Title
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Publication Date
1969-05-01

Submitted to Review of Scientific Instruments as a Note

UCRL-18893
Preprint

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AEC Contract No. W-7405-eng-48

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The use of microwave interferometers to measure electron density of laboratory plasmas is a well-developed technique.[1,2] When, however, the density is low, say $\lesssim 10^{11}/cm^3$ for typical plasma diameters, the interferometer phase shift is small and a high-sensitivity detection system is required. Such systems can evolve into quite complicated and expensive pieces of equipment. In addition, for many laboratory plasmas there is also the problem of avoiding spurious phase shifts due to reflections from the vessel wall. We have constructed an interferometer system which functions satisfactorily at densities as low as $\approx 10^9/cm^3$, and which is simple and inexpensive to construct--much more so than we had originally expected.

The basic interferometer circuit is quite standard (Fig. 1). The required high sensitivity is achieved by employing phase-sensitive detection. A 100-kHz modulation is injected into the klystron reflector through its stabilized power supply (Universal Type FXR Z815B), and phase shift is measured with a lock-in amplifier (P.A.R. Type HR-8). Because of the required long integration time ($\approx$ 0.3 sec) of the lock-in amplifier, this system is inapplicable to pulsed plasma sources; but if the plasma repition frequency is sufficiently high, a boxcar integrator can be used. Our plasma is formed by resonant microwave breakdown at 10 GHz and $\lesssim$ 1 kW c.w. Phase shift is determined simply by switching on and off the high-power microwave source. Plasma and reference waveguide arms of the interferometer were made of approximately equal length, and plasma and reference microwave signals were adjusted for approximate equality at the point of entering the hybrid-T mixer. We have not found it necessary to resort to a more elaborate interferometer system. We have also used the double-pass system described by Levine et al.,[3] but found that the additional signal attenuation in this case results in a much greater random fluctuation in the lock-in amplifier reading.

The diameter of our plasma column is $\approx$ 5 cm; that of the copper vacuum vessel is $\approx$ 20 cm. In such a geometry, reflections of the microwave signal from the vessel wall can result in unwanted phase shifts. This can be rectified in either of two ways--by using microwave lenses to focus the beam (a quite expensive method), or by making the wall nonreflective at the microwave frequency. We have chosen the latter course, and put in the vacuum vessel an absorbing liner, which is extremely easily and cheaply made. It consists of a sheet of 1/16-in.-thick Teflon ($\approx \lambda/4$ at our frequency of 35 GHz), whose surfaces are roughened by sanding and are coated on one side with conducting silver paint (Dupont 4817) and on the other with resistive paint (Low-resistant paint RLL, Micro Circuits Co., New Buffalo, Mich.), nominally 377 Ω/square, though actually varying widely across the surface. The sheet has holes cut in it for the microwave horns, whose apertures are coplanar with the Teflon, is rolled into a cylinder, silver side outwards, and inserted into the vacuum vessel; our absorber extends ≈ 30 cm on either side of the horns. With absorber in place, the vacuum base pressure is as low as 5×10^{-8} mm Hg after about a week of outgassing. Although the absorber is good in vacuum, it is not necessarily good in contact with plasma; in our case this does not present a problem. A microwave absorber of this type is 100% efficient only for normal incidence; however, it does in actual application reduce reflection problems to a negligible level. On should also recall that for low-density plasmas ($n_e \ll n_c$), reflection, refraction, and absorption of the microwave beam by the plasma are very small, therefore any standing wave pattern within the vessel due to wall reflections is not greatly different with or without plasma; i.e., the condition is approached of the introduction of only a constant phase shift due to wall reflections. This fact doubtless reduces the efficiency of wall absorption required for satisfactory operation.

A remaining requirement for a system using a nonfocused microwave beam is that the effective beam width (≈ horn width) be sufficiently small compared with the plasma diameter. Our horns are 1.9 cm wide in the direction normal to the plasma axis, which for most plasma density profiles is sufficiently small for a plasma of diameter ≈ 5 cm. In any case, once the density profile is known--for example, from a scan with a Langmuir probe (for which the absolute response need not be known)--a correction can be made for this departure from "slab geometry";[5] such corrections are for our case normally small, $\lesssim 5\%$.

We have used the system described to investigate the effect of a strong magnetic field on the response of a Langmuir probe,[5] covering a density range of from $\approx 3 \times 10^9/cm^3$ ($\approx$ 0.2 deg phase shift) to $\approx 5 \times 10^{11}/cm^3$, in a magnetic field of from 1.5 to 7 kG.

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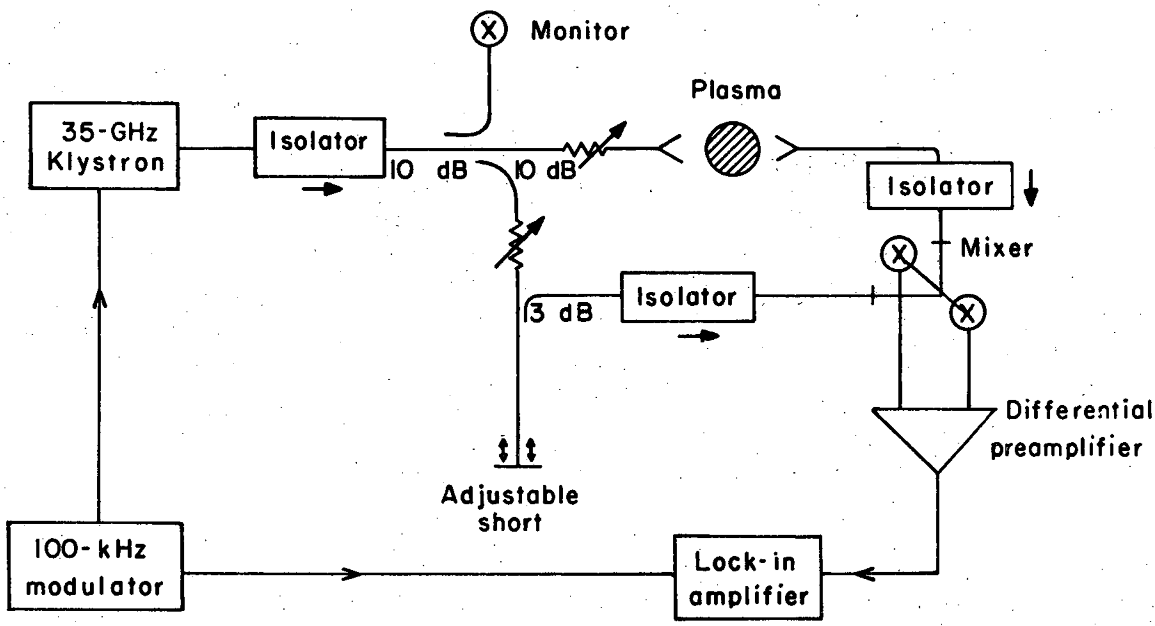
FIGURE LEGEND

Fig. 1 Schematic diagram of interferometer.



XBL695-2809

Fig. 1

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