially stopping the discharge.

2.4 Operating Bandwidth

To enable a resonant ring to function, providing gain, the correct phase path round the ring must be achieved. Slight variation on this will decrease the gain achieved.

Figure 8 Ring gain reduction caused by phase error in the ring

The operating bandwidth of a resonant ring can therefor be determined from the length of the ring and the frequency change producing a phase change in the ring of more than say +/- 5 degrees. For the ring structure used: 7dB coupler and around 4m length (9 wavelengths) at 896MHz, this is around 1 MHz. A repeat resonance occurs at 951MHz. (10 Wavelengths)

For a large ring, the resonances exhibit high Q, and are closely spaced in the frequency spectrum. A small ring has lower Q, but the resonances are wide apart. Factors affecting the choice of ring size, beyond simple geometry constraints include the tuning method chosen, the power source (TWT, Magnetron, Klystron: fixed or adjustable frequency), and the operating frequency band of the device. It is easy to verify performance of a device at power using a fixed ring adjusted for 2 or 3 in band resonances

A negative side to the testing using resonant rings is the frequency selectivity of the ring. Devices normally operating over a broad frequency spectrum (Chirped or coded radar pulse, or poor magnetron spectrum) can only be ring tested at relatively narrow bandwidths. Whilst these significantly increase confidence levels for final performance functionality, the final integration test, where spurious and harmonic signal are also present, may still be required.

2.5 Ring Tuning

To ensure optimum resonance can be achieved, the resonant ring needs to be tuned. A number of techniques are available, each with their own advantages:

2.5.1 Frequency Adjustment:

For verification of a unit at frequency points within an operating band, adjustment of frequency to tune the resonance gives excellent results.

2.5.2 Ring Length adjustment:

To achieve a ring of the correct length for a fixed frequency source requires either careful design of the ring size ensuring resonance, or the ability to modify the ring length. Phase adjustment techniques are well known:

2.5.2.1 Shim Insertion

Maintaining a ring but increasing the length by shims. In WG04 this is just under 1 degree per mm of shim, making fine adjustment by this method very achievable but time consuming. In WG22 this is closer to 20 degree per mm, and thin shims are required for fine tuning a ring. This method is excellent for devices, (and rings) whose performance does not change with power, but for units where the thermal effects of power dissipation within a ring cause the resonance to move, it is not practical to adjust the ring by this method.

2.5.2.2 Phase shifter units

Usually a dielectric vein moved across the waveguide to change the phase length of a fixed section of guide. If this type of unit is to be used, the removal of thermal energy from the unit needs to be considered. Low loss devices are common, and less than 0.1dB absorbed power is easily achieved, but thermal heat removal paths are poor. Radiated power from the movement rod holes needs to be avoided.

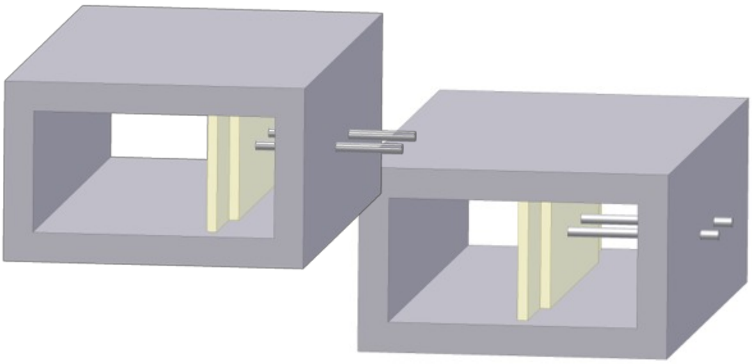


Figure 9 Dielectric based Phase Shifter

Fixed phase shift sections, through dielectric loading of waveguide sections gives a defined heat flow path, and can be used if physical adjustment is limited. These are then constrained by the limitations on adjustment discussed above.

2.5.2.3 Reflection Phase Shift units

Achieved by using two variable short circuits (a device easily realised for high power operation) and a coupler arrangement.

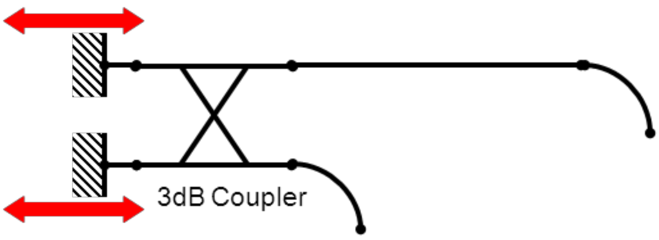


Figure 10 Dual Short-Circuit Phase Adjuster

This arrangement can also be adjusted to create a mismatch in the ring when the short circuit positions are independent. Full variation is not available as the difference can only create a magnitude of a mismatch. Phase adjustment of the mismatch is possible with this type of unit, but in the ring situation, this is used to vary the ring size. When introducing a mismatch, the effect is the same as adding loss, and the forward ring power is reduced.

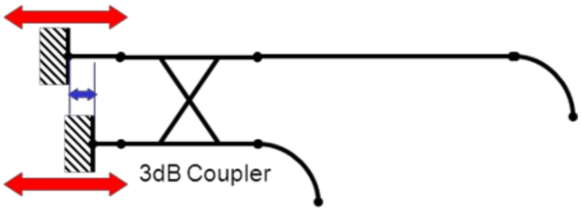


Figure 11 Offset short circuits producing a mismatch

An alternative to the coupler and dual short circuit arrangement is a circulator and single short circuit. Here the circulator needs to handle full power in a double pass arrangement, and the short circuit is handling full power as opposed to half power in the coupler arrangement.

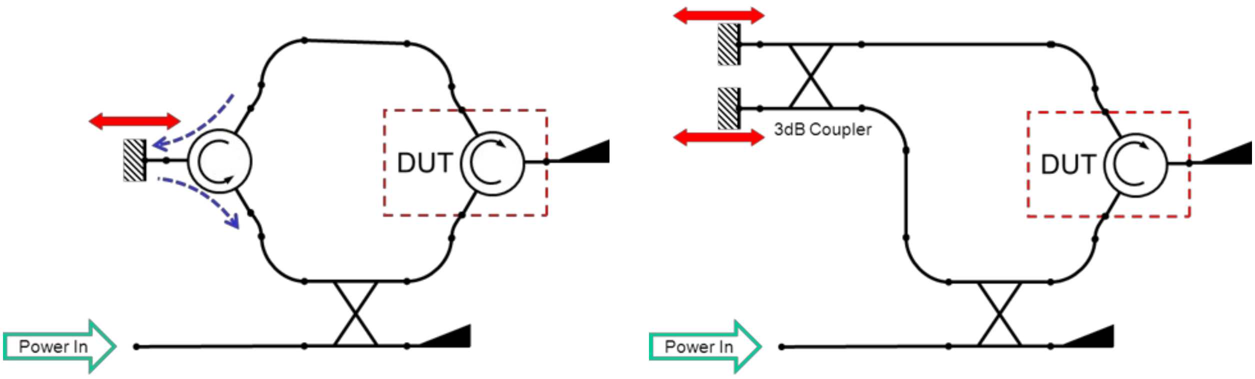


Figure 12 Ring circuits with a) Circulator and single short circuit, b) Coupler and dual short circuit.

3 Testing of High Reflection Devices

As shown, resonant ring structures can be used to increase high power test capability of low loss devices. A step on from this is testing highly reflective devices like Receiver Protectors. [3] [4]
Balanced reflective duplexer devices can be tested at power in a condition similar to operation.

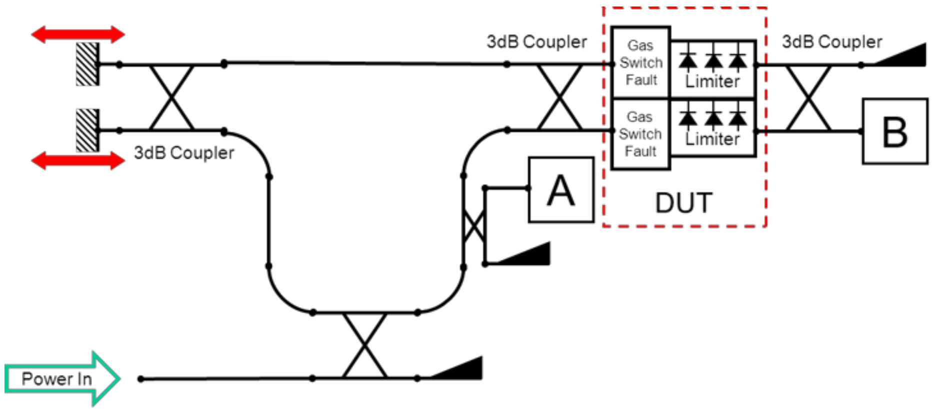


Figure 13 Resonant Ring Testing of a Balanced Duplexer

Receiver protector devices and PIN switches continue to be tested at e2v utilising a circulator within the resonant ring structure. The circulator must be capable of the ring power through 2 passes.

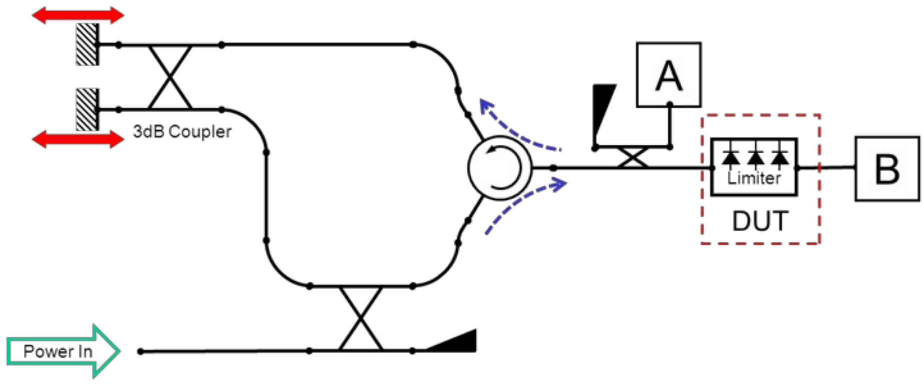


Figure 14 Resonant Ring for testing reflective devices

Here power is measured at point A via a high directivity coupler, with point B measuring leakage power levels from the device.

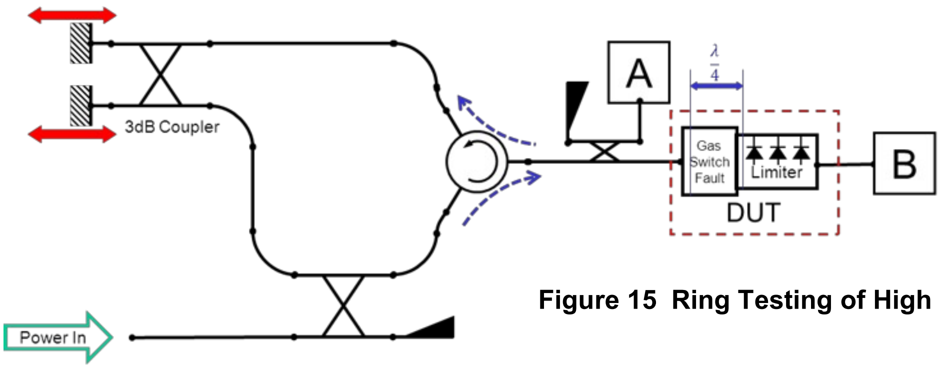


Figure 15 Ring Testing of High Power PreTR unit

The position of short circuit and its variation at switch on and during operation presents further problems for ring operation. This is particularly a problem for passive receiver protectors and gas discharge devices. Testing for high peak power operation of a PreTR Limiter device within a resonant ring necessarily has a phase shift between reflection from the diode limiter section and the breakdown of the gas PreTR device. Careful selection of couplers allows this to occur on the leakage through the coupler for an un-tuned ring, the ring being tuned for the final short circuit position of the PreTR device.

4 Measurement

4.1 Absolute Power

The power achieved within a resonant ring cannot be directly measured, as this would absorb the power and destroy the resonance effect. Microwave coupling of the power is required, at a level sufficient to add little insertion loss to the ring. For high gain rings, a loss of 0.05dB will significantly reduce the achievable gain (see Figure 1) and a coupler of 20dB will add 0.044dB loss to the ring. (Figure 16)

Calibration accuracy of a coupler at 40dB plays a significant role in confirming the level achieved within the ring. This, together with power meter accuracy leaves a large error window on the power measurement within the ring. Where significant power levels are achieved, over 300kW mean power in our case, an 80dB coupler is required (to get down to 3mW), and calibration of this becomes an issue, contributing to as much as 5% error in the absolute power measurement accuracy.

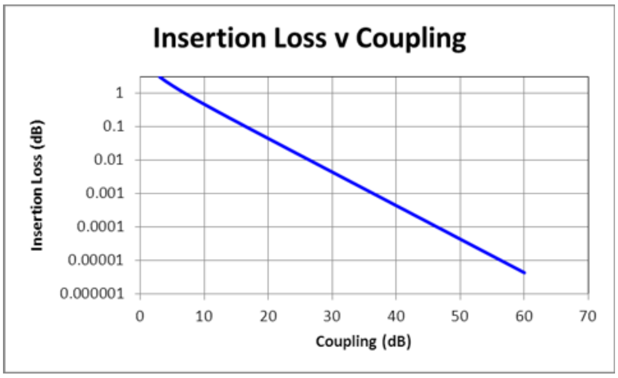


Figure 16 Added ring insertion loss for measurement coupler

4.2 Loss Measurement

For measurement of insertion loss of a device within a resonant ring, the usual errors associated with source match and load match come into play, with the added complication that a ring can be resonant in the reverse direction, potentially introducing large standing waves and causing significant measurement errors. With the inclusion of a non-reciprocal component [5](a gyrator: low insertion loss but different phase for each direction, typically used with 90° difference forward to backward), the standing waves can be reduced. This occurs due to the removal of the reverse resonance in the system. Further reduction of reflected waves can be achieved with inclusion of an isolator creating the condition where the reflected wave is not only not resonant, but absorbed by the isolator. The inclusion of an isolator in the for accuracy in loss measurement is therefore recommended.

4.3 Accuracy of the Loss Measurement

4.3.1 Direct Measurement of Device Loss in a Resonant Ring

The direct measurement of the loss of a device within a ring by sampling power before and after the unit should achieve the same accuracy as a standard through measurement performed as BS EN 160200 and using standard measurement techniques for error analysis. Error removal techniques include performing a zero measurement with the couplers together, and then the loss of the device is measured by inserting the device between the couplers. To ensure the same resonance condition, the components can be arranged as shown in Figure 17

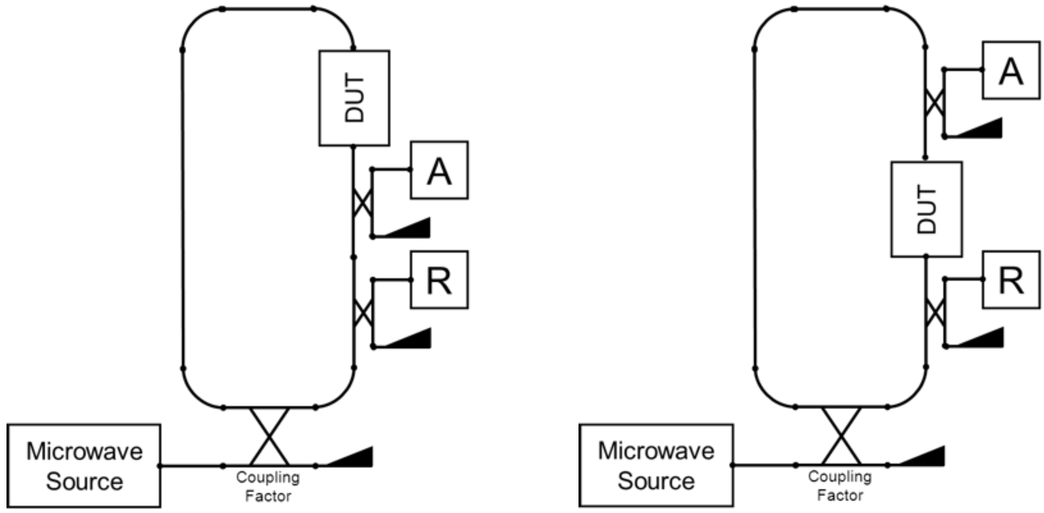


Figure 17 A method for zeroing through coupler differences in a ring.

If we assume a reasonable match of 30dB for the ring and 20dB for the Device Under test, the measurement of a 0.3dB nominal device can be calculated as EN160200-2 3002 method B. Without an isolator, the effective source match is the match of the output of the device with slight modification caused by the coupler.

4.3.2 Indirect Measurement of Device Loss by Measurement of Ring Gain

As shown above the gain achieved in the ring is related to the loss of the components within the ring. From this an alternative loss measurement is available through measurement of the ring gain. Accurate calibration of the ring coupler is required, together with (if possible) accurate measurement of the ring loss. Taking the specific example of a coupler at 7.35dB coupling, the following values for gain v total ring loss are achieved.

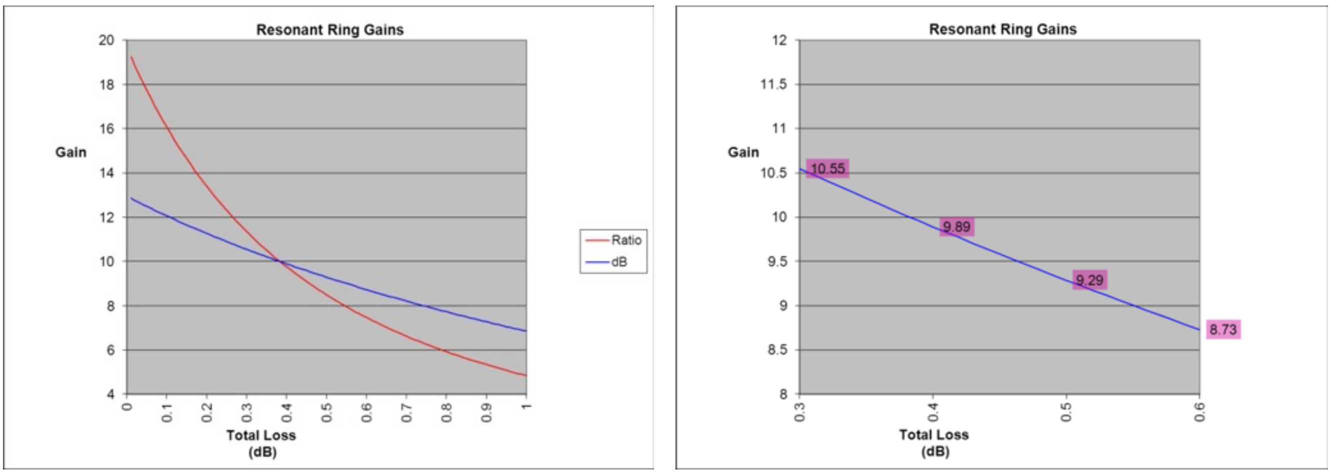


Figure 18 Specific Ring Gain v Loss

There is amplification in the effect of insertion loss that can be measured, giving an indication of the actual insertion loss of the device under test. That is to say, the difference in insertion loss between 0.4dB and 0.5dB can be measured as a change in gain from 9.89dB to 9.29dB, a 6 times increase in the change of value being measured.

In order to achieve a degree of accuracy in this measurement, zeroing of the couplers to each other is required, together with confidence in the dynamic range of the measurement equipment.

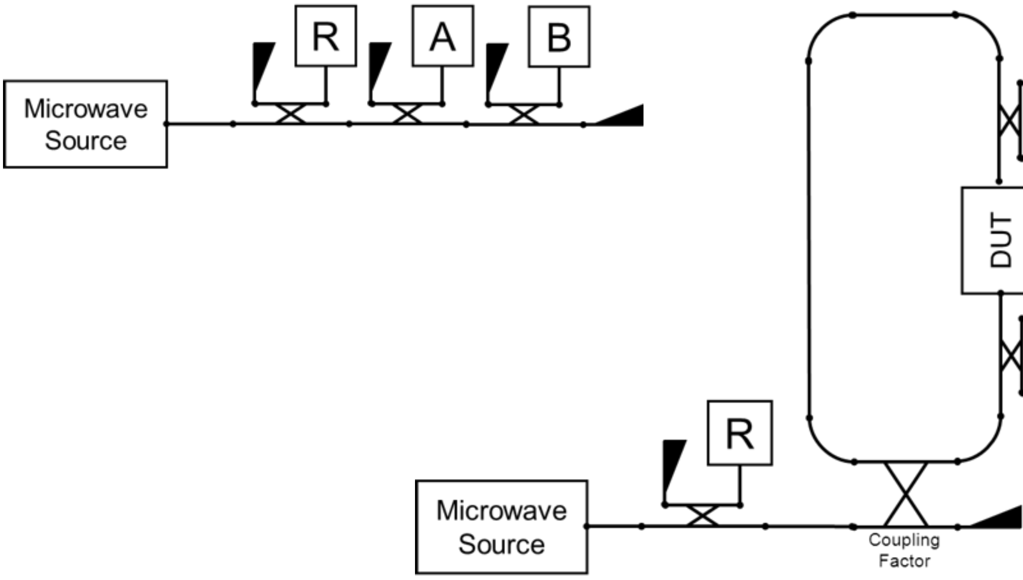


Figure 19 Insertion Loss Measurement within a ring

The difference in the measurement point within the ring clearly makes a difference to the power achieved in the ring (by the insertion loss of the DUT) and modifications to the calculations are required to account for this. The power measured at A should be increased by the device loss to achieve the gain at the drive point of the ring as used in the initial calculations. Full detailed analysis requires a complicated spread sheet, or a circuit simulator.

5 Case Example - Resonant Ring Testing of WG04 Circulator

The widening application of microwave generators to industrial processes has brought about requirements for high-power sources and Isolators. Figure 20 illustrates a waveguide-4 Circulator (later coupled with a Load to create an Isolator), which has been tested to its RF power handling design limit using a resonant ring test approach.

This test strategy has enabled a full verification of the Circulator design under

(i) normal operation and
(ii) fault operation power levels,

and also to establish

(iii) maximum design limit performance and
(iv) ultimate onset of performance degradation (at power levels beyond the normal, fault and design limit thresholds).

The unit fits in e2v's ProWave Industrial Processing Microwave generators, currently capable of output power up to 100kW. Testing beyond this power level is only possible with the resonant ring structures described. This test method will also be used to investigate margin on current isolator and other components.

Figure 20 WG04 Circulator

Purpose built components have been designed and sourced to build up a ring structure with the inclusion of available components. Available components included a 3dB sidewall coupler and remote operation sliding shorts specifically used to allow phase adjustment of the ring.

Figure 21 and Figure 22 show the structure of the waveguide ring structure in WG04 (WR975). The overall size of the ring is around 1.8m x 0.8m with the additional supporting structure of the choking section of the short circuit and motor drives for the short circuit adding a further 2m length requirement for the space layout.

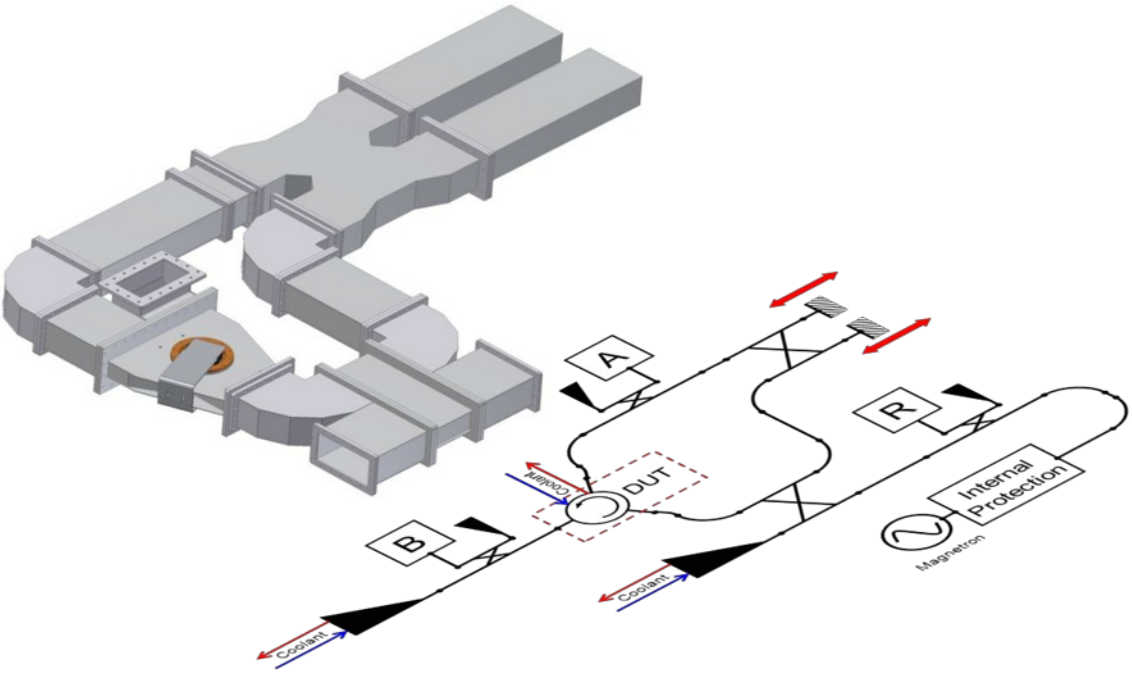


Figure 21 WG04 Resonant Ring Structure

Not shown on the waveguide assembly are the high power loads, input waveguide and monitor couplers.

Figure 22 Assembling the waveguide structure
Note the EM Field detector for monitoring leakage levels.

Operation of the ring structure at maximum gain took some time to achieve. (~10min including an off period to move the short circuit position through the full cycle) Once achieved, a reasonable run at 300kW mean power was achieved. This testing achieved 50% margin on specification requirement of 100kW in a full reflection. While local heating conditions are more severe, the standing wave in the circulator creates conditions slightly less than 4 times peak E and H fields, the overall heating effect is demonstrated as capable with some margin. As the power level increases to over 40kW input, and a ring power over 350kW the gain has dropped, probably due to mean power heating within the circulator causing a drop in isolation, as much as the ring moving off tune.

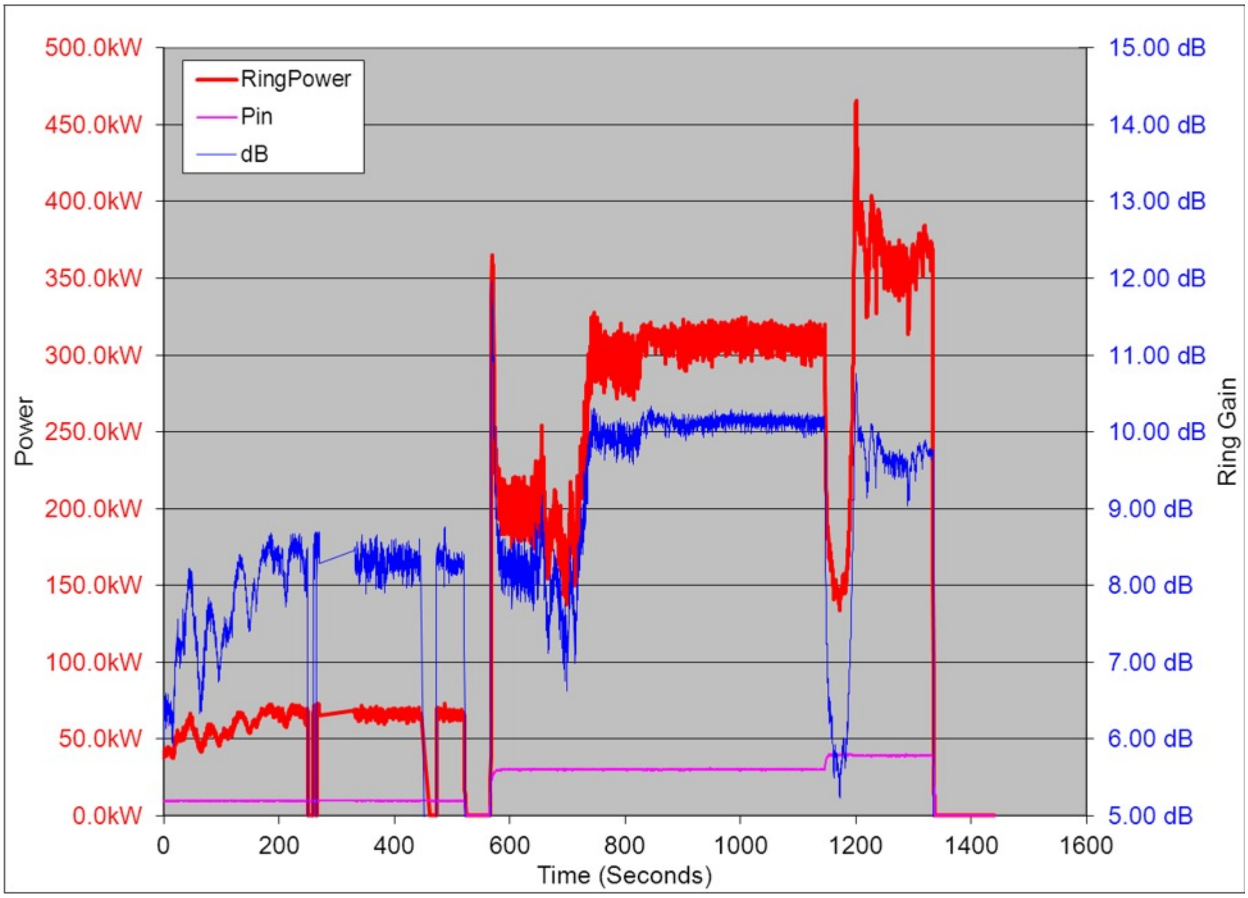


Figure 23 Initial Testing with the Resonant Ring Structure

Electrical breakdown effects were observed in the ring at power levels approaching 600kW peak power (reduced mean power), demonstrating the need for arc detection circuitry, and confirming sufficient design margin for the peak power handling requirement.

6 Conclusions

Resonant Ring Structures, travelling wave resonators, are an effective and relatively simple way of extending the power availability from test equipment sources. Full understanding of the benefits and drawbacks of this test method have been discussed. A travelling wave resonator structure can easily extend the peak power capability of high power test equipment by a factor of 10, a valuable feature for capital equipment. Demonstration of design margin with system equipment is therefore possible with the addition of a resonant ring, the alternative being construction or hire of higher power equipment. The e2v circulator for use in 100kW Industrial Processing System (ProWave) has been demonstrated to have significant design margin, utilising the host system as a test fixture.

7 Acknowledgment

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