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Waveguides have been designed with special corrugations to convert the incident power to a surface wave and then increase the attenuation gradually to absorb the power uniformly. Advantages include small size, minimal reflected power, and fast time response. We describe measurements of the power deposition profile and the total absorption in 31.75 mm waveguide loads designed for 110 and 170 GHz. Loads have been fabricated in dispersion-strengthened copper with internal nickel plating to increase the absorption and external corrugations to improve the water cooling. When 1 MW was incident in several 5 s pulses, about 800 kW was absorbed at 110 GHz in a load 1.8 m long.

We also describe small TiO_2-coated aluminum tank loads designed to absorb up to 250 kW-CW residual power exiting these waveguide loads. The tank loads have also been used to absorb 1 MW with pulse widths around 0.2 s. We describe special features used to maintain uniformity of the power deposition in the tank walls and to minimize reflections into the input waveguide. A novel low-power technique for measuring total reflected power indicated that 1% or less of the power is reflected from these tank loads.

1. Introduction

Dummy loads are needed for conditioning high power microwave tubes and as calorimetric devices for determining the output power of these tubes. They are also used to determine the power delivered to the end of a transmission line.

As very long pulse lengths are becoming available from high power gyrotrons, dummy loads suited for continuous power absorption are becoming necessary. An additional requirement for all loads is low reflected power, since relatively low levels of reflected power can disturb gyrotron operation.

At present, there are at least two types of loads available for absorbing continuous 1 MW power levels from gyrotrons operating between about 60 and 170 GHz. The first type is a cylindrical tank coated on the inside with lossy titanium dioxide. In order to prevent hot spots and to minimize reflections, an internal mirror is rotated continuously to spread the incident microwaves around the internal surface of the tank. Since the tank is large, it can be used at atmospheric pressure [1].

This paper describes the characteristics of a second type of load for 1 MW continuous input power; namely, a special corrugated 31.75 mm waveguide. Advantages of this type of load include small size, very fast thermal response, low reflections, relatively low water cooling flow requirement, and absence of internal moving parts. The fast thermal response is useful in conditioning gyrotrons, since the effects of changing operating parameters can be observed quickly.

Sections 2.1 and 2.2 review the basic theory of the waveguide load, including the microwave and thermal aspects. Section 2.3 describes the fabrication. In Section 3, we describe the measured characteristics of waveguide loads. Sections 3.1 and 3.2 describe high and low power measurements, respectively. Uniformity of the power deposition was measured to try to verify the absence of hot regions.

Since the waveguide load is a two-port device, another load must be attached at the output of the waveguide to absorb the residual power. A suitable small tank load has been developed for this purpose. Section 4.1 describes the design of a small tank load for absorbing the residual power exiting the waveguide load. Section 4.2 describes low-power total power measurements of the reflections from this type of load using a novel beam splitter.

2. Design and Fabrication of Waveguide Loads

2.1. Microwave Design

A smooth-wall phase shift section followed by a corrugation depth taper converts the incident HE_{11} mode to a surface wave [2]. The attenuation (fractional power absorbed per unit length) of the surface wave increases with corrugation depth. To keep the power absorbed per unit length reasonably uniform, the corrugation depth is increased with increased distance along the waveguide axis. The attenuation doubles each time the corrugation depth increases by about 0.05 mm at 110 GHz.

Since the surface wave has a phase velocity slower than the speed of light, its wavelength along the axis of the waveguide is smaller than that of free space radiation. In order to prevent reflections due to Bragg scattering, the period of the corrugations much always be less than one-half of the axial wavelength. Since the axial wavelength decreases with increased corrugation depth, there is a practical limit on the corrugation depth and thus the attenuation in a given material. Nickel plating is used to increase the achievable attenuation without the danger of reflections.

To avoid conversion of the residual surface wave power to backward waves, the corrugation depth is tapered down near the end of the load. This depth taper reduces the phase velocity of the surface wave so that it is close to low-loss modes. Then the abrupt transition to low-loss corrugations can be done safely.

2.2. Thermal Design

The outside of the load is corrugated with relatively wide corrugations to improve the heat transfer to the cooling water. When water flows between the waveguide and a concentric water stainless steel water jacket, the cooling is similar to that of a hypervapotron, originally invented in France as a way of cooling microwave tubes [3].

To make the load resistant to thermal fatigue, Glidcop® dispersion strengthened copper is used. This material retains its strength far above the normal annealing temperature of copper, which is about 300°C.

The main attenuating region of the load is 1 m long. When 0.75 MW is absorbed uniformly over this length, the flux for heat transfer is about 535 W/cm^2. The calculated temperature drop from the water to the bottom of the external waveguide corrugations is about 107°C. The calculated temperature drop across the waveguide wall is about 57°C. The heat capacity of water itself will cause a 45°C difference in temperature between the water at the inlet and the outlet, at the rated flow of 4 ℓ/s. Since the intrinsic thermal time constant of this load is short (about 0.2 s), the full water flow must be used even for relatively short pulses.

Assuming an inlet water temperature of 20°C, the maximum internal wall temperature is 20° + 45° + 107° + 57° = 229°C. This is a safe level, and allows for some nonuniformity in the absorption. To accommodate thermal expansion of the load, the water seal to the cooler water jacket is made with O-rings designed for the relative motion. In addition, either a waveguide bellows or unrestrained connecting waveguide and miter bend are required. In practice, the load expands about 5 mm, corresponding to an average temperature rise of about 200°C in the absorbing part of the load.

2.3. Fabrication

Rods of Glidcop® material were straightened, bored, and honed to the desired inner diameter. The inner corrugation profile was produced on the GA waveguide-corrugating machine. The inside of the waveguide was then plated electrolytically with nickel. This coating is only a few µm thick, or a few skin depths at 110 GHz. Electroplated nickel is typically used on Glidcop® to prepare the material for brazing, so it has a very high temperature capability. Finally, the external corrugations were machined.

A completely assembled waveguide load is shown in Fig. 1. Water manifolds at each end of the water jacket with multiple holes provide for azimuthal uniformity of the cooling. Both ends of the waveguide have standard low-loss internal corrugations in the regions machined for the waveguide couplings where there is no cooling.

3. Measured Characteristics of Waveguide Loads

3.1. High Power Measurements

Nickel-plated Glidcop® waveguide loads have been connected to CPI 1 MW long pulse 110 GHz gyrotrons at DIII–D. Calorimetric measurements during 1 MW 5 s pulses of one of these gyrotrons in 2001 indicated that about 80% of the incident power was being absorbed in the waveguide load [4]. The remainder was absorbed in large Inconel tank loads. The time response of the waveguide load was a few seconds, limited by the devices measuring the input and output water temperatures.

Two years earlier, infrared camera measurements were made of a prototype aluminum load with no water jacket. Repetitive 10 ms pulses of about 650 kW from a 110 GHz Gycom gyrotron were input to the load. The camera simultaneously measured the temperature at several locations along the load, as shown in Fig. 2. Note that the power deposition appears quite uniform over the main portion of the load. As expected, the power absorbed in the mode converter region increases as the groove depth increases.

3.2. Low Power Measurements

The total power was measured by a Scientech laser power meter with absorbing dielectric. The power meter head was attached to a smooth copper waveguide inserted in the 31.75 mm corrugated waveguide. The 25 mm inside diameter of the copper waveguide matched the aperture of the power meter. The input to the copper waveguide was flared to 31.6 mm with a 15° taper. Short (~15 cm) and long (~2 m) copper tubes were used. To measure the total attenuation in the load with the short tube, the power was first measured at the output of a transition from the small waveguide of a 110 GHz gunn oscillator to 31.75 mm waveguide propagating the HE_{11} mode.

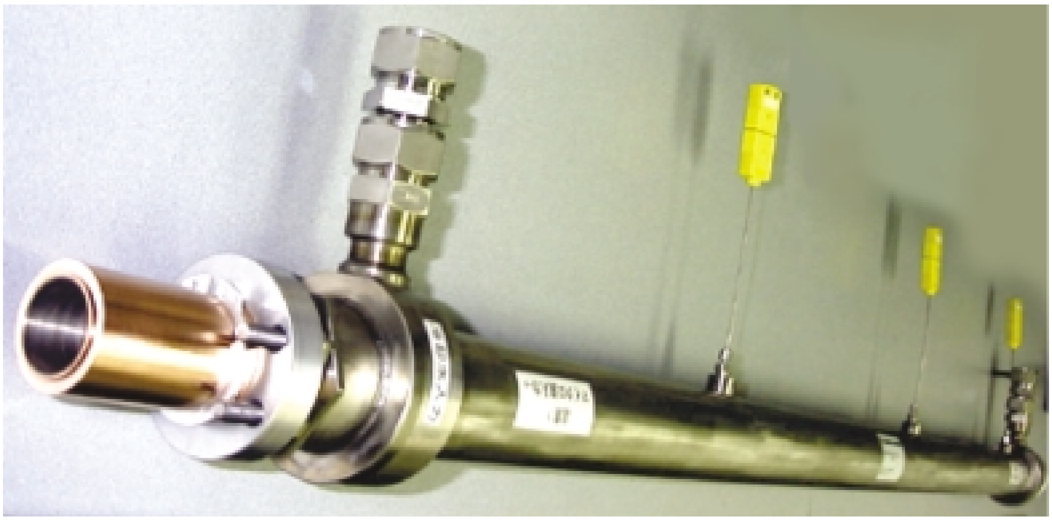

Fig. 1. 110 GHz 1 MW load (attenuator) in 31.75 mm corrugated waveguide with stainless steel water jacket.

The measured attenuation in several nickel-plated 110 GHz loads varied from about 67% to 85%. Measurements on one load before and after plating were 69% and 84%, respectively. The attenuation in the load should depend on the amount of the incident HE_{11} mode converted to a surface wave, as well as the square root of the effective surface resistance of the load. Using the ideal resistivities of Glidcop® and sulfamate electrolytic nickel (1.86 and 8.6 μΩ cm, respectively), and assuming the typical increase in the effective surface resistance by 20% due to surface roughness, one can infer that about 88% of the incident HE_{11} power was converted to the surface wave in this load. The efficiency of this conversion is very sensitive to the corrugation depth control at the start of the mode converter section.

A prototype 170 GHz load made in aluminum was also measured. The measured attenuation was only slightly higher than 50% in this load. Since the required corrugation depths at the higher frequency are smaller, fabrication of the mode converter section is more difficult. Improved ways of controlling the initial very small depth are being developed. On the other hand, fabrication of loads for frequencies somewhat lower than 110 GHz should be relatively easy.

To measure the uniformity of power deposition in a load, a long copper tube was attached to the power meter head. The head was attached to a motorized rail, and also to a linear potentiometer for measuring distance. The tube was then inserted into the load, and the power meter output was fed to an X-Y recorder.

Figure 3 shows the power measured in a load as a function of the position of the input to the copper tube. The plot is the average of two measurements made when the tube was pushed into the load and pulled out. As expected, the power is rather constant in the input region through the phase shifter, and also near the output after the attenuating region. The measured power decrease in the mode converter region may be due to a change in the coupling through the input taper of the copper tube. The mode converter region in this load was the same as for the prototype load measured in Fig. 2, which indicated that the power absorbed in the mode converter region was small.

4. Compact Tank Loads

4.1. Microwave Design

These loads are designed to absorb 250 kW continuously. They have been also been used at JAERI in Japan to absorb 1 MW in 0.2 s pulses at the output of gyrotron matching optics units (MOUs).

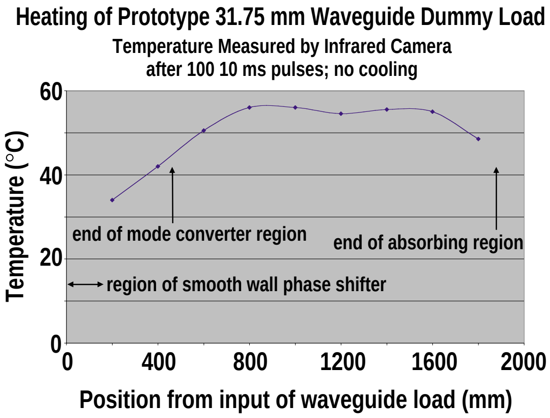

Fig. 2. Infrared camera measurement of power deposition uniformity in prototype aluminum waveguide load.

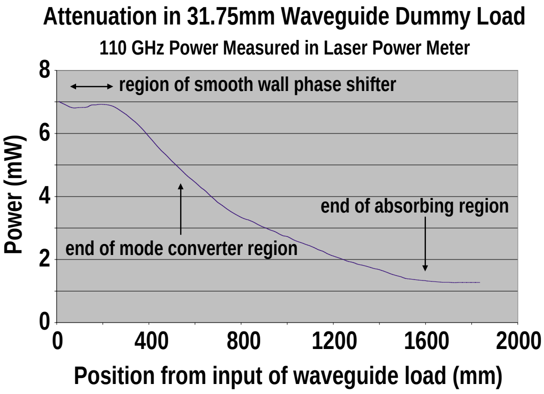

Fig. 3. Low power measurement of attenuation in a nickel-plated Glidcop® waveguide load.

The input waveguide is attached to an end plate of a large aluminum cylinder with thick walls. The cylindrical wall is coated about 0.2 mm thick with titanium dioxide from a plasma spray. After spraying, the titanium dioxide becomes TiO_X, where x is slightly less than 2. Earlier 110 GHz measurements on miter bends with mirrors coated with this material indicated that its effective resistivity was about 0.1 ohm-cm, with a skin depth of about 0.06 mm.

Power radiates out the open-ended waveguide at a 9° angle to the endplate normal. The endplates of the cylinder are not coated and absorb only 0.2% or less of the incident radiation per reflection. Radial conduction in these thick plates keeps them relatively cool.

The actual absorption at the coated surface is strongly dependent on the polarization, particularly for angles near grazing incidence such as in this load. When the first incidence on the cylindrical surface is in the high loss polarization, then the central region of the area absorbing the power from this reflection will become significantly hotter than the rest of the cylinder. This “hot spot” is caused by the concentration of power in the center of the beam.

A “hot spot” could be avoided by arranging the input polarization to be perpendicular to the plane of incidence on the cylindrical surface. The absorbed power is only 4% per reflection in this case. Unfortunately, the polarization of the central part of the beam does not change after each reflection. Many reflections are then required to absorb all the power. During the many round trips in the load, a significant portion of the power will leak out the input waveguide. (In low power measurements, about 8% of the power input to the load was observed to return out the input waveguide in this case.)

A solution is to rotate the polarization of the central part of the beam each round trip in the load. The most favorable polarization in the input waveguide is now in the plane containing the waveguide axis and the axis of the cylinder. Only during the ninth round trip in the load does the central portion of the beam reflect from the cylindrical surface in the high loss polarization. The absorption occurs soon enough, however, so that very little power now returns out the input waveguide.

4.2. Low-Power Measurements

The setup to measure reflected power from a compact tank load is shown in Fig. 4. Note that water-cooling channels on the outside of the absorbing cylinder are visible. The endplates were later removed, and an outer cylinder was slid over the large O-rings to make a water seal. The outer cylinder is not rigidly attached, in order to accommodate thermal expansion of the inner cylinder.

The test equipment included a 110 GHz Gunn oscillator, a precision attenuator, a transition from small waveguide to 31.75 mm corrugated waveguide, a beam splitter and a total power meter. The beam splitter consisted of a double miter bend with no mirrors. A thin sheet of polyethylene was pressed between the two back-to-back miter bends. The total power was measured by a Scientech laser power meter with absorbing dielectric.

The four ports of the beam splitter are shown in Fig. 4. The input from the Gunn oscillator was connected to port 1, and the output to the dummy load was connected to port 2. A wooden conical absorbing load was inserted in a waveguide connected to port 3. The power meter head was attached to a smooth copper waveguide (described in Section 3.3) that was inserted in port 4.

The calculated reflection from the polyethylene sheet in the beam splitter is 29% in the H-plane polarization (electric field perpendicular to the plane of the miter bends) and only 3% for the orthogonal E-plane polarization. The input was in the H-plane polarization. Most of the power incident on the beam splitter (about 71%) is then transmitted straight through to the conical wooden load where it is absorbed. However, almost all of the power (71% of the

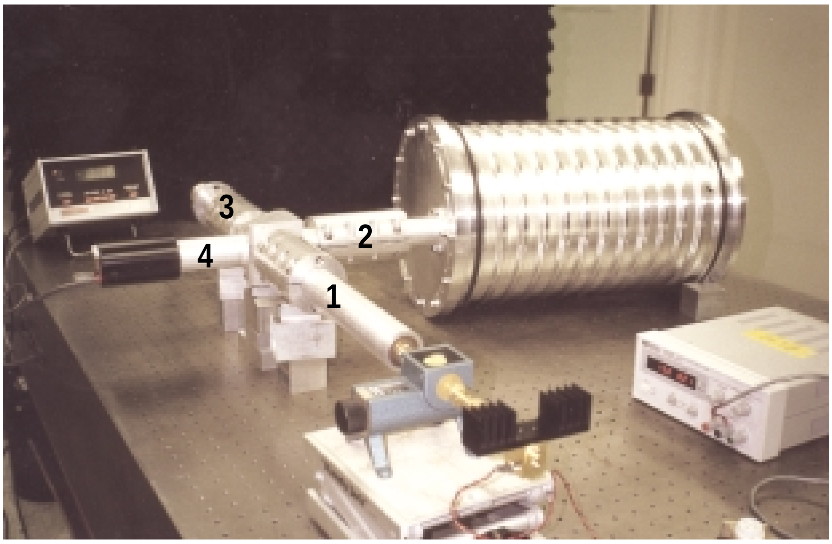

Fig. 4. Measurement of the power reflected from an aluminum tank load using a dielectric sheet beam splitter and a laser power meter.

H-plane power and 97% of the E-plane power) reflected from the high power load is transmitted straight through the beam splitter to the power meter.

Each power measurement was the average of 10 individual measurements made by taking the difference between the power meter readings when the precision attenuator was changed from 0 to 50 dB. In this way, the effects of power meter drift were minimized.

First, the load was oriented so that the input electric field was polarized perpendicular to the plane containing the input waveguide axis and the axis of the cylinder of the load. This is the orientation shown in Fig. 4. The power measurement was 0.023 mW. Finally, the load was oriented so that the input electric field was polarized parallel to the plane containing the input waveguide axis and the axis of the cylinder of the load. The power measurement was 0.018 mW.

Neither of these reflected power measurements was significantly greater than when an absorbing sheet was placed at port 2 (0.018 mW). Also, when a flat metal plate ("short circuit") was placed at port 2, 1.8 mW was measured. Hence we can conclude that the power reflected from the load is only 1% or less.

Acknowledgments

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