A quasi-optical Resonant Ring for high power millimeter-wave testing

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ABSTRACT

A quasi-optical resonant ring is being developed for testing of millimeter wave components, windows and low-loss materials at very high power levels using medium power level sources. The resonant ring generates a traveling wave resonance of uniform amplitude along the waveguide that is ideal for testing components and materials. Both smooth-wall TE$_{01}$ mode and a corrugated-wall HE$_{11}$ mode versions have been constructed. These units use highly oversized waveguide and four miter bends to form a quasi-optical resonant ring. A perforated plate miter bend serves as the input directional coupler. A water-cooled tube array is being designed for a coupler capable high-power cw operation. A theoretical power gain of >10 is possible using the 63.5 mm HE$_{11}$ version at 53 GHz. Low power measurements have been performed to confirm the operation and >1.5 MW high power tests using a 200 kW gyrotron are expected in the near future.

INTRODUCTION

Gyrotrons of >1-MW cw power in the 110- to 160-GHz frequency range with HE$_{11}$ output beams are being developed for electron cyclotron heating (ECH) of plasmas. Windows are required for gyrotrons and for waveguideline transmission systems at the plasma device to provide vacuum isolation and containment. Windows are difficult to build for these systems because the window dielectric losses increase with frequency and the centrally peaked output power beam concentrates the power deposition near the center. Development and testing of a window independent of gyrotron development is desirable since window failure on a cw gyrotron usually means an expensive reprocessing of the entire tube or possibly even total loss. Testing new window designs to equivalent power levels using an off-line facility provides significant savings in tube development costs.

The resonant ring technique has been successful in the past for testing single-mode, rectangular waveguide windows above the power level available from existing sources. The resonant ring is preferred for window and other component testing because it provides traveling waves as opposed to the standing waves that exist in typical resonant cavities. A waveguide resonant ring is formed using four bends and a phase shifter for adjusting the total path length to equal an integral number of guide wavelengths. Power is coupled into the ring with a high directivity directional coupler having an optimized coupling value. A resonant ring can be easily adjusted to have low input reflection to the source provided the components under test have low reflection coefficients. At resonance and with optimum coupling, the uncoupled source power straight through the coupler is canceled exactly by the power coupled back out of the ring so that all the power enters the ring. The buildup of power level in the ring is limited only by losses in the ring components which can be quite low. A ring path loss of 0.45 dB results in a power level gain of 10.

Low-loss TE$_{01}$ mode in smooth-wall waveguide or the HE$_{11}$ mode in a corrugated waveguide are the common transmission modes used in highly oversized ECH waveguide systems. Typical waveguide diameters used for ECH range from 30 to 90 mm for a 1-MW transmission system [3]. A quasi-optical resonant ring can be formed using four miter bends with a small adjustable gap or bellows in two legs as shown in Fig. 1.

![Figure 1. Quasi-optical resonant ring configuration](image)

The gap spacing is adjusted for resonance at the operating frequency and, if kept small, has very low loss. Power is coupled into the ring at one of the miter bends that is set up as a cross-guide directional coupler. A dummy load is placed on the other arm of the coupler to absorb uncoupled power. A quasi-optical directional coupler can take the form of a parallel wire grating, a perforated plate, a dielectric sheet for the HE$_{11}$ mode and a perforated plate or dielectric sheet for the TE$_{01}$ mode. A water-cooled wire grating is being designed for HE$_{11}$ high-power cw operation. The wires must be sized and spaced to avoid grating lobe effects. Cooling of a dielectric sheet can be accomplished by using a double sheet with a liquid dielectric cooling layer flowing between.

Modeling of the resonant ring for power gain follows the conventional resonant ring approach [2] with additional loss terms for mode conversion at the miter bends. The electric field ratio from the input to the ring side of the directional coupler is given by

\[
\frac{E_{\text{ring}}}{E_{\text{in}}} = \frac{1}{\sqrt{C - \sqrt{C-1}} e^{-\alpha}} \tag{eq. 1}
\]

where \(C\) is the directional coupling factor and \(\alpha\) is the total ring loss including miter bend mode conversion loss, resistive loss, and window loss. The maximum possible power gain
also equals the optimum directional coupler value and is given by

\[ C_{\text{opt}} = \frac{1}{1 - e^{-2\alpha}} = \left( \frac{P_{\text{ring}}}{P_{\text{in}}^{\max}} \right) \quad (\text{eq. 2}) \]

which is equal to the reciprocal of the total ring loss including resistive and mode conversion loss at the miter bends.

An 88.9-mm-diameter corrugated-waveguide resonant ring operating at 110 GHz in the HE\(_{11}\) mode with 2 gaps, 3 miter bends, 1 miter bend cross coupler (assume an additional 1% loss), and a window with 1% loss will have a total loss of \(-6\%\) and a ring power gain of 16. If a 200-kW gyrotron is used, the equivalent power in the ring would be 3.2 MW. At 53 GHz with 63.5-mm waveguide, losses would be \(-13.5\%\) and the maximum power gain would be 7.5. The 53 GHz, 200-kW cw Varian gyrotrons currently operating at ORNL could produce \(-1.5\) MW in a 63.5 mm ring waveguide.

In most cases, the total ring loss is dominated by mode conversion loss which can be minimized by using larger diameter waveguide. Pairs of miter bends can be configured to reduce mode conversion loss by separating them by a half beat wavelength\(^{41}\). At this spacing, mode conversion to the next higher order mode at a bend, is canceled by mode conversion from the previous bend.

**Low Power Measurements**

Low power measurements have been performed on a TE\(_{01}\) smooth-wall resonant ring constructed from 63.5 mm diameter waveguide, a perforated plate directional coupler and a second perforated plate directional coupler to monitor ring gain. A high mode purity TE\(_{01}\) swept-frequency source from 50-75 GHz was used with a scalar network analyzer to display ring gain. Since a swept frequency source is used, there is no need for tuning the ring path length to a particular resonance. To establish a reference level, one of the miter bend plates downstream from the monitoring directional coupler is removed so that the ring is "spoiled". As indicated in figure 2, a signal increase of nearly 13 dB (20x) over the reference level is measured at four resonances in the frequency range shown. Also shown is a calculated ring gain based on (eq 1) adjusted to have lower net loss so that the peaks line up. For this frequency range, the calculated gain with full miter bend loss is 7.5 which is very close to that found at a slightly higher frequency. The \(-50\) GHz range for this figure is very close to the TE\(_{01,02}\) beat wavelength for two legs of the ring. The significantly wider width for the measured resonances may be caused by FM noise from the BWO sweep oscillator.

Further low and high power tests on the TE\(_{01}\) and HE\(_{11}\) resonant rings are planned.

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**References**


![Figure 2](image-url)
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