A Wide-Bandwidth Coupler for a Free-Electron-Maser Amplifier

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***Abstract*—The coupler described in this paper is designed to separate the hot electron beam and the high-power microwave signal in a free-electron-maser amplifier. This coupler has been designed, built, and tested and is intended for operation across the 8–18-GHz frequency band. It consists of an arc of quadridged waveguide with the electron beam entering between ridges. The RF performance was found to be critically dependent on the radius and length of the arc. The measured return loss is better than −30 dB across the band with an insertion loss of less than 0.1 dB.**

***Index Terms*—High power, waveguide coupler, wide bandwidth.**

I. Introduction

THE free electron maser (FEM) [1]–[3] has been developed to meet the possible needs of future electronic warfare (EW) and radar applications. The physics of this device are common to those of the FEM operating at optical and IR wavelengths. The FEM is a relativistic electron beam device capable of providing very high microwave power over a wide frequency bandwidth (1-MW continuous wave (CW) at J-band, 125% bandwidth). To exploit the full potential of this device, it is necessary to develop components that have both a high average power and a wide-bandwidth capability. High power, together with wide bandwidth, is believed to be a novel requirement.

As part of the program of component development, the waveguide coupler described in this paper has two roles. Firstly, it is required to combine the hot electron beam emanating from a thermionic gun with the input microwave signal to the amplifier. Once this signal has undergone amplification, a second identical coupler is now required to separate the electron beam and high-power amplified signal prior to recovering the remaining energy from the electron beam.

The coupler must be designed to have excellent microwave performance both in terms of low insertion and return loss and also in mode conversion. It must be designed to allow propagation of the electron beam without beam scraping occurring at either the input or output ports, while preventing the microwave energy from propagating into the electron gun or energy recovery regions.

II. Coupler Design

The standard techniques for T-junctions or mitred bends are not applicable here since all the RF power from the input side arm must travel along the RF output arm. Ideally, no power should travel backward toward the electron gun or, in the output case, toward the beam energy recovery system. In addition, this is a wide-bandwidth device, which prevents the inclusion of frequency-sensitive matching. The high power also precludes the use of matching posts, irises, or sharp changes in dimensions. A previous example [4] has been published, but this has a narrower bandwidth (8.5–11.5 GHz) and lower peak power (55 kW) than the component discussed here. A smooth-walled circular waveguide was considered, which would support the frequency band 8–18 GHz (set by system requirements). The waveguide diameter was set by the need to have a clear central section of 12-mm diameter for the electron beam and to support propagation of the fundamental over the required frequency band. A diameter of 25.4 mm was set by the FEM requirements and the cutoff frequency for the fundamental $\mathrm{TE}11$ mode is 6.9 GHz.

A smooth-walled circular waveguide of diameter 25.4 mm formed into a 90.0° mitred bend was considered, with the electron beam arm, which has a smaller diameter of 12 mm, entering through the mitred section, but it was not possible to obtain the required return loss over the required bandwidth even without including the electron beam arm. Radial bends in a circular waveguide were more promising without the electron beam arm although higher order modes ($\mathrm{TM}01$, $\mathrm{TM}11$, $\mathrm{TE}21$, and $\mathrm{TE}31$) were generated. The first three of these higher order modes were enhanced when the beam arm was included. The amount of each higher order mode was dependent on the bend radius of curvature of the circular waveguide.

In order to raise the cutoff frequencies of the higher order modes, a circular quadridged waveguide [5] was used, where the ridges were set at 45.0° to the plane of the coupler so that the beam arm entered between two ridges. The diameter of the waveguide was maintained at 25.4 mm for compatibility with the smooth-walled waveguide of the FEM. The fundamental mode cutoff was unchanged at 6.9 GHz because the ridges were quite shallow at 6 mm. The $\mathrm{TM}11$ mode was moved to 18 GHz and the other troublesome modes were raised in cutoff frequency. The ridged waveguide was bent in an arc of a circle and it was found that the radius and the angle of the arc could be used together to optimize the return and transmission losses and to limit the amount of energy going into the higher order modes. Fig. 1 shows the general geometry.

All the optimization was carried out using the fnite-element program HFSS [6] from the Ansoft Corporation, Pittsburgh, PA, which allows the higher order modes generated to be examined, as well as the return and insertion losses. The accuracy of the program has been compared with another computational electromagnetic (CEM) method, modal matching, and with

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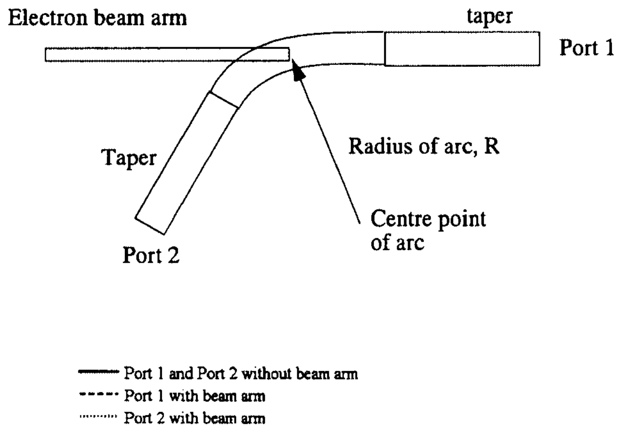

Fig. 1. Geometry of the coupler with an electron beam arm present. The polarization vector is orthogonal to the plane of this paper.

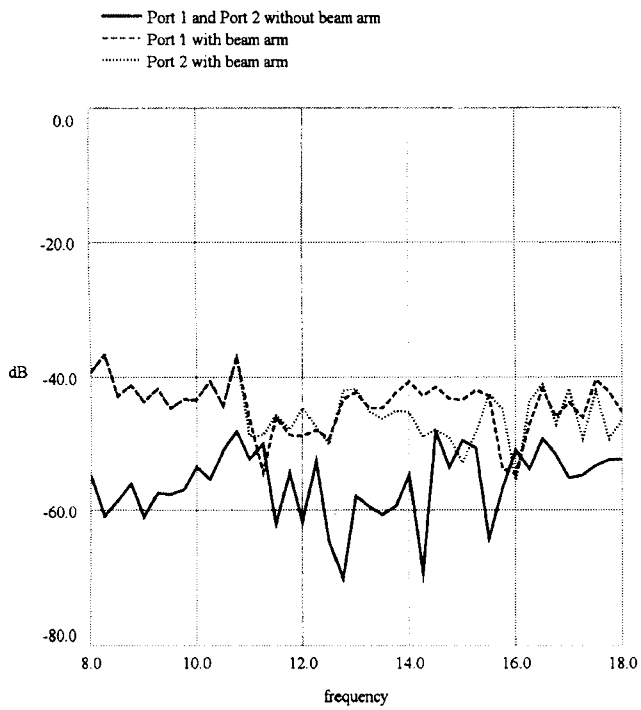

Fig. 2. Computed return loss for an arc of 60.0° with and without the electron beam arm.

measurement [7]. The agreement for waveguide components is very good. Due to the size of this waveguide component and its complexity, the number of tetrahedra for a half-model using symmetry was from 80 000 to 95 000 and runtimes over such a large bandwidth were correspondingly large at up to 72 h on a 700-MHz Pentium III machine with 1-GB RAM.

When a straight section of circular ridged waveguide was examined, the content of the first five higher order modes was at least 50 dB below the fundamental mode across the whole frequency range. The RF performance for several radii of curvature and arc lengths was computed across the frequency band. For a radius of the center line of 150 mm, and with an arc length of 60.0° or greater, the return loss was found to be less than −40 dB across the band. When the beam arm was added, there was a degradation in performance. A typical example for an arc of

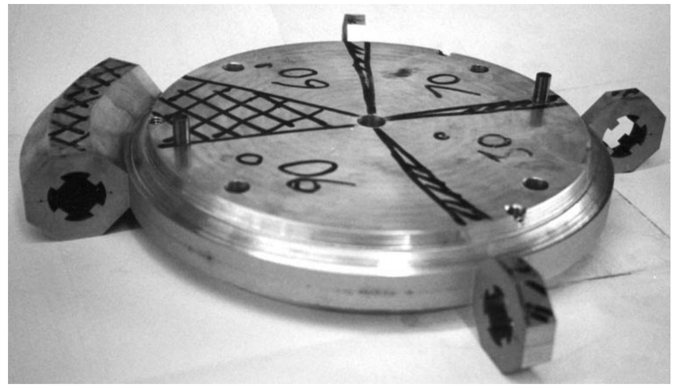

Fig. 3. Circular ridged waveguide, constructed from two half-sections. Four arcs have been cut from the assembly.

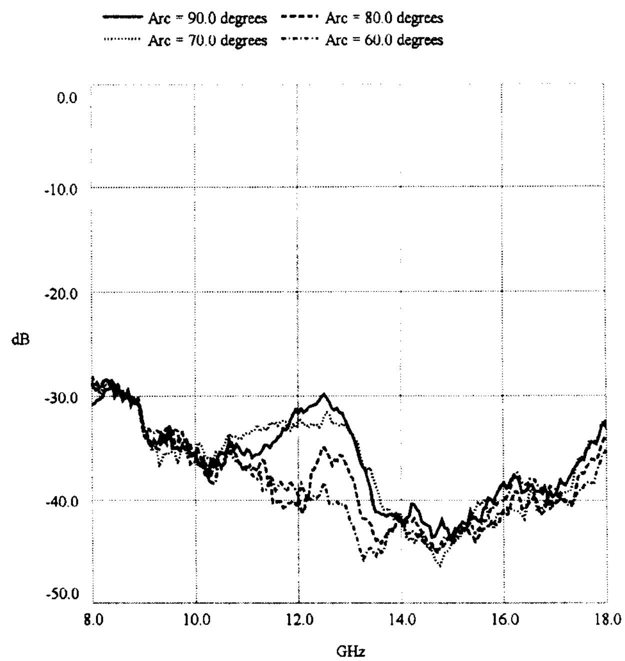

Fig. 4. Measured return loss for four arcs without the beam arm.

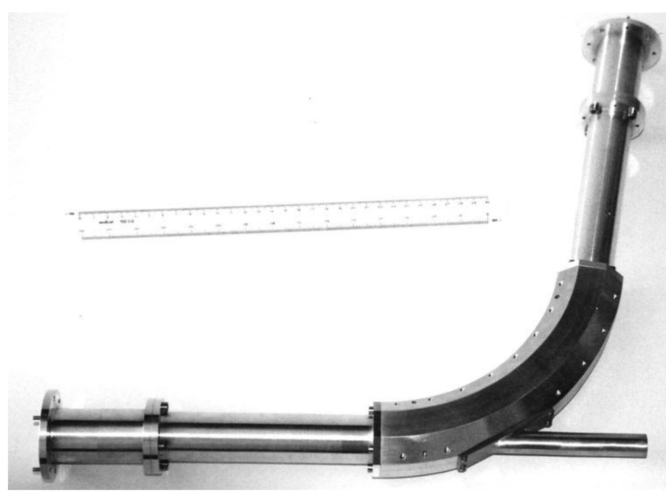

Fig. 5. Coupler with an 80.0° arc and complete with the beam arm inserted.

60.0° is shown in Fig. 2 where the return loss rose from less than −50.0 dB to less than −38.0 dB when the beam arm is added.

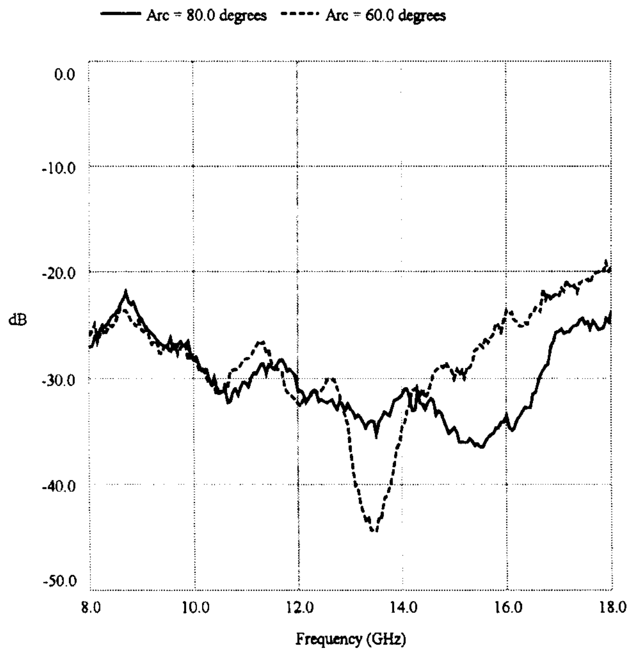

Fig. 6. Measured return loss for two arcs with the beam arm present.

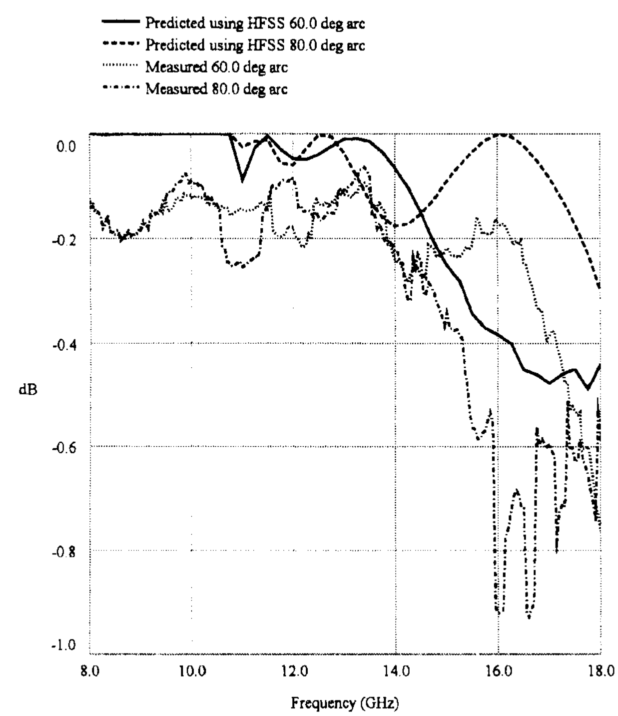

Fig. 7. Measured and predicted insertion loss for two arcs with the beam arm present.

The insertion loss with and without the beam arm is only marginally different. The loss rises to 0.5 dB above 14 GHz. This is due to the generation of higher order modes, in particular TE01, which is not a problem in the FEM, as only the fundamental mode is amplified.

There was little to choose between the arcs of 60.0°–80.0° and an experimental program was devised to verify these predictions and select a final value for the arc.

In order to avoid generating further higher order modes when manufactured, a sensitivity analysis was carried out and the manufacturing tolerances were set as ± 50 μm.

III. Build and Test

Since an experimental setup was envisaged, it was decided not to electroform the component parts, but to manufacture a complete 360.0° ridged waveguide in two halves, which were then doweled and bolted together. Sections of the wanted arc length could then be cut out from this ring, as shown in Fig. 3. Two tapers from a ridged to circular waveguide were manufactured, which were doweled and bolted to the arc under test. Four arcs were manufactured—60.0°, 70.0°, 80.0°, and 90.0°. All faces were provided with a 1.0-mm triangular groove for the insertion of indium seals when used in vacuum.

These four arcs were measured without the beam arm (Fig. 4). The best two were then selected (60.0° and 80.0°), the beam arm inserted—a photograph is shown in Fig. 5—and the measurements were repeated. The arc of 80.0° was clearly better than that of 60.0° (Fig. 6) although insertion losses in both cases are higher than predicted (Fig. 7).

IV. Conclusions

A coupler capable of combining or separating an electron beam and a high-power microwave signal has been successfully designed, built, and RF bench tested. The measured results are slightly worse than predicted, but this may be due to errors introduced by additional components required to interface the vector network analyzer with the coupler. The increased insertion loss may also be due to this and to modal conversion. The future program will involve the integration of this coupler into the FEM for hot testing under vacuum with an electron beam present.

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