

Graphite Millimeter-Wave Waveguide and Mirror for High Temperature Environments

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Abstract—A graphite helix corrugated waveguide with a miter mirror has been fabricated and used for 135 GHz pyrometer measurements on a high temperature plasma arc furnace. The guide has an internal diameter of 3.81 cm, a length of 123 cm, and a corrugation of 32 grooves/inch. One end of the guide was sealed with a Teflon window having moth eye surfaces to reduce reflections. The room temperature insertion loss of this guide assembly for HE₁₁ mode propagation and launch was measured to be 0.5 ± 0.1 dB. It was used successfully in a high temperature environment where the miter mirror end reached incandescent temperatures in excess of 1200°C. High temperature graphite surface corrosion typically increased the insertion loss to 1.2 ± 0.2 dB but did not significantly affect the beam divergence.

I. INTRODUCTION

CLEANING UP AND SAFEGUARDING the environment is currently an important technological challenge. High temperature processes using furnaces, incinerators, and boilers are in widespread use and under development for the disposal of hazardous and municipal wastes, the generation of power, and in many industrial processes such as aluminum and steel making. The development of real time monitoring technologies for these high temperature processes are key for optimization and control, and for pollution prevention. In addition, the next phase in the development of a magnetic confinement fusion energy source will require diagnostics that can access a hot reactor core.

Microwave and millimeter-wave sensors can make an important contribution in these areas. For example, active millimeter-wave pyrometry [1] is a robust and accurate furnace temperature measurement technology in comparison to conventional infrared pyrometers and thermocouples. Millimeter-waves can penetrate smoky atmospheres with good spatial resolution and are less affected by contaminated and degraded windows and mirrors than infrared pyrometers. They are also more reliable and can access higher temperatures than thermocouples. In addition, a unique feature of a heterodyne radiometer, local oscillator leakage, can be used as an active probe of the surface emissivity.

In the area of fusion energy plasma diagnostics, millimeter and near millimeter-wave techniques can be used for localized

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reactor core measurements of electron temperature [2], ion temperature [3], and fusion ion products [4]. These are key parameters for monitoring the performance of a fusion reactor core for which alternative optical and particle based diagnostic techniques may not be suitable in the next generation of large fusion burning experiments.

In order to make practical these applications, microwave and millimeter-wave components which can be used in harsh, high temperature environments are needed. Use of graphite mirror components at near millimeter-wavelengths at low temperatures has been reported [2]. In this paper we present the design and performance results of a 135 GHz graphite waveguide and mirror antenna system that was used inside a plasma arc furnace at temperatures up to 2200°C as part of an active temperature measurement radiometer. We show here that efficient waveguide and mirror components, that perform well in a harsh, high temperature environment, can be fabricated from the same graphite material as a furnace hearth or the limiter in a fusion reactor core.

II. ANALYTIC BASIS

The most efficient waveguide mode is the HE₁₁ mode propagated in overmoded corrugated waveguide [5]. For a waveguide diameter many times larger than the wavelength, the HE₁₁ mode electric field at the guide walls approaches zero. It is therefore possible to efficiently propagate millimeter-waves over short distances even if the waveguide is constructed from a conductor material with high resistivity. The attenuation coefficient for HE₁₁ propagation in corrugated guide with a corrugation depth close to $\lambda/4$ and with a free space internal medium has been shown to be given by [6]

$$\alpha = \frac{0.00767 R_s}{k^2 a^3} \quad (1)$$

where $R_s = \sqrt{\pi f \mu_0 / \sigma}$ is the surface resistivity, k is the wavenumber, and a is the internal radius of the waveguide.

Ideally, the corrugations should be individual circular grooves along the inside circumference of the guide. However, it is much more convenient to use a screw-type threading process to fabricate the corrugations, resulting in a helical groove running the length of the guide. The main consequence of using a helical corrugation is that the polarization direction of the linearly polarized HE₁₁ mode will be rotated on propagation through the guide. This is not important for detection of unpolarized thermal emission in a furnace, unless the surface emissivity is polarization dependent, but could be

TABLE I
CALCULATED ATTENUATION AND POLARIZATION ROTATION FOR HE₁₁ PROPAGATION
IN CIRCULAR HELIX CORRUGATED GRAPHITE WAVEGUIDE

Internal Guide Diameter (cm)	Attenuation (%/m)		Polarization Rotation (deg./m)	
	94 GHz	135 GHz	94 GHz ¹	135 GHz ²
1.27	1.28	0.75	21.27	7.73
2.54	0.16	0.09	1.33	0.48
3.81	0.05	0.03	0.26	0.10
5.08	0.02	0.01	0.08	0.03

¹ P=0.33λ (24 grooves/inch)

² P=0.36λ (32 grooves/inch)

important for active probing with a polarized beam and is definitely important for fusion plasma diagnostic applications.

The angular rotation of the direction of the polarization of the HE₁₁ mode far from cutoff in a helix waveguide is to a good approximation given by [6]

$$\Psi \cong \left(\frac{2.405}{ka} \right)^3 \frac{LP}{\lambda a} \text{ radians} \quad (2)$$

where *P* is the groove pitch (inverse of the number of grooves per unit length), *L* is the length of waveguide, and *λ* is the wavelength. The condition on the pitch is that there should be 2.5 or more grooves per wavelength, or *P* ≤ 0.4λ, to avoid higher order modes in the corrugations.

Equations (1) and (2) are evaluated for a number of graphite waveguide diameters at frequencies of 94 and 135 GHz in Table I. A surface resistivity of 2 Ω was used for the attenuation calculations at 135 GHz and decreased as the square root of frequency for the 94 GHz calculations. This value is an upper limit determined by experimental reflectivity measurements at 135 GHz at near normal incidence off a block of fine grained graphite at room temperature. This value is also consistent with published values of graphite electrical resistivity [7] which would give surface resistivities in the range of 1.3–2.3 Ω at 135 GHz.

The calculations show that for a short run of corrugated, overmoded graphite waveguide losses for propagating millimeter-waves should be very small. In addition, the electrical resistivity of graphite generally decreases with increasing temperature [7] so that millimeter-wave attenuation should not increase and may even decrease in a high temperature furnace environment. The polarization rotation is also shown to be small for short runs of helix graphite guide with diameters of about 2.5 cm or greater.

III. GRAPHITE WAVEGUIDE DESIGN

A helix corrugated graphite waveguide with a miter mirror at one end was constructed for use with a 135 GHz pyrometer on a graphite electrode dc arc furnace [1]. The waveguide internal diameter was 3.81 cm (1.5 in) with a screw thread of 32 grooves/in. It was machined from fine grain grade graphite such as that obtainable from the Great Lakes Carbon Co. Fig. 1 illustrates the design of this guide where the width-to-length dimensions are not to scale, and the dashed lines indicate threaded surfaces.

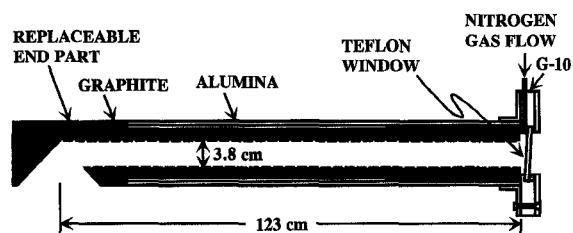


Fig. 1. 135 GHz graphite waveguide assembly with a miter end mirror.

The total internal length of this guide is 123 cm, made up of three sections: a short 19-cm length, a long 93-cm length, and a replaceable miter mirror end part which accounts for approximately 11 cm of the corrugated length. The short and long guide lengths are butted to each other and captured inside of a stepped alumina sleeve made by cementing two alumina tubes together. The miter mirror end part screws onto the outside of the long guide length which extends beyond the alumina sleeve by about 9 cm. The outside diameter of the end part is flush with the approximately 7 cm outside diameter of the alumina sleeve.

A window seal on the waveguide is required to block air inflow because the furnace is operated under a slight vacuum. A 63.5-mm diameter by 6.35-mm thick Teflon (polytetrafluoroethylene) window was used, which had a moth eye scribed surface on each of the two faces to minimize surface reflectivity [8]. Furthermore, the window was mounted at a 5° angle to the guide axis to deflect any residual reflection away from the pyrometer. It was important to eliminate window reflections so that the active probing of internal furnace surface reflectivities would not be interfered with.

Provision was made for nitrogen gas flow across the inside surface of the window. This serves two purposes. First, it helps keep the window cool. The maximum usable temperature for Teflon is 500°C, but the end of the waveguide inside the furnace reaches a temperature in excess of 1200°C. A cool gas flow across the inside window surface eliminates a convective heating path and removes radiative heat. Second, it purges oxygen and furnace off gases from the graphite guide. This is important because graphite burns at temperatures above 400°C if oxygen is present, and furnace off gases could leave unwanted surface depositions inside the guide.

Besides mechanical support, the alumina sleeve along with the Teflon window in its G-10 insulator flange electrically insulate the graphite guide from the outside of the furnace.

TABLE II
SUMMARY OF FURNACE RUNS AND MEASURED GRAPHITE WAVEGUIDE/MIRROR TRANSMISSION

Run Number	Length of Run (days)	Max. Temperature (°C)	Measured Waveguide/Mirror Transmission	
			Start of Run	End of Run
#1	11	960	0.89 ± 0.02	0.68 ± 0.04
#2	10	2200	0.88 ± 0.02	0.79 ± 0.02
#3	5	1450	0.89 ± 0.02	0.72 ± 0.02
#4	1	725	0.76 ± 0.02	0.80 ± 0.02
#5	3	1640	0.80 ± 0.02	0.77 ± 0.02

This waveguide assembly was hi-potted to 1 kV to insure that the graphite waveguide would not pose an electrical hazard to personnel or the furnace.

IV. EXPERIMENTAL RESULTS

Transmission losses through the graphite waveguide assembly were determined by making radiometer noise temperature measurements with a liquid nitrogen cooled black-body (EccosorbTM, manufactured by Emerson and Cuming). The difference in the black-body signal was measured between the input and output of the guide assembly. The radiometer frequency was centered 135.5 GHz, and the IF frequency range was 0.4–1.5 GHz double sideband. The radiometer field-of-view was launched by a corrugated horn, and the resulting Gaussian field-of-view was matched to the graphite guide input by focusing with a 90° off-axis parabolic mirror [9].

The transmission was determined to be 0.89 ± 0.02 , or approximately 0.5 dB insertion loss. The transmission increased to 0.91 ± 0.02 when the miter mirror end part was removed and to 0.93 ± 0.02 when the Teflon window was also removed. A 2% increase in transmission would be expected if a reflection off a graphite mirror surface with 2Ω surface resistance is eliminated. The approximately 7% loss of the remaining 112-cm length of corrugated guide is much higher than calculated in Table I. This could be attributed to the nonperfect nature of the corrugations that were visibly broken in a number of locations and to a possible slight misalignment between the butted short and long guide lengths. However, the measured insertion loss is quite acceptable for the intended application.

The graphite waveguide and mirror assembly was used for active millimeter-wave pyrometer measurements on the Mark II dc graphite electrode arc furnace at MIT, which is being evaluated for the treatment of hazardous wastes [10]. The waveguide assembly was inserted horizontally into the furnace through a gate valve and penetrated through approximately a 53-cm thickness of insulating refractory material to protrude about 10 cm into the furnace chamber. It was sealed with a silicon rubber gasket outside the gate valve and free to rotate so that the pyrometer field-of-view could be scanned for temperature profile measurements inside the furnace.

The waveguide assembly was used in a total of five furnace runs. The length of each run, the maximum temperature achieved in the furnace hearth, and waveguide/mirror transmission measured at the start and end of each run are summarized

in Table II. The waveguide protrudes into the furnace about 60 cm above the slag melt surface at a location where the temperature is typically 150–350°C cooler than the maximum temperature measured. The temperature at the miter mirror was sufficiently hot during some of the furnace runs to make this part of the guide incandescent, the glow of which was evident through the Teflon window. However, there was no evidence of any melting of the inside surface fine structure of the Teflon window on careful examination after furnace run #5.

After exposure to high temperatures the miter mirror surface and the outside surfaces of the graphite inside the furnace acquired a pitted powdery surface that was noticeably eroded. The interior guide corrugations, however, remained in good condition throughout all the runs except for a few corrugations located immediately at the guide aperture. The waveguide system transmission factor was measured to degrade to 0.68 at the end of the first furnace run, but at the end of subsequent runs #2–#5, it was measured to fall fairly consistently into the range of 0.76 ± 0.04 .

All the transmission degradation was determined to be due to the surface corrosion of the graphite mirror because once this mirror was repolished with fine emery cloth, as it was done for the start of runs #1–#3, the transmission factor was restored to its original value. At the end of run #3 the graphite mirror was not repolished. In the following runs #4 and #5 the transmission line losses were measured to remain about the same at the start and end of those runs. Apparently, the initial graphite mirror surface corrosion provides some protection against further surface corrosion.

The miter mirror end part was replaced only once. This occurred halfway through run #2 when the mirror end broke off inside the furnace and fell into the hearth. The waveguide broke due to significant erosion of the graphite during that run, which weakened the waveguide at the V cut. The erosion was caused by a poor air seal around the waveguide allowing oxygen to get to the hot graphite. The waveguide was removed (the gate valve was installed on this port in case of this eventuality) and repaired with a new end piece. A new silicon gasket seal was also installed. The graphite mirror and waveguide protruding into the furnace continued to erode after this repair but not as fast and no replacement through to the end of run #5 was required.

For making quantitative surface reflection measurements inside the furnace it is important to know not only the magnitude of the change in the waveguide and mirror losses due to corrosion, but also if the field-of-view divergence and

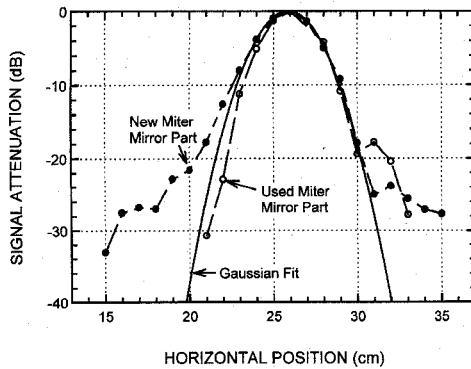


Fig. 2. Horizontal beam profile measurements at 135.5 ± 1.5 GHz, 40 cm from the graphite guide miter mirror launch aperture.

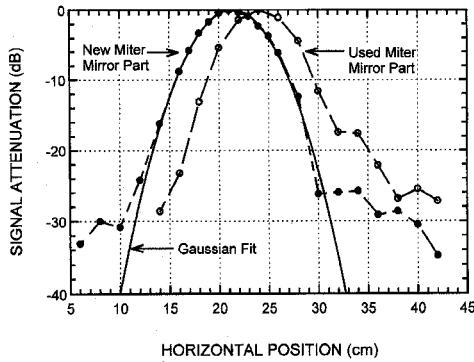


Fig. 3. Horizontal beam profile measurements at 135.5 ± 1.5 GHz, 80 cm from the graphite guide miter mirror launch aperture.

direction of view are affected. After run #5 the launched beam profile of the graphite waveguide assembly was measured with the miter mirror end part that survived through to the end of run #5, and with a new miter mirror end part. The beam profile measurements were made by coupling a rapidly frequency swept (134–137 GHz) Impatt diode beam into the graphite waveguide assembly with the same pyrometer corrugated horn and focusing mirror used for the furnace measurements and scanning the launched beam profile with the pyrometer using a truncated wr-6 waveguide as an antenna. A calibrated attenuator was used at the output of the Impatt source to always detect a constant signal level to avoid signal strength nonlinearities in the radiometer.

Horizontal profile scans were made parallel to the waveguide axis. Figs. 2 and 3 show the results of these measurements. The measurements were increasing horizontal position values correspond to moving away from the window end of the guide. The profiles in Fig. 2 were taken at a distance of 40 cm from the miter mirror aperture and those in Fig. 3 at a 80-cm distance. This corresponds to the distance and round-trip distance to the side wall and ceiling inside the furnace.

The data with the new miter mirror is well fit by Gaussian profiles that agree with the predicted beam divergence [9]. The side lobes only become significant at levels below -20 dB. The data for the corroded miter mirror end part also have beam profiles that are approximately in agreement with the new mirror data. There are some differences in the low level side lobes, but the main difference is that at a 80-cm distance

the beam has been steered in a slightly different direction. It is off between 2–3 cm over a path length of 80 cm or an angular deflection of $1.4\text{--}2.1^\circ$. This change in beam alignment would need to be taken into account in making quantitative reflection measurements. However, the profiles taken with the corroded mirror show that the spatial resolution has not changed for surface emission temperature measurements. In fact, the corroded graphite mirror functions satisfactorily at millimeter-wavelengths despite its poor visible appearance.

V. CONCLUSION

The experimental results demonstrate that efficient millimeter-wave waveguide and mirror components can be fabricated from high temperature robust graphite. Even when the graphite is heated to incandescent temperatures the millimeter-wave performance remains good. The observed high temperature surface corrosion, mainly due to the trace oxygen in the present arc furnace setup, does not degrade the millimeter-wave components sufficiently to preclude their continuous use for diagnostic measurements. The initial surface corrosion also seems to provide some protection to continued corrosion. In a vacuum environment without oxygen, such as in a fusion reactor core, surface corrosion should be significantly less. In other oxidizing environments, nonoxidizing refractory surface coatings such a zirconium oxide or silicon graphite [11] could be developed without significantly affecting the millimeter-wave performance.

There are many high-temperature applications where diagnostic access is crucial to the process. The work described here shows that millimeter-wave access is definitely possible in such environments. Millimeter-wave sensors would provide the ideal compromise between robust access and spatial resolution for many measurement needs.

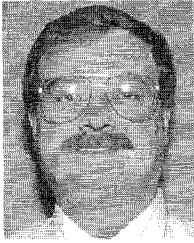
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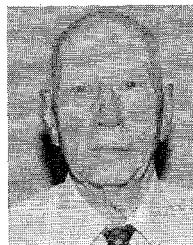
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