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A STUDY OF MICROWAVE INTERFEROMETERS FOR ELECTRON DENSITY MEASUREMENTS IN REB-PLASMA EXPERIMENTS

by

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Plasma Physics Section

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ABSTRACT

In order to select a suitable microwave interferometer for electron density measurements in Relativistic Electron Beam (REB) - Plasma Experiments, a study has been carried out of four types of interferometers, viz. simple interferometer, standing-wave interferometer, frequency and phase modulated interferometers. Various direct reading interferometers which give a voltage proportional to the phase shift, are also discussed. Systems have been analysed in terms of time resolution, phase sensitivity, system stability, ease of measurement etc. Theoretical and experimental limitations of various systems have been indicated. Summary of the various system is presented in a table to aid the experimentalist to select the most appropriate system for the prevailing experimental conditions.

Finally, an attempt has been made to find out the interferometer system best suited for REB-Plasma Experiments.

CONTENTS

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I. INTRODUCTION

Electron density and electron temperature are the two basic parameters which characterize any plasma. Microwaves provide a powerful diagnostic method in the general field of plasma physics research because electron density of many interesting plasmas (e.g. in Controlled Thermonuclear Fusion Research[(1),(2)] Magnetohydrodynamics (MHD) - energy conversion experiments[(3)], shock-heated plasmas[(4)] etc.) can be determined with centimeter or millimeter waves. The microwave frequencies in the range 1-300 GHz can be used to determine the electron density in the range 10^{16} - 10^{21} m^{-3}. The choice of a particular frequency depends on the plasma parameters.

The plasma properties other than electron density that can be measured with microwave techniques are : electron temperature[(5)], collision frequency for momentum transfer, internal magnetic field and current density using coupling of characteristic electromagnetic modes[(6),(7)]. From the time variation of density together with collision frequency measurement, one can study the loss mechanisms in a decaying plasma (such as recombination, diffusion with or without magnetic field etc.) With microwave techniques, one can also study the position or motion of plasma vacuum boundary, turbulence and instabilities etc.

Microwave experiments for plasma diagnostics can be divided into three classes :

1) Microwave Free-Space Propagation Experiments

In this method, the plasma under investigation is allowed to interact with a electromagnetic radiation. By investigating the wave which passes through, reflected or scattered, one can obtain information regarding plasma parameters. Electron density and electron temperature are measured using transmitted or reflected wave from the plasma whereas instabilities and turbulence can be studied using microwave reflectometry[8] and scattering[8],[9].

2) Resonant Cavity Diagnostics[10]

In this technique, plasma to be studied must be enclosed in a cavity resonator or a waveguide which makes it impossible to apply in many cases.

3) Microwave Radiation Experiments[8],[11],[12]

Here, we study the frequency spectrum and measure the power of the microwave radiation emitted by plasma. This radiation can be used to obtain valuable information regarding electrom temperature, electron velocity distribution, instabilities etc.

In the report we will be concerned only with free-space method where we obtain information concerning electron concentration, using transmitted wave from the plasma. Plasma under study is located in one arm of a microwave interferometer, consisting of a two arm balanced bridge. The measurement of phase shift introduced by plasma, with respect to a reference signal, enables one to determine the electron density.

Microwave techniques have some basic advantage as compared to other methods (e.g. probes etc.) of diagnosing plasma. Firstly, the perturbation caused by them is negligible. It is because measurements can be carried out at field strength low enough so to have very little effect on plasma characteristics. Secondly, in free space propagation techniques, plasma can be probed by microwave field without introducing any foreign body into plasma itself.

The purpose of the present work is to find out a suitable interferometer for electron density measurement in REB-Plasma Experiments for which four type of interferometers have been studied (viz. simple interferometer, standing-wave interferometer, frequency and phase modulated interferometers). Some direct reading interferometers which provide a voltage proportional to phase shift, are also discussed.

Section II describes the REB-plasma experiments where microwave interferometer will be used for plasma density measurements. Table 1 shows the various plasma parameters in the REB-plasma experiments being done at BARC. The principle of plasma density measurement has been discussed in Section III. At plasma densities, close to critical electron density, plasma column acts as a divergent lens, thereby, reducing microwave power collected by receiving antenna. This point has also been discussed in Section III.

Section IV discusses the various types of interferometer. Basic circuit of each interferometer has been considered and its output signal for phase-shift determination has been found out. The merits and demerits of each system have been outlined. They have been rated as far as their use in REB-plasma experiments is concerned. The summary of various interferometers is presented in Table 2. Lastly, the interferometer system for electron density measurement is suggested.

II. DESCRIPTION OF REB-PLASMA EXPERIMENTS

The plasma heating by relativistic electron beams (REB) plays an important role in controlled thermonuclear fusion research[13-15]. The microwave interferometer to be designed will be used for electron density measurements in REB-plasma interaction experiments where pulsed electron beams with electron energy 200-500 keV, current 20-100 kA and pulse duration 20-100 ns are used for heating of a preformed plasma. This preformed plasma will be confined in a magnetic mirror with a ratio 1.5 to 2 with a steady field of 5-10 kG.

The schematic view of the experimental set-up is shown in Fig. 1. There are mainly two types of experiments which are being done at Bhabha Atomic Research Centre (BARC).

1) Electron Beam Transport Studies[16]

In experiments for electron beam transport studies, REB is propagated in various gases at different pressures. Various transport properties like beam focussing, scattering etc. are studied with or without magnetic field present. The electron beam creates a plasma as it propagates through the drift column in a fraction of nanoseconds which helps in beam propagation in rest of the beam pulse.

2) Plasma Heating Studies[17]

In REB-plasma heating experiments REB is injected in a preformed long duration plasma confined in a mirror magnetic field, and associated heating is studied. The electron density of the plasma changes after beam injection, if it is not fully ionized. Various plasma parameters of REB-plasma experiments are shown in Table 1.

Table 1

S.No.	Name of Experiment	Electron Beam Transport Studies	Plasma Heating Studies
	Plasma Parameter		
1.	Length of plasma column	100 cm	100 cm
2.	Diameter of plasma Cross-section	10 cm	10 cm
3.	Plasma Density	10^{11}-10^{13} cm^{-3}	10^{11}-10^{13} cm^{-3}
4.	Electron Plasma Frequency	2.84-28.4 GHz	2.84-28.4 GHz
5.	Gas pressure	10^{-3}-100 Torr	10^{-2}-10^{-4} Torr
6.	Total plasma duration	100 ns - 1 μs	100 μs - 1 ms
7.	Electron Collision frequency for momentum transfer (Ar, Te = 10 eV)	10^{7}-10^{11} sec^{-1}	10^{6}-10^{8} sec^{-1}
8.	Magnetic field	0.10 K Gauss	0-10 K Gauss
9.	Mirror Ratio	1.5	1.5
10.	Electron Cyclotron Frequency	0-28.0 GHz	0-28.0 GHz

III. PRINCIPLE OF ELECTRON DENSITY MEASUREMENT

The dispersion relation[3] for an ordinary wave propagating through a plasma is given by,

$$\bar{K} = \bar{\mu}^2 = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{1}{1 - j\,\nu/\omega} \qquad (1)$$

where $\bar{K}$ = complex dielectric constant

$\bar{\mu}$ = complex refractive index

ω_p = $\left(\frac{ne^2}{m_e \epsilon_0}\right)^{1/2}$ is the electron plasma frequency

ω = probing wave frequency

ν = collision frequency for momentum transfer

n_e = electron density of the plasma

m_e = mass of electron

ϵ_0 = permitivity of the free space

For a high temperature, highly ionized plasma for which $\nu^2 << \omega_p^2$ dissipative attenuation is very small and equation (1) reduces to,

$$\mu^2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n}{n_c} \qquad (2)$$

where n_c is the cut-off density corresponding to probing frequency ω and is given by,

$$n_c = \frac{m_e \epsilon_0 \omega^2}{e^2} \qquad (3)$$

Now, the phase constants for vacuum and plasma are, respectively,

$$\beta_o = \frac{2\pi}{\lambda} \tag{4}$$

and

$$\beta_p = \mu \frac{2\pi}{\lambda} \tag{5}$$

where λ is the wavelength of the probing wave. When plasma density varies slowly near the boundaries, reflection and interference effects are negligible and it is possible to treat plasma as a slab. It is called adiabatic approximation.

Now, in adiabatic approximation, the phase advancement introduced by plasma in the transmission path of length L is given by,

$$\begin{aligned} \Delta\phi &= -\int_0^L \left(\beta_p - \beta_o\right) dx \\ &= \int_0^L \left\{1 - \mu(x)\right\} \frac{2\pi}{\lambda}\, dx \end{aligned} \tag{6}$$

From equation (2), we get

$$\Delta\phi = \int_0^L \left\{1 - \left(1 - \frac{n(x)}{n_c}\right)^{1/2}\right\} \frac{2\pi}{\lambda}\, dx \tag{7}$$

where integration is carried out along a chord of plasma cross section i.e. along the direct path from the transmitting to receiving antenna. When $n << n_c$, we can neglect the terms other than first order in the binomial expansion of $\left\{1 - n(x)/n_c\right\}^{1/2}$ and we get,

$$\Delta \phi = \frac{\pi}{\lambda n_c} \quad n(x)\ dn \qquad (8)$$

or

$$\Delta \phi = \frac{\pi \bar{n} L}{\lambda\ n_c} \qquad (9)$$

where average density $\bar{n}$, along the chord of plasma cross-section of length L, is given by,

$$\bar{n} = \frac{\int_0^L n(x)\ dx}{L} \qquad (10)$$

substituting the value of m_e, e, ϵ_0 in equation (9), we get,

$$\bar{n}\ [m^{-3}] = 1.18 \times 10^{8}\ \frac{f\ [Hz]\ \ \Delta \phi\ [rad]}{L\ [m]} \qquad (11)$$

Thus, for $n << n_c$, the phase shift introduced by plasma in the transmission path of the plasma, is linearly proportional to the average electron density along the path. Therefore, by measuring plasma thickness and phase shift, plasma density can be easily determined.

The maximum density that can be measured with a probing wave frequency is limited by dissipative and refractive effects. When $n << n_c$ is not valid, the equation (8) is not correct and non linear effects become significant. Also when $n << n_c$, for which plasma is transparent, the refractive index is less than unity and plasma column acts as a divergent cylindrical lens (See Fig. 2). This reduces the microwave power collected by the receiving horn. Moreover, the measured phase shift will be that along the refracted path which may be quite different from the line of sight path depending on the value of n/n_c. The refractive effects play an important role[8],[18], in the choice of frequency for plasma density measurement. The probing wave frequency should not be very high, otherwise μ has a value very close to one and phase shift $\Delta\phi$ introduced by plasma is too small to be measured with sufficient accuracy. On the other hand frequency should not be very low, approaching the cut-off frequency, one has $\mu \simeq 0$ and the approximation $n << n_c$ does not hold good. In this case wave is refracted or reflected and its path through the plasma will no longer follow a chord.

Thus, choice of frequency depends upon the maximum density to be measured and the plasma diameter. Fig. 3 shows a plot of phase shift versus electron density for various probing frequencies. Conservative upper operational limit has been indicated by a dotted line.

IV. MICROWAVE INTERFEROMETERS

A large variety of interferometers(3),(11),(19-21) have been used for plasma density measurements. Various interferometers with direct phase measurement can be divided(21) into two classes:

Class A : This includes those interferometers in which phase is measured at carrier frequency (Carrier Frequency or Unmodulated Interferometers)

Class B : This includes those interferometers in which phase is measured at an intermediate frequency (Modulated Interferometers)

A. Carrier Frequency Interferometers

Carrier frequency or unmodulated interferometers are the fastest interferometers with highest time resolution. Here we will discuss two basic types of the unmodulated interferometers viz. Elementary Interferometer and Standing-Wave Interferometer. Various arrangements have been used depending on the experimental plasma parameters. Various modified improved versions of the unmodulated interferometers have been discussed in Section AIII.

AI. Elementary Interferometer

This simple, unmodulated interferometer(11),(22) was in use in the early days of Plasma Physics research. This interferometer (Fig. 4), basically, consists of two isolated arms, fed from a common microwave source. Signals from reference and measuring arm (which contains the plasma whose electron density is to be measured) are combined and applied to a crystal detector.

Let us represent the signal from the reference path and incident on the power combiner by

$$e_1 = E_1 \ \mathrm{Cos}(wt + \phi_1) \qquad (12)$$

and signal from the plasma path by,

$$e_2 = E_2 \ \mathrm{Cos}\ (wt + \phi_2 + \Delta\phi_p(t)) \qquad (13)$$

where w is the probing wave angular frequency, ϕ_1, and ϕ_2 the relative time phases of the signals e_1 and e_2 respectively, and $\Delta\phi_p(t)$ is the time dependent phase shift introduced by plasma.

Now the video output e of a square law detector will be given by,

$$e = k\left[E_1^2 + E_2 + 2E_1 E_2 \ \mathrm{Cos}\left(\phi_2 - \phi_1 + \Delta\ \phi_p(t)\right)\right] \qquad (14)$$

where k is a constant.

Initially, when there is no plasma (i.e. $\Delta\phi_p(t) = 0$) output can be made minimum by setting $(\phi_1 - \phi_2) = \pi$. An initially nulled interferometer will produce several maxima and minima continuously as plasma path is filled with a transient plasma causing phase angle to rotate successively through π to 2π. The typical response of this type of interferometer to a transient plasma event is shown in Fig. 5. The number of maxima and minima or fringes are related to the average plasma density along the plasma path by equation (11).

Apart from simplicity, following are the main advantages of this interferometer system :

1) It is the fastest interferometer with highest time resolution. The maximum time resolution depends only on the mixer diodes and the bandwidth of the following DC amplifier.

2) Since the reference path and plasma path can be made equal in this interferometer, it is insensitive to microwave source frequency fluctuation and generator noise. Therefore, transit-time microwave tubes with higher output power can be used as microwave source.

3) Length of the waveguide, used is small as compared to popular Zebra-stripe interferometer. Therefore loss of microwave power, which is high at higher frequencies, is also small. Hence it requires lesser power microwave source.

This interferometer system suffers from following drawbacks :

1) Unless plasma density approaches cut-off, it is impossible to find the direction of density change (i.e. whether electron density is increasing or decreasing)

ii) From equation (14), it is clear that when E_1 and E_2 differ too much, the minima become shallow and it becomes difficult to differentiate between maxima and minima.

iii) Display is not direct i.e. phase is not displayed directly on the oscilloscope. Moreover, continuous time evolution of density is not obtained by this interferometer.

iv) In case of multichannel interferometer, where we pass microwaves along different chords of the plasma column simultaneously, the problem of cross-talk among the channel is more severe. Therefore, unmodulated system requires good directional characteristics of mechanical structure of the antennas to minimize the problem of cross-talk.

However, the second disadvantage of this interferometer can be removed by combining the signals in a balanced mixer. The output from differential DC amplifier following the balanced mixer is given by,

$$e = k\, E_1\, E_2\, \text{Cos}\, (\phi_2 - \phi_1 + \Delta\phi_p\, (t)) \qquad (15)$$

where k is a constant.

In equation (14), the two nonlinear terms E_1^2 and E_2^2 have been cancelled. Thus null in e can be obtained independent of the relative amplitudes of E_1 and E_2.

AII. Standing-Wave Interferometers

In this type of interferometer, the reference and plasma signal are propagated through a waveguide in opposite direction. An interference or standing-wave pattern is created in the waveguide which can be sampled by a standing-wave detector probe.

Let us represent the reference travelling-wave by

$$e_1 = E_1 \text{ Cos } (\omega t - \beta x) \tag{16}$$

and the wave travelling through plasma by,

$$e_2 = E_2 \text{ Cos } (\omega t + \beta x + \Delta\phi_p(t)) \tag{17}$$

where x is the position of the probe from some arbitrary fixed plane.

The video output e from the square law detector probe will be given by,

$$e = E_1^2 + E_2^2 + 2E_1 E_2 \text{ Cos } (2\beta x + \quad (t)) \tag{18}$$

Initially, when there is no plasma, the interferometer can be nulled by adjusting x or with a phase shifter. An interferometer that is initially nulled will produce maxima and minima or fringes as the plasma path is filled with a transient plasma causing phase angle to rotate continuously from π to 2π. This interferometer has not been used for plasma diagnostics, probably because of no extra advantage over the simple interferometer.

However, if we use standing wave detectors to sample interference pattern at two different points in the waveguide, the utility of the resulting Double Probe Standing-Wave Interferometer(23),(24) (Fig. 6) is greatly increased. With this arrangement, one can determine the direction of density change also.

Equation (18) represents the output of a standing wave detector. Probes give oscillatory output as plasma density changes causing a phase change $\Delta\phi_p(t)$.

Differentiating equation (18) with respect to x and t, respectively, we get,

$$\frac{de}{dx} = 4\beta E_1 E_2 \, \text{Sin}\,(2\beta x + \Delta\phi_p(t)) \tag{19}$$

and

$$\frac{de}{dx} = 2E_1 E_2 \, \text{Sin}\,(2\beta(x) + \Delta\phi_p(t)) \frac{d}{dt}(\Delta\phi_p(t)) \tag{20}$$

Dividing equation (20) by (19), we get,

$$\frac{dx}{dt} = \frac{1}{2\beta}\frac{d}{dt}(\Delta\phi_p(t)) \tag{21}$$

This represents the velocity with which the field pattern moves along the wave guide. Let the two standing-wave detectors 1 and 2 be located at distances x and x + dx respectively. The two probes give the identical outputs except with the difference that they reach their maxima and minima at different times. Now when the plasma density increases, the phase shift $\Delta\phi_p$ (t) increases giving positive dx/dt. Therefore, standing wave pattern moves in a positive direction when plasma density increases. Then maximum of the signal from probe 1 will lead the signal from probe 2 (Fig. 7a). On the other hand; when plasma density decreases, the standing wave pattern will move in the negative x-direction and maximum of the signal from probe 2 will lead that from probe 1 (Fig. 7b). Thus direction of movement of standing wave pattern enables us to determine the direction of density change.

AIII. Direct Reading Interferometers

Depending on the requirements, several modified versions of the elementary interferometer and standing-wave interferometers have been used. Garcin[25] has used frequency detector with integrator for obtaining a signal proportional to the phase shift introduced by plasma. Osborne[26] displayed the phase and amplitude information simultaneously by means of a four probe standing-wave interferometers. Time marking can be obtained by applying pulses to Z-axis of the oscilloscope for intensity modulation. Kaiser et al[27] developed an alternate method which employs a three legged bridge network to polar display.

The main disadvantage of the polar display is that it becomes ambiguous when large phase shifts (multiradians) are encountered.

The simple standing-wave interferometer can be improved by adding a counting logic circuit to it as described below. It generates an output voltage proportional to the number of fringes and also indicates the direction of density changes.

Standing Wave Interferometer with Counting Logic[28]

This interferometer provides an oscilloscope display of temporal evolution of plasma density in the form of a histogram. The output voltage from the interferometer is also convenient in processing an electron density evolution with digital computer where various correction (like non-linear relation between phase shift and electron density) can be applied for accurate measurement.

The schematic of this interferometer is shown in Fig. 8. The standing wave pattern developed by two travelling waves (Reference and probing) propagating in opposite directions is sampled by three detector probes which are located so that the phase shift between them is less than $\pi/3$. The standing wave pattern in the wave guide shifts with the changes in plasma density and the direction of pattern shift depends upon the direction of density change. The outputs of these probes are fed to a counting logic circuit. All the three probes give identical signal which are shifted in time (Fig.9). Signal from the first probe is used for counting whereas the rest two are used to control the counting process. The counted pulses results in voltage increase or decrease depending upon the direction of phase changes. This voltage signal when displayed on an oscilloscope gives an histogram of the electron density (Fig.9). The main drawback of this interferometer is that minimum phase shift that can be measured is 2π. Therefore it is suitable only for plasmas creating large phase shifts.

Nagashima et al[29] have developed a 2 mm digital interferometer without source frequency modulation. Because no complicated decoding process for source modulation is needed, the data processing by a computer is easily performed.

8. <u>Modulated Interferometers</u>

Modulated microwave interferometers provide output signal with controlled repetitive modulation. In these systems, unknown phase shift introduced by plasma, is transferred to signal of intermediate frequency which enables the use of narrow bandwidth amplifier with their desirable noise characteristics following the microwave detector. High sensitivity and stability are the two main advantages of the modulated interferometers.

Because of high sensitivity, modulated interferometers require lesser power microwave source which is preferable in order to avoid any influence of the microwaves on the plasma. Moreover, the adjustment of zero phase is essentially very simple and any changes of the zero phase in the course of a long series of measurement could easily be corrected.

The modulation frequency is decided by the information bandwidth and noise consideration. The main disadvantage of the modulated systems is that their time response is limited. O. Brien[30] has clearly demonstrated the difference between a simple phase-sensitive receiver at carrier frequency and receiver at modulated frequency.

BI. Frequency Modulated Interferometers

Among various modulation techniques, homodyne frequency conversion techniques are preferred because they require only one microwave oscillator. In comparison with superheterodyne method of phase conversion, homodyne interferometers do not require accurate stabilization of the frequency difference of the two microwave signals since the system is a phase coherent system. In this an automatic frequency control becomes unnecessary.

a) Serrodyne Interferometer with Delay Lines

Serrodyne interferometer is a homodyne frequency modulated interferometer in which source frequency is modulated with a saw-tooth generator. It has been widely used(8),(11),(18),(31) in plasma physics research along with Zebra-stripe type of display. Schematic of a serrodyne interferometer with delay lines is shown in Fig. 10. Sawtooth modulated output of the microwave source is propagated along two channel : reference channel and measuring channel. The reference channel is generally very short and passes the signal without any delay whereas the measuring channel which contains plasma alongwith a long length of waveguide delays the signal for the time required for homodyne frequency conversion. The reference channel can also be made long but in order to avoid strong noise from the plasma device and to keep measuring apparatus away from the plasma device, measuring channel is always made longer.

The signals from the two channels are combined and fed to the input of a mixer. At the output of the mixer, we get a spectrum of oscillations consisting of harmonics of the modulating frequency. A single frequency is selected with the help of I.F. amplifier. In case of short return time of the modulating sawtooth and short delay times in the measuring channel, the oscillation spectrum resulting from the frequency modulation consists mainly of a single harmonic at the output of the mixer. Therefore, amplifier need not be highly selective. By choosing correctly the frequency deviation, modulating voltage and length of delay lines the phase is transferred to a particular harmonic of the modulating frequency. Let the two microwave signals reaching at the input of the mixer from reference and measuring channel be represented by,

$$e_1 = E_1 \text{ Cos } \omega t \tag{22}$$

$$e_2 = E_2 \text{ Cos } (\omega t + \phi(t) + \phi_p(t)) \tag{23}$$

where $\phi_p(t)$ is the phase shift introduced by plasma and $\phi(t)$ is the phase difference between the signals from the two channels.

The phase difference between the two signals from the reference and measuring channel is given by,

$$\phi(t) = \frac{2\pi \ell}{\lambda_g} \tag{24}$$

where ℓ is the path difference between the two channels and λ_g is the guide wavelength.

Let the frequency of the output signal from microwave oscillator be modulated according to following sawtooth law,

$$f(t) = f_0 + \frac{\Delta f}{T_m} t \quad ; \; t \text{ modulo } T_m \qquad (25)$$

where f_0 is carrier frequency, Δf the maximal frequency deviation and T_m is the modulation period.

Now the guide wavelength is given by,

$$\frac{1}{\lambda^2_g} = \frac{1}{\lambda^2} - \frac{1}{\lambda^2_c} \qquad (26)$$

where λ is the wavelength in vacuum and λc is the cut-off wavelength in the waveguide. Since, in our case frequency of wave is time dependent, the guide wave length will also be time dependent. Hence

$$\frac{1}{\lambda_g^2 (t)} = \frac{1}{\lambda^2(t)} - \frac{1}{\lambda c^2}$$

$$= \frac{f^2(t)}{c^2} - \frac{1}{\lambda c^2}$$

$$= \frac{1}{c^2}\left(f_0 + \frac{\Delta f}{T_m} t\right)^2 - \frac{1}{\lambda c^2}$$

$$= \frac{1}{\lambda_0^2}\left(1 + \frac{\Delta f}{f_0}\,\frac{t}{T_m}\right)^2 - \frac{1}{\lambda_c^2}$$

or

$$\frac{1}{\lambda_g^2 (t)} = \frac{1}{\lambda_0^2}\left(1 + \frac{2\,\Delta f}{f_0}\,\frac{t}{T_m}\right) - \frac{1}{\lambda_c^2} \qquad (27)$$

when $\Delta f << f_0$

But

$$\frac{1}{\lambda_{go}^2} = \frac{1}{\lambda_o^2} - \frac{1}{\lambda_c^2} \tag{28}$$

where λ_{go} is the guidewavelength corresponding to wavelength λ_o.

Therefore, subtracting (27) from (28) we get

$$\frac{1}{\lambda_g^2(t)} - \frac{1}{\lambda_{go}^2} = \frac{1}{\lambda_o^2} \frac{2\,\Delta f}{f_o} \frac{t}{T_m} \tag{29}$$

or

$$\frac{1}{\lambda_g^2(t)} = \frac{1}{\lambda_{go}^2} \left(1 + \frac{2\,\Delta f}{f_o} \frac{\lambda_{go}^2}{\lambda_o^2} \frac{t}{T_m}\right) \tag{30}$$

or

$$\frac{1}{\lambda_g(t)} = \frac{1}{\lambda_{go}} \left(1 + \frac{2\,\Delta f}{f_o} \frac{\lambda_{go}^2}{\lambda_o^2} \frac{t}{T_m}\right)^{1/2}$$

or

$$\frac{1}{\lambda_g(t)} = \frac{1}{\lambda_{go}} \left(1 + \frac{f}{f_o} \frac{\lambda_{go}^2}{X_o^2} \frac{t}{T_m}\right) \tag{31}$$

when $\Delta f << f_o$

Therefore phase shift $\phi(t)$, from equation (29) and (31) is given by

$$\phi(t) = \frac{2\pi\ell}{\lambda_g(t)} = \frac{2\pi\ell}{\lambda_{go}} + 2\pi\ell \frac{\Delta f}{f_o} \frac{\lambda_{go}}{\lambda_o^2} \frac{t}{T_m}$$

$$= \frac{2\pi\ell}{\lambda_{go}} + \frac{\ell\,\Delta f\,\lambda_{go}}{c\lambda_o}\, 2\pi \frac{t}{T_m} \tag{32}$$

or

$$\phi(t) = \frac{2\pi l}{\lambda go} + r\omega m\ t \qquad (33)$$

where

$$r = \frac{l\ \Delta f\ \lambda go}{c\lambda o} \qquad (34)$$

and ωm is the angular modulation frequency.

From equation (22), (23) and (33) we find, low frequency signal from the output of the mixer will be

$$e \propto e_1\ e_2\ \text{Cos}\ (\phi(t) + \phi_p(t)) \qquad (35)$$

or

$$e = k\ e_1\ e_2\ \text{Cos}\ (n\omega mt + \frac{2\pi l}{\lambda go} + \phi_p(t)) \qquad (36)$$

Thus the phase information $\phi_p(t)$ has been transferred at a frequency $n\omega m$.

Hillil[32] and Andreyev[33] have presented a thorough mathematical analysis of the serrodyne microwave interferometer with delay lines after taking finite retrace time of sawtooth into account. Andreyev has determined the dependence of phase distortions in the frequency conversion process on the maximum phase deviation at the input of the mixer, length of the retrace and the nonlinearity of the forward phase modulation. He has also determined the maximum speed of serrodyne phasemeters using delay lines. The maximum modulation frequency is determined by the condition $Tm > 5\,\tau$ where $\tau = l/v_g$ is the delay time in the long line, v_g is the group velocity in the delay line. Therefore, maximum speed possible in this type of interferometer amounts to about $0.1/\tau$. Moreover, the intermediate frequency for detection must be corresponding to approximately fourth or fifth harmonic.

In addition, when retrace of modulating voltage is not negligible and delay time in the long length of waveguide is commensurate with the modulation period, the maximal phase deviation θ (which is given by $\theta = \tau \Delta f \times 2\pi(1 - \tau/T_m)$) must be $2\pi n(1 + \beta)$ when working at one of the first two or three harmonics and $2\pi(1 - \beta)$ when working at higher harmonics where β is the ratio of the duration of retrace of the phase modulation to its period and is given by

$$\beta = \frac{T_2}{T_m} + \frac{\tau}{T_m}\left(1 - \frac{2T_2}{T_m}\right) \qquad (37)$$

T_2 is retrace time of the sawtooth.

Also nonlinearity of the sawtooth should be minimum and for practical purposes should not exceed 20-30%.

From the analysis of Hillil it is clear that it is best to use the first harmonic of modulation frequency since the requirements of the modulating sawtooth are less strict. Also, even when using the first harmonic, value of β should be less or equal to 0.2, in order to have a low conversion loss. This, in addition, allows a simple design of the selective amplifier. If these conditions are satisfied, then phase shift of the first harmonic is a linear function of actual (unknown) phase shift and amplitude of the signal is constant with phase shift.

b) Fringe-shift or Zebra Stripe Interferometer

It is a serrodyne interferometer using delay lines in which display is in the form of fringes called Zebra Stripes . The shift of these fringes is related to the phase shift introduced by plasma. The display is convenient in visualizing the electron densities of time-varying plasma.

From equation (36), it is clear that when there is no plasma in the measuring channel (i.e. $\phi_p(t) = 0$), the above interferometer develops several maxima and minima as source frequency is swept back and fourth. The fringe signal which is sinusoidal is preamplified, filtered and fed to a zerocrossing detector which generates squarewave pulses of constant amplitude independent of the fringe input signal except when the fringe signal is imbeded in noise. These pulses are applied to the intensity modulation electrode of the oscilloscope and modulating sawtooth is applied to Y-axis. Corresponding to the intermediate frequency rwm, there appear r-spots on the sawtooth voltage on the oscilloscope. When horizontal sweep is much slow compared to sawtooth period, then spots from r fringes or stripes on the screen. The number of these stripes (in steady state) depends on the total frequency deviation Δf and the length ℓ of the waveguide (delay-line). Increase in ℓ is limited by the large attenuation in the waveguide along with long propagation time whereas increase in Δf is limited by increase amplitude modulation accompanying frequency modulation. Moreover, the number of fringes w, should be determined by considering the error introduced due to phase distortion[33].

When measuring channel is filled with a transient plasma, the fringes shift vertically, each fringe shift corresponding to a phase shift of 2π. A measurement of this shift gives the phase shift introduced by plasma in the microwave signal. The block diagram and signal pattern are shown in Fig. 11 and Fig. 12 respectively.

Following are the advantages and disadvantages of Zebra Stripe microwave interferometer of this type.

Advantages

1. Since fringes on the oscilloscope shift vertically up or down according to direction of density changes. Therefore, in Zebra-Stripe presentation, direction of density changes are indicated unambiguously in contrast to the direct fringe presentation of simple interferometer.

2. It provides a very clear display of the phase variation of the microwave signal in the plasma and is convenient in visualizing the density evolution of time-varying plasma.

3. Display is insensitive to microwave signal amplitude fluctuations either due to source or due to plasma permitting a separation of reactive density effect from lossy scattering and absorption effects.

4. In case of multichannel interferometer, different

intermediate frequencies can be chosen for each channel by using different lengths of delay line. With the help of selective filters it is possible to avoid the stray signal coming from the other channel.

Disadvantages

1. Transient response is poor. When plasma density changes rapidly, the fringes tend to blur and it is very difficult to find the exact number of fringe shift.

2. It uses a long length of waveguide in the measuring channel causing large attenuation, therefore wasting more microwave source power.

3. Measurement of small phase shift is not possible.

Other difficulties with this type of interferometer are :

i) Adjustment of the reflector voltage for the Klystron signal source is critical in order to produce desired fringe pattern on the oscilloscope.

ii) False fringes are produced due to impedance mismatch in the long waveguide in the measuring channel which on distort or even override the true interferometer fringes.

iii) Due to the dispersive nature of the waveguide network system is highly sensitive to frequency instability of the signal source which manifests itself by changes in the display pattern. Therefore frequency adjustment is necessary.

In frequency modulated interferometer employing delay line, unintentional phase shifts due to incidental frequency variation of the source can be eliminated by comparing the measuring interference signal with an interference signal from an auxiliary circuit subjected only to unintentional phase shifts[(18),(34)].

8II. Phase Modulated Interferometers

It is an alternate scheme of frequency translation in which microwave signal source is operated at a fixed frequency and transmitted signal in one arm of the bridge is phase modulated. A phase modulated carrier signal produces equivalent frequency modulation where change of frequency is proportional to the time rate of phase variation.

Phase Modulated Zebra Stripe Interferometer[(35),(36)]

Frequency translation can also be achieved by linear phase variation. Let the linear phase variation be given by :

$$\phi(t) = \phi_{max} \frac{t}{T_m} \quad ; \ t \text{ modulo } T_m \qquad (38)$$

where ϕ_{max} is the maximum phase variation and T_m is the period of linear phase change.

Let the two signals viz. from the reference and measuring channel, incident on the crystal detector be represented by equations (22) and (23) respectively.

The low frequency signal output e of the detector will be

$$e \;\alpha\; E_1 E_2 \;\mathrm{Cos}\; (\phi(t) + \Delta\phi_p(t)) \tag{39}$$

The instantaneous frequency is the time derivative of the phase term of equation (40) and is given by

$$f(t) = \frac{1}{2\pi} \frac{d}{dt} \left[\phi\,(t) + \phi_p\,(t)\right]$$

or

$$f(t) = \frac{1}{2\pi} \frac{\phi_{max}}{T_m} + \frac{1}{2\pi} \frac{d}{dt} \phi_p(t) \tag{40}$$

From equation (30), it is clear that a linear phase change of ϕ_{max} in time T_m produces a frequency change of ϕ_{max}/T_m. Thus, in effect, a continuous linear variation of phase of an rf signal will produce single side band with suppressed carried (SSBSC) modulation(37) of that signal.

Thus output signal consists of a sinusoidal fringe pattern whose frequency depends upon the constant frequency of phase modulation and change of phase due to plasma density changes. In serrodyne interferometers, the simplest procedure would be to display the output from the mixer directly on the oscilloscope. Then envelope of the modulated output will give the amplitude of the transmitted signal through plasma. The phase shift introduced by plasma can be determined by subtracting the phase term due to beat frequency from the displayed phase.

The schematic of phase modulated Zebra-stripe Interferometer is as shown in Fig. 13. It is same as frequency modulated interferometer except instead of a delay line, a phase modulator is used in measuring channel and there is source frequency modulation. The amplified and clipped output from the mixer is used for intensity modulation of the oscilloscope. A linear sawtooth waveform from the modulator driver is applied to y axis of the oscilloscope. Fringes in the form of Zebra stripes appear on the oscilloscope which shift when plasma density changes.

Following are the advantages of this interferometer over corresponding Frequency Modulated Zebra Stripe Interferometer.

1. It avoids the long delay line in one arm of the bridge and thereby reducing the transmission losses.

2. It eliminates the formation of false fringes which could be developed by impedence mismatch reflections in the frequency modulated interferometer.

3. Klystron reflector voltage tuning does not effect the fringe linearity developed by phase modulator.

Since it avoids the long delay line the differential phase changes due to source frequency drift can be minimized by making the two arms of the bridge equal.

Disadvantages

1. High conversion loss ($\sim$ 30-35 dB) at multimeter wavelength in the single side band generation process.

2. The finite switching time of the phase modulator limits the time resolution of the transient phases observed.

BIII. Direct Reading Interferometers

A microwave interferometer that would produce an output voltage that is directly proportional to the phase change would be ideal from the standpoint of data interpretation. The various requirements of such a direct reading interferometer are :

i) to respond to a multiradian phase shifts without ambiguity

ii) be capable of handling a wide range of rates of phase change

iii) be unaffected by plasma noise and signal amplitude variations. Various interferometers have been made to fulfil the above requirements.

Discriminator-Integrator Detection System

Ernst[38] has made an interferometer in the 70 GHz band which makes use of the fact that a phasemodulated carrier signal will produce equivalent frequency modulation where the change of frequency is proportional to the time rate of change of the phase variation. In this interferometer a microwave carrier frequency f_c, is shifted in a single band generator to a frequency $f_c + f_m$. The upper sideband is transmitted through the phase modulating medium (plasma) and then mixed with the original unmodulated carrier. The difference frequency f_m contains the phase modulation information and after preamplification, the signal is put through a wideband limiter discriminator of center frequency f_m. The discriminator output voltage will be directly proportional to the rate of phase change. In order to get the output voltage proportional to phase variation only, the discriminator output is followed by an integrating network. Calibration is done by imposing a known amount of phase modulation on the sideband modulating signal f_m and observing the system output signal.

The main problem with the detection metho is the need for a very wide band integrator. Another problem is the lack of dynamic range since the single side band generation process at multimeter wavelength has a conversion loss in the order of 30-35 dB.

Digital Phase Comparator System

Commercially available phase meter which provide a linear analog output voltage proportional to phase change have two main drawbacks : (1) their inability to measure a phase shift of more than 2π, (2) and their slow response time. Several methods[39-42], have been devised to overcome the above problems. All these methods are based on (a) conversion of the transmitted microwave signal to a convenient intermediate frequency (i.f.) in a phase preserving manner and (b) phase measurement at the i.f. by digital techniques in a manner that follows and displays phase shifts greatly exceeding 2π. Several methods[41] have been used for accomplishing each of above functions. But the most widely used is the one which employs a sawtooth modulation of the microwave frequency as is done with a *Zebra-stripe* interferometer.

Unlike operation in Zebra-stripe mode, and amplitude of the saw-tooth is adjusted such that exactly one fringe is obtained in the sawtooth period at the output of the crystal detector i.e. the total microwave frequency shift between the signal and reference arm during, one period of the sawtooth should be 360°.

The phase change introduced by plasma corresponds to an instanta-neous change in the frequency of the fringe signal. This leads to time shifts of the zero crossing of the fringe signal with respect to the reference signal and is detected by means of a digital counter circuit. These circuits provide an output voltage proportional to phase shift (and consequently plasma density.)

<u>Two Level Frequency Modulation</u>

Matsuura et al[43] have reported an improved method of the two level modulation to a 70 GHz Klystron and shown its usefulness to data processing. In this interferometer, microwave source is modulated with a square wave so as to have a frequency shift around the centre frequency. The modulated signal is propagated in two channels viz. reference channel and measurement channel which contains the plasma alongwith a delayline (to create a desired phase difference of π/2) The principle is based on the digitization of fringe shifts utilizing the phase detection of microwave signals which are identical except a phase difference of $\pi/2$. This interferometer provides an output voltage proportional to the number of fringe shifts in the form of a histogram. The resolution of the interferometer is quarter of fringe shift.

V. DISCUSSION AND CONCLUSIONS

A microwave interferometer for obtaining time varying density data should have following main characteristics :

a) Wide dynamic range
b) Fast transient response
c) Easily interpretable data
d) Insensitivity to amplitude variation in the transmitted signal from scattering and absorption as plasma approaches critical density and
e) Insensitivity to frequency drift of the microwave devices.

The time resolution that can be attained in modulated interferometers is limited by the modulation frequency of the microwave source. However, this modulation frequency can not be increased indefinitely since certain requirements[32] have to be imposed on the shape of the modulating pulse. To obtain a continuous interference signal, the modulation voltage has to be discontinuous. In case of serrodyne frequency modulated interferometers, the flyback time of the sawtooth modulating pulse has to be negligible compared to cycle. In addition the modulation voltage has to have high amplitude linearity. Both of these requirements viz. the switching action for the part of discontinuity and the constant linearity of amplitude, create problems in practice if excessive modulation frequencies with resulting high time resolution are aimed at. Moreover, the frequency modulated interferometer suffer from an additional disadvantage of being sensitive to frequency drifts of the microwave source. This drawback can be overcome in a phase modulated interferometer but there is a high conversion loss of 30-35 dB during single side band generation process. Since unmodulated interferometer does not require linear modulation characteristics and is free from frequency drift problems, transit time tubes with higher output power can be used as generator.

The unmodulated interferometers (such as elementary interferometers used in early days of plasma physics) are the fastest interferometers with highest time resolution. In this type of interferometer, the maximum time resolution depends on only the response time of mixer diodes and the bandwidth of the following D.C. amplifier. Wide band amplifiers upto 1 GHz are nowadays standard in oscilloscope techniques.

If there is no modulation, the amplifier used must have good zero stability. This used to be a problem with valve units but is no longer critical since the advent of hybrid technique and integrated circuits. Nowadays, all the components can be mechanically mounted on the same base and hence kept at the same temperature, thus eliminating the temperature drift problems. In the popular Zebra Stripe technique, the phase is displayed directly on the oscilloscope as a function of time. The same can be done with computer modules.

But in case of multichannel operation, modulated interferometers have definite advantages over unmodulated ones. It is possible in the modulated system to achieve a certain channel separation by choosing different modulation frequencies, and the respective selective amplifiers for the various channels. In unmodulated system, cross talk can only be reduced by making the antennas having good directional characteristics.

Among the unmodulated systems, multiple probe interferometers are more useful but fabrication of probe assembly is difficult in millimeter wave region. Nagashima et al[29] have made a 2 mm digital interferometer without source frequency modulation. Because of the real time processing, it can also be applied for feed back control of the plasma column. Summary of various interferometer is presented in Table 2.

Thus, we have studied the various microwave interferometers critically. The merits and demerits of various systems have been outlined. Since for REB-Plasma experiments we require a single channel interferometer with high time resolution, the unmodulated system will be the most suitable system for obtaining time evolution of plasma density.

In this type of interferometer, mixing is done with a discrete frequency and not with a frequency spectrum, ambiguity due to undesired mixture products would not arise. It will give electron density better than a modulated system and allow fast temporal evolution of the plasma to be investigated. For knowing the direction of density change one can either use a two probe standing wave interferometer or a three arm interferometer. With suitable digital circuits it can also be converted into a direct reading type interferometer.

Table 2

S.No.	Interferometer Type / Characteristics	CARRIER FREQUENCY INTERFEROMETERS: Elementary Interferometers	Standing Wave Interferometer: Double Probe Interferometers	Standing Wave Interferometer: 3 Probe with Continuous Logic	REDUCED FREQUENCY INTERFEROMETERS: Frequency Modulated (Serrodyne) Interferometer: Zebra Stripe	Frequency Modulated (Serrodyne) Interferometer: Discriminator Integrator	Frequency Modulated (Serrodyne) Interferometer: Phase Comparator	Two level Frequency Modulated Interferometer	Phase Modulated Interferometer
		1	2	3	4	5	6	7	8
1.	Time Resolution	Very fast: depends upon crystal detector response time; limited by DC amplifier bandwidth (upto few nanoseconds)		Depends upon logic circuits response time.	Depends upon the modulation frequency and is limited by the delay in the long waveguide and retrace time of the sawtooth pulse.			Depends upon the modulation frequency	Depends on the rate of phase change and is limited by the finite switching time of the ferrite phase modulator.
2.	Phase Sensitivity	$\pi/2$		2π	$2\pi/10$ Governed by the width of the intensity modulation trace.	$2\pi/100$	$\pi/100$	$\pi/2$	$2\pi/10$ Governed by the width of the intensity modulation trace
3.	Attenuation in the interferometer system	Small Since the length of the waveguide used is less.			Large as it requires a long length of waveguide in the plasma arm				Large as there is less in single side band generation.
4.	Direction of density change	No, unless density approach cut off	Give the direction of density change						
5.	Effect of frequency drift of the source	No, if the two arms of the interferometer are made equal.			Since one of the bridge is much longer than the other display is highly sensitive to frequency drifts				Insensitive to frequency drifts.
6.	Ambiguity due to mixture products	Unlikely			Very likely				
7.	Channels operation in multichannel operation	Channel separation is possible only by means of mechanical design of antennae			Channel separation can be achieved by choosing different modulation frequencies for different channels				
8.	Display Characteristics	Display is in the form of sinusoidal fringes. It is not direct and does not give continuous evolution of electron density.		In the form of histogram; voltage proportional to phase shift.	Direct display of phase shift convenient in visualizing the time evolution of electron density	Direct reading type; Voltage proportional to phase shift.		In the form of histogram; voltage proportional to phase shift	Direct Display; voltage proportional to phase shift.
9.	Other Comments	Simple and fast response	Fabrication of probe assembly is difficult in millimeter range.		Suitable for slowly rising plasma so and multiradian phase shifts.	Suitable for plasmas having fast rate of density change.	Suitable for non cut off plasmas		Better than corresponding frequency modulated.

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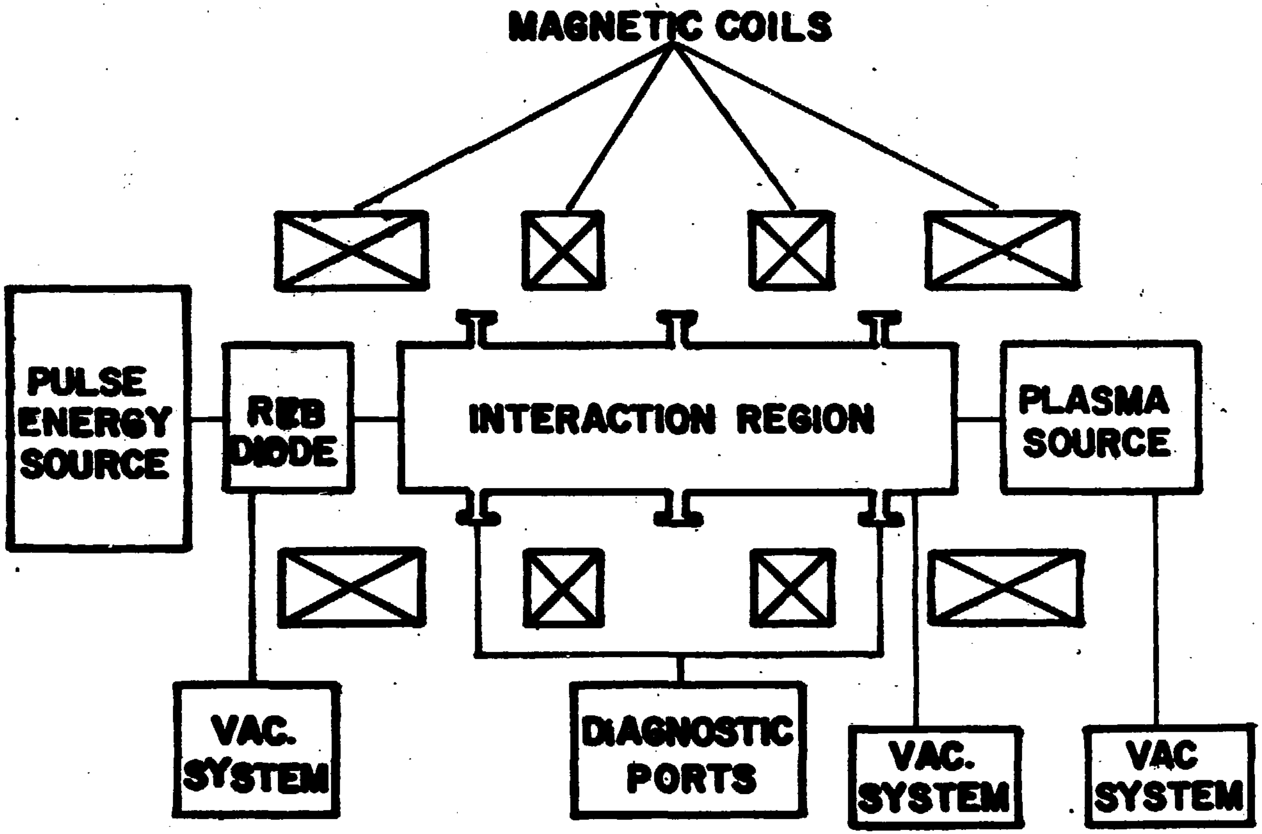

FIG.1 SCHEMATIC OF SYSTEM FOR REB-PLASMA STUDIES

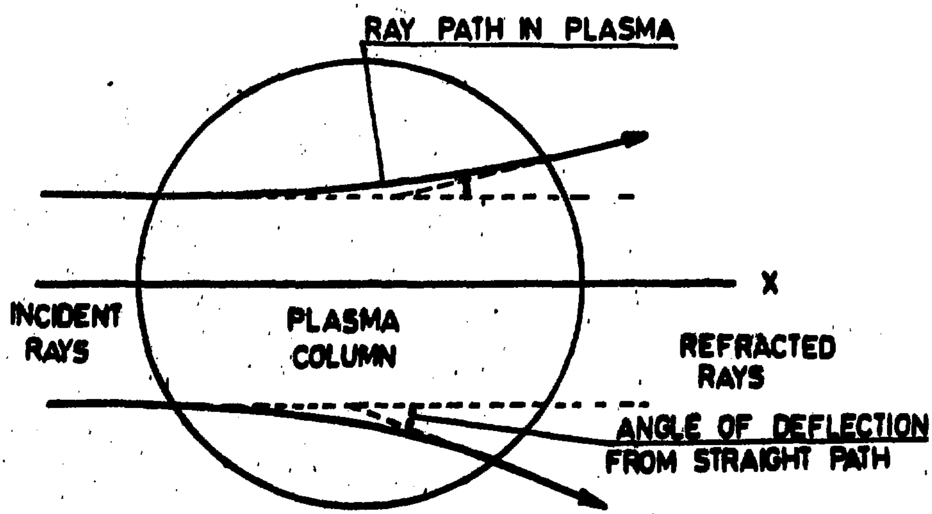

FIG. 2-WAVE REFRACTION IN PLASMA ($\mu < 0$)

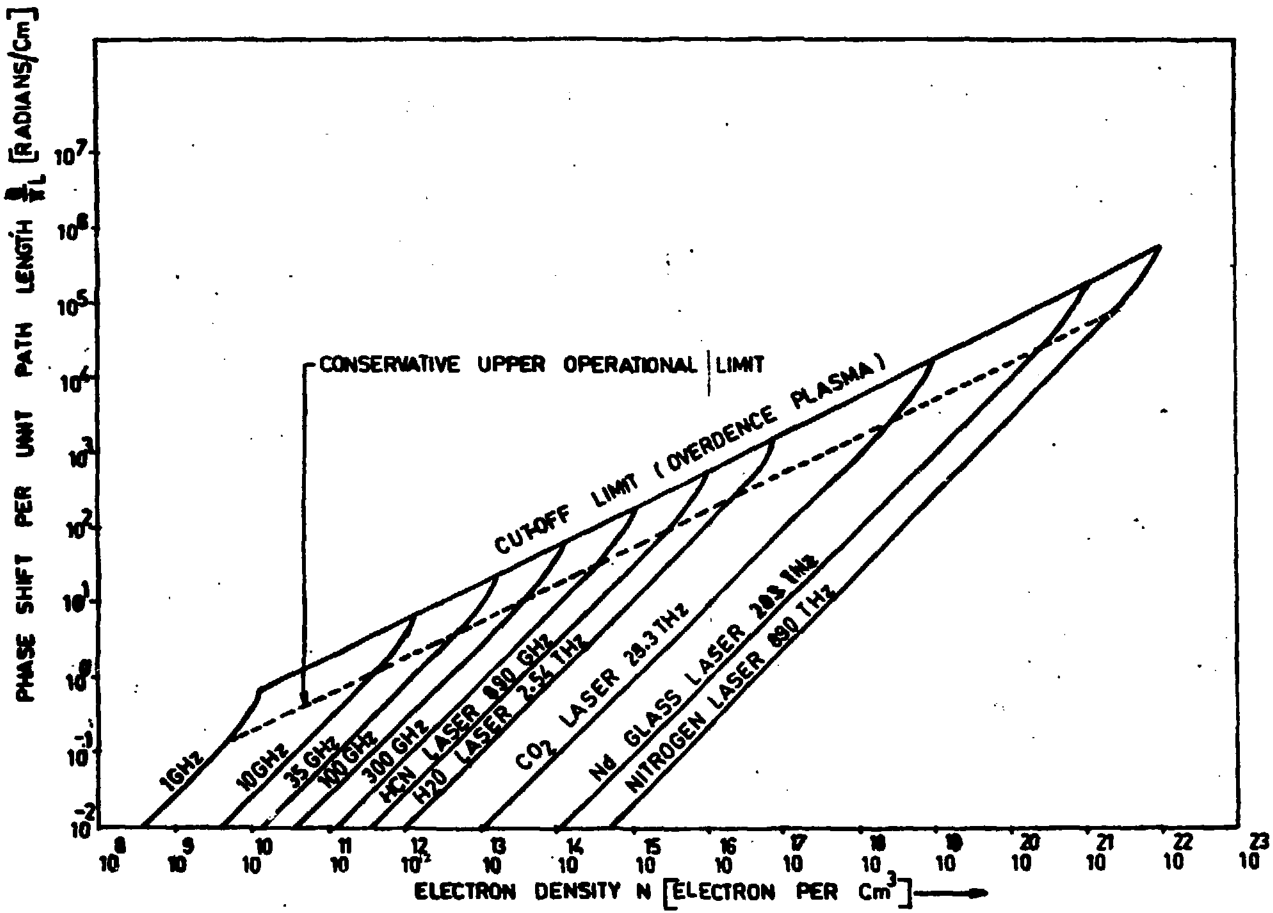

FIG. 3 : PHASE SHIFT VERSUS ELECTRON DENSITY FOR VARIOUS PROBING FREQUENCIES

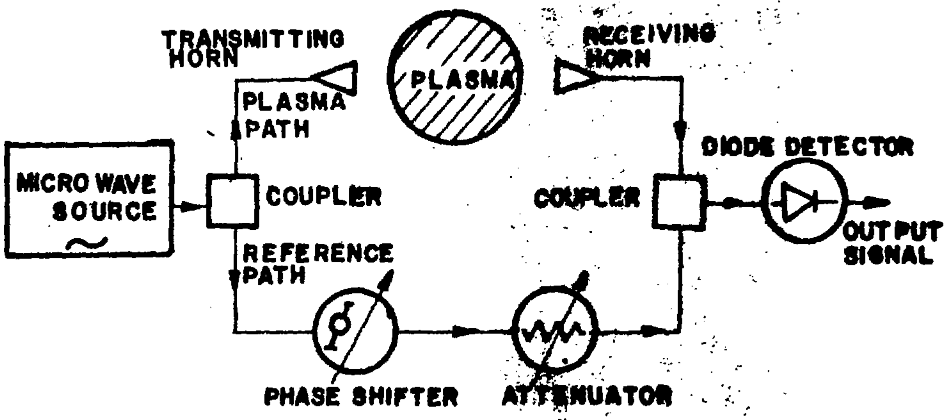

FIG. 4. SCHEMATIC DRAWING OF AN ELEMENTARY INTERFEROMETER.

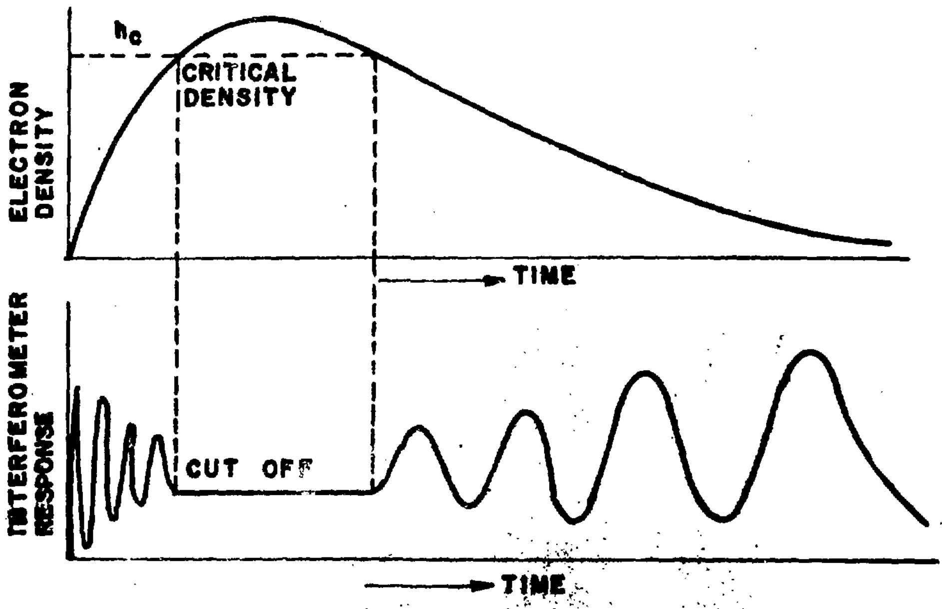

FIG. 5. TYPICAL RESPONSE OF THE INTERFEROMETER TO A TRANSIENT PLASMA EVENT.

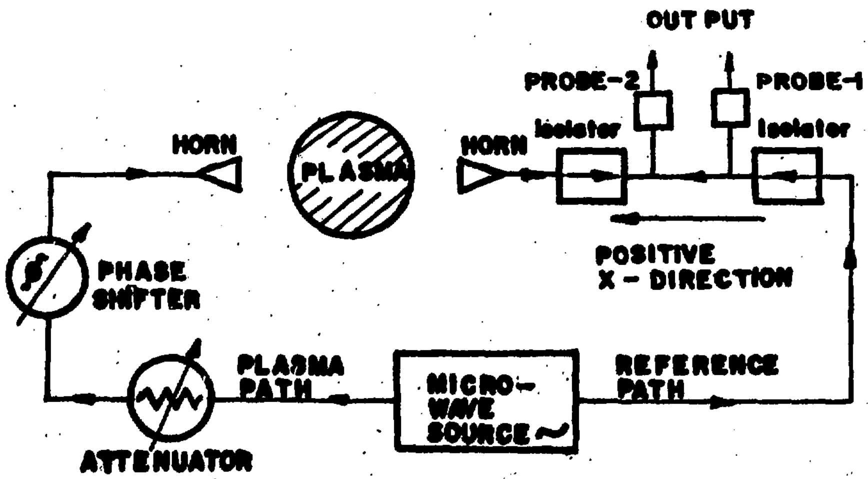

FIG. 6. SCHEMATIC OF DOUBLE PROBE STANDING-WAVE INTERFEROMETER.

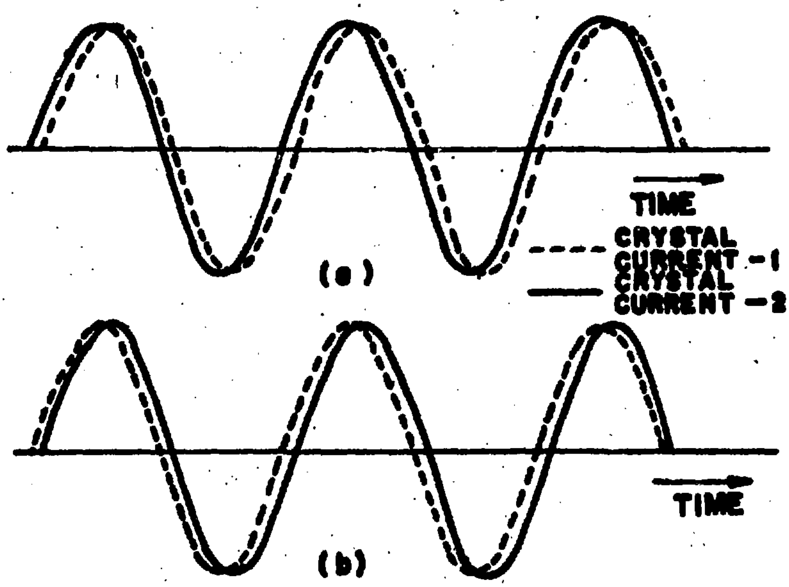

FIG. 7. CRYSTAL CURRENTS WHEN PLASMA DENSITY (a) DECREASES (b) INCREASES.

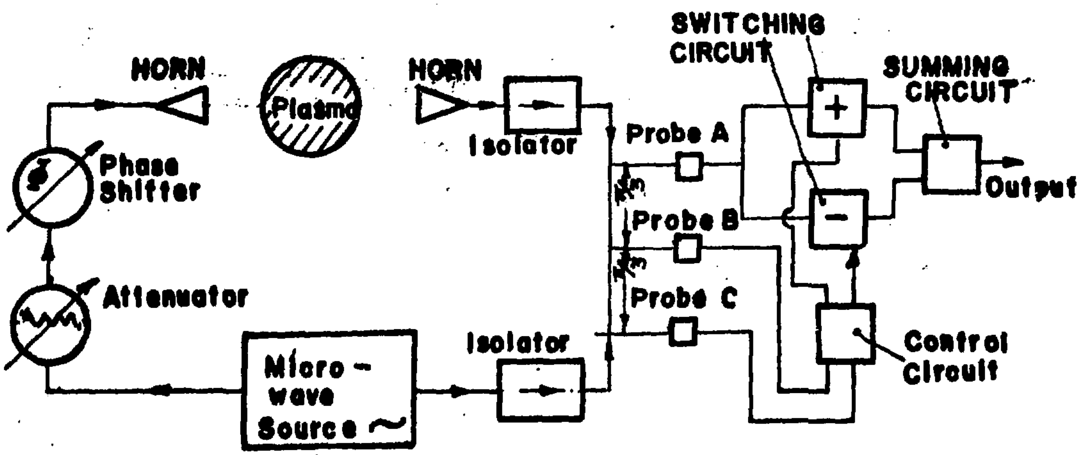

FIG. 8. SCHEMATIC OF THE STANDING-WAVE INTERFEROMETER.

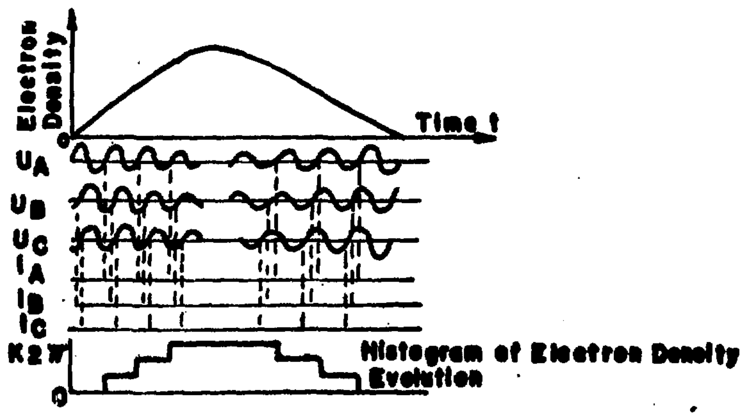

FIG. 9. CONVERSION OF INTERFERENCE PATTERNS INTO PULSES.

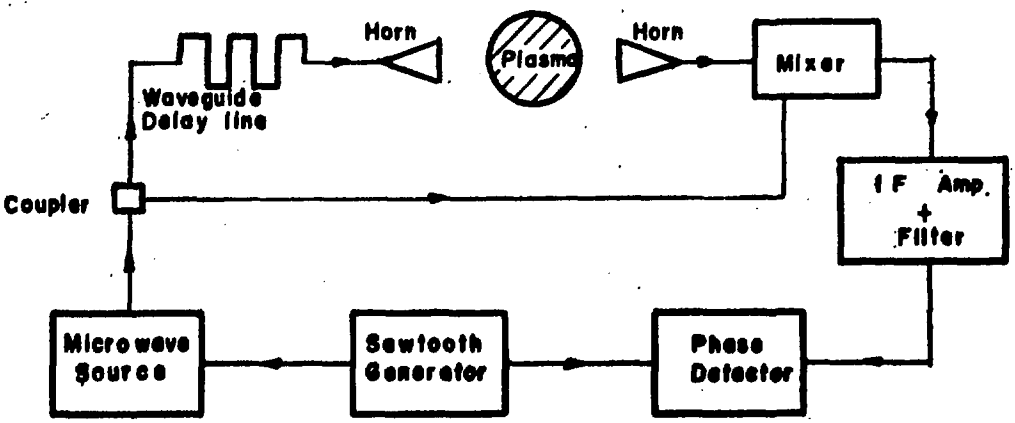

FIG. 10. SCHEMATIC OF THE SERRODYNE INTERFEROMETER DELAYLINE.

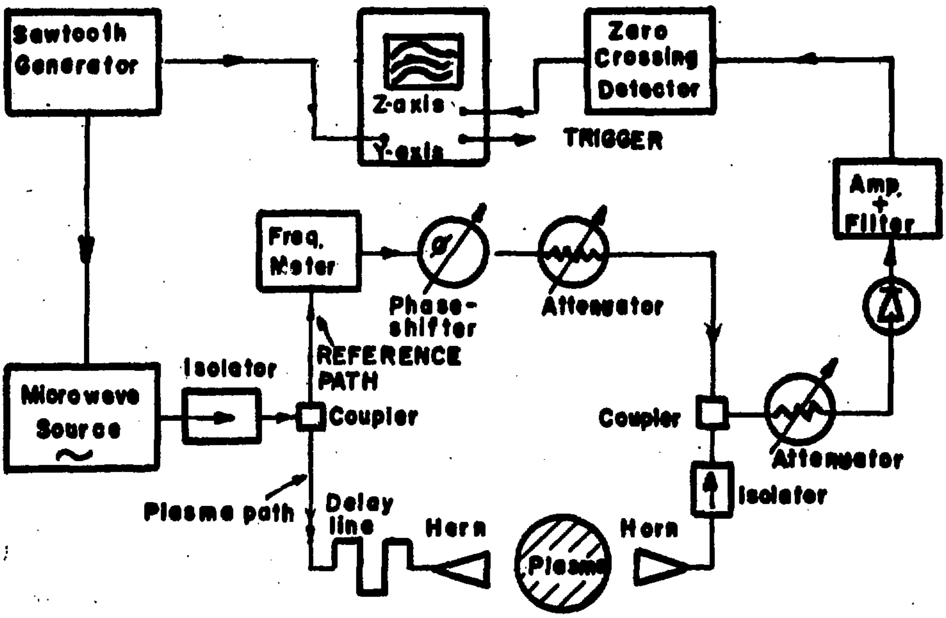

FIG. 11: BLOCK DIAGRAM OF THE FREQUENCY MODULATED ZEBRA STRIPE INTERFEROMETER.

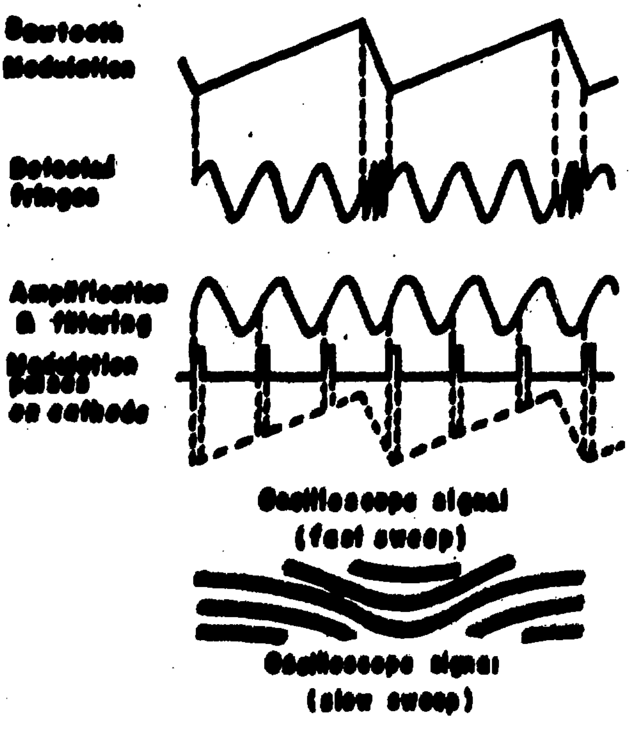

FIG. 12: SIGNAL PATTERNS IN THE 'ZEBRA-STRIPE' MICROWAVE INTERFEROMETER.

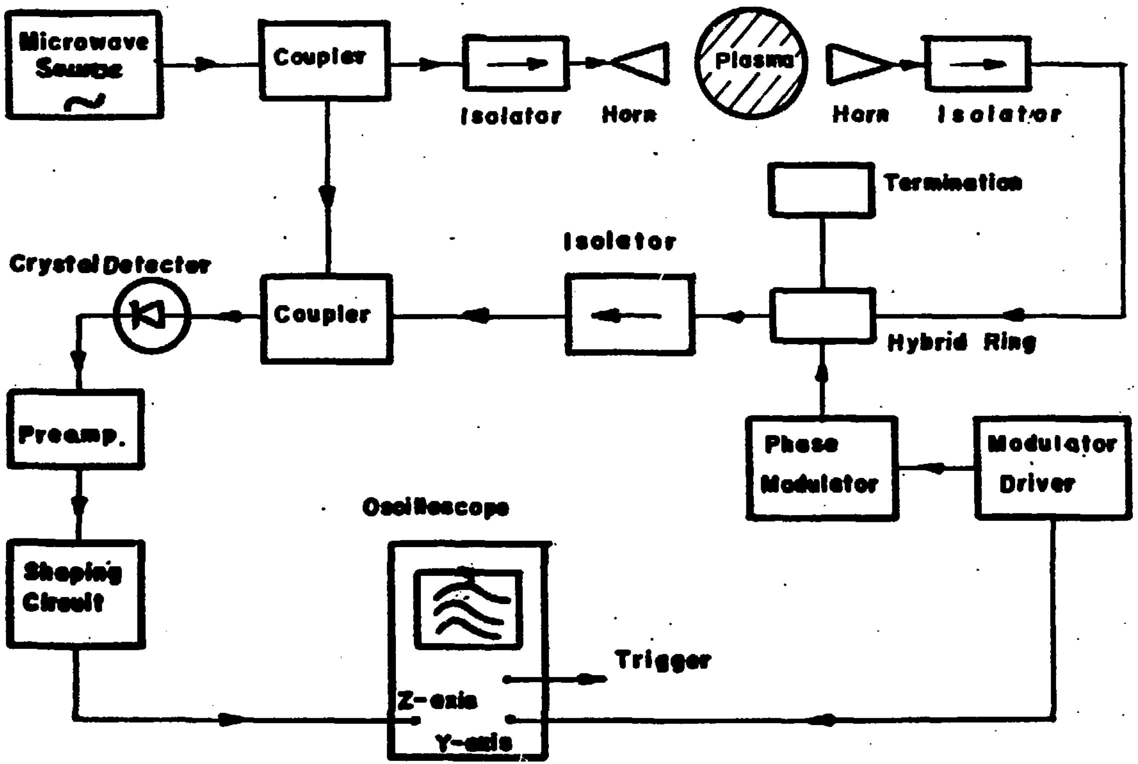

FIG. 13: BLOCK DIAGRAM OF PHASE MODULATED ZEBRA-STRIPE INTERFEROMETER.