Fusion Engineering and Design 93 (2015) 1–8

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

# Power monitor miter bends for high-power microwave transmission

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ARTICLE INFO

*Article history:*
Received 21 October 2014
Received in revised form 16 January 2015
Accepted 19 January 2015
Available online 4 March 2015

*Keywords:*
ECH heating
Corrugated waveguides
Power monitors

ABSTRACT

Two miter bends are described for monitoring the power transmitted in an oversized corrugated waveguide. One has an array of holes in its mirror that couples a small fraction of the incident power to a rectangular waveguide directly machined into the mirror. Millimeter-wave detectors on the outputs of this miter bend can respond very rapidly to the transmitted power, but the coupling is sensitive to the mode purity in the oversized waveguide. The other miter bend monitors the power by measuring the rise in temperature of the cooling water passing through the mirror. The mirror is well isolated from the miter bend housing to prevent heat from neighboring waveguides from reaching the mirror. The measurement requires about 200 s to reach steady state, but it is relatively insensitive to mode purity. The measurement does require knowledge of the input polarization.

Thermo-mechanical analyses of the miter bends indicate that they are capable of reliable operation with 1.5 MW transmitted through them. High-power long-pulse 170 GHz tests of these miter bends at the Japan Atomic Energy Agency (JAEA) are described.

## 1. Introduction

Power monitors in high-power waveguide transmission lines have been used for three main purposes: (1) monitoring the performance of the microwave source, typically a gyrotron or gyroklystron; (2) protecting the microwave source by turning it off when significant amounts of power are detected that is traveling back toward the source; and (3) determining the power delivered to the load, which is typically a plasma or antenna. For the first two of these purposes, fast response time is normally required. If the pulse length of the source is relatively short, then determining the power delivered to the load also requires a relatively quick response.

Power monitors have generally used two major techniques to couple a fraction of the high-power transmission into a low power detector: (1) multiple coupling holes in the mirror of a waveguide miter bend; and (2) a shallow diffraction grating in a mirror. In a waveguide miter bend with coupling holes, the coupled power passes through cutoff holes in the mirror and is typically focused by a thin fused quartz lens into a standard gain microwave horn [1]. The fused quartz can be sealed with epoxy to the mirror to allow evacuation of the miter bend waveguide. Shallow diffraction grating mirrors have been incorporated into waveguide miter bends without vacuum seals [2]. Shallow diffraction gratings can also be convenient in non-evacuated quasi-optical transmission lines [3] where it is relatively easy to detect the radiation reflected from the grating at the angle of the diffraction lobe. With both techniques, the coupled power originating from forward and reverse traveling high power exits the mirror in different directions and so can be detected separately. Both techniques also provide rapid response when the coupled power is detected by diode detectors.

Similar techniques image the entire field propagating in the high-power transmission line. In a miter bend, an array of coupling apertures across the entire mirror can provide a coupled output that is the image of the field in the evacuated high-power waveguide [4]. By tapering the output down to single-mode or few-mode waveguide, the relative power in various low-order modes can in principle be determined. In such a manner, the alignment of the microwave beam in the high-power waveguide can be monitored. A grating coupler can be used for the same purpose on a mirror in a non-evacuated quasi-optical transmission line [5].

While the original multiple-hole coupling arrangement has been used extensively in waveguide transmission lines, it does have limitations. First, because there are typically only a small number of coupling holes, the coupling can be very sensitive to mode impurity. The coupling ratio is typically calibrated against the dominant $HE_{11}$ mode propagating in corrugated waveguide. However, if a few percent of the incident power is in other $HE_{1n}$ modes, the ratio of coupled power to incident power can change by several dB. This is not a serious drawback if one is only interested in a qualitative

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http://dx.doi.org/10.1016/j.fusengdes.2015.01.012
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monitoring of the microwave source or reflected power. Since the coupling holes are located near the center of the mirror, the coupling is also not affected significantly by most non-$HE_{1n}$ modes (including $LP_{1n}$ modes), because those modes do not have significant power near the center of the waveguide.

A second limitation arises because the mirror must be thin in the region of the coupling holes. The coupling holes must be cutoff to the incident microwave power in order to prevent serious leakage through the mirror. Hence the hole diameter must be somewhat less than the microwave wavelength. On the other hand, cutoff holes generally attenuate the coupled power by almost 32 dB times the ratio of the length of the hole to its diameter. In order to couple enough power, the length of holes must then not exceed a wavelength. Cooling the region near the holes then becomes difficult. With high power transmission, the thermal stresses near the coupling holes can easily exceed the yield strength of the mirror material and can eventually cause localized cracking of the mirror.

To improve the cooling near the coupling holes, a small coupled rectangular waveguide can be machined parallel to the surface of the mirror from one edge to the other. With arrangement, it is not necessary to remove all the material behind the entire array of coupling holes. A mirror with a coupled rectangular waveguide for a non-evacuated miter bend has previously been described [6]. A prototype mirror with five coupled rectangular waveguides at five different locations in the mirror was recently fabricated to determine the coupling to $HE_{12}$ and $LP_{11}$ modes as well as to $HE_{11}$ by suitable combinations of the outputs [7]. This mirror also was intended for non-vacuum use. A power monitor miter bend (PMMB) with a coupled rectangular waveguide designed for an evacuated waveguide transmission line is described in this paper.

With the advent of long-pulse gyrotron sources, another power monitoring arrangement becomes feasible; namely, monitoring the power absorbed in the mirror. The absorbed power is monitored calorimetrically through the water used to cool the mirror. Such a technique was described in principle many years ago, and has been implemented in large mirrors for free-space quasi-optical transmission [8]. For linearly-polarized modes, the absorbed power depends in a known way on the incident polarization. Hence if the incident polarization is known, then the incident power can be determined. This approach also requires that the mirror be well isolated from the housing of a miter bend. Otherwise, power absorbed in the neighboring waveguide could reach the mirror. This paper also describes a calorimetric miter bend (CMB) for evacuated waveguide with the required construction. One advantage of the CMB relative to the multiple-hole PMMB is that it is relatively inexpensive to fabricate.

After describing the basic construction of the PMMB and CMB, the results of thermal modeling are presented. Finally, the results of high-power long-pulse tests of both the CMB and the PMMB at 170 GHz are presented.

## 2. Miter bend construction

The multi-hole PMMB mirror is machined from one piece to allow efficient cooling. The mirror includes an array of cutoff coupling holes near the center of the mirror that are drilled through to a rectangular waveguide parallel to the mirror surface. The region around these coupling holes experiences the highest heat loading and thermal stress. Cooling channels are machined close to the mirror surface to provide good heat transfer near these coupling holes. A channel on each side of the coupling holes is directed toward the center of the mirror from the mirror edge, making a channel with an overall *V*-shape; the point of the *V* is near the mirror center. The two channels are connected externally by a loop of copper tubing.

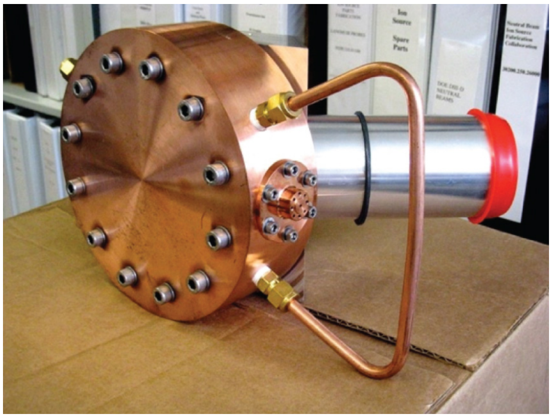

**Fig. 1.** Power monitor miter bend (PMMB), showing water cooling line and output port in small circular waveguide. A transition to WR6 rectangular waveguide, a level set attenuator, and a WR6 detector are normally connected to this port.

Copper–chromium–zirconium alloy is used to provide high yield strength with little degradation in conductivity.

The coupling is designed to respond only to the component of the high power input that is polarized perpendicular to the plane of the miter bend, since that polarization produces the lowest ohmic loss on the mirror. The width of the rectangular waveguide perpendicular to the electric field must match the phase velocity of the $TE_{10}$ mode in rectangular waveguide to the component of the high power input parallel to the mirror surface. For 45° incidence as in a miter bend, the width must then be $\lambda/\sqrt{2}$. At 170 GHz where the wavelength $\lambda$ is 1.764 mm, the corresponding width is 1.25 mm. For convenience in machining the waveguide into the mirror by a wire EDM process, the other dimension of the waveguide was made large enough to propagate the rectangular waveguide $TE_{01}$ mode. Nevertheless, the phase velocity of that cross-polarized mode was sufficiently mismatched to the high power input that it would not be excited.

A transition to circular waveguide and a circular waveguide uptaper are machined into the mirror at each end of the rectangular waveguide in order to reduce the effect of the discontinuities at vacuum windows. Each window consists of a small disk of fused silica sealed with a Helicoflex® metal seal. On the atmospheric side of the window a separate circular waveguide downtaper to relatively small circular waveguide is attached. The fused silica window material is chosen to be fairly lossy in order to minimize the effect of any modes trapped between the tapers on either side. A standard commercial transition between the circular and fundamental WR6 waveguide completes the mirror assembly. Since the construction is symmetric, the mirror can be used to detect power in the reverse as well as the forward direction in the high power waveguide.

In order to allow space for flanges for the output tapers at the windows, the central part of the mirror is recessed. The miter bend housing is inserted into that recess. The entire power monitor assembly is shown in Fig. 1.

The calorimetric miter bend uses reentrant cooling through a small-diameter shaft in order to keep the mirror isolated as much as possible from the miter bend housing. A rotatable water union allows a convenient connection of the external water-cooling tubing to the mirror. This union is the same as used in polarizer miter bends. However, in the calorimetric miter bend the union is not actually rotated.

A thin-walled stainless steel cylinder provides high thermal resistance between the rear of the mirror assembly and the main part of the miter bend housing. Deep water channels are machined into the thicker rear part of this cylinder to short circuit the flow of any residual heat heading toward the rear of the mirror assembly. A