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Direct reading fast microwave interferometer for ELMO Bumpy Torus

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A simple and inexpensive 4-mm direct reading fast (rise time $\sim 100\,\mu$s) microwave interferometer is described. The system is particularly useful for density measurements on the ELMO Bumpy Torus (EBT) during pulsed operation.

Recent pulse experiments on the ELMO Bumpy Torus (EBT) fusion device,[1] which normally runs steady state with electron cyclotron heating, necessitated the measurement of plasma density n ($\sim$few$\times 10^{12}$ cm^{-3}) and its time evolution. To do this, a direct reading fast 4-mm microwave interferometer has been developed and used on EBT. The system is capable of responding to the change of density within $100\,\mu$s, which is faster than a typical confinement time for the electrons (on the order of 1 ms).[1] The interferometer described here does not utilize the standard method of fringe counting[2] of phase-shift changes. Instead, the phase-shift changes are continuously measured and displayed with the help of a servocontrol fast ferrite phase (FPS), which keeps the interferometer arms nulled. The FPS is the main component of the system. It takes about 20 μs to switch from 0 to $\pi/2$ phase shift and can provide up to 2π phase-shift increase to a signal passing through it.

The basic elements of the interferometer are shown in Fig. 1. This interferometer operates at $\omega/2\pi = 70$ GHz with a $\omega_m/2\pi =$ 50-kHz amplitude modulation excited by a pin diode. The microwave beam from a low-power ($\sim$100-mW), reflex klystron is divided after an isolator and the pin diode into two parts by a 10-dB directional coupler for plasma and reference arms of the system. The reference arm signal goes to a balanced mixer through an attenuator and a direct reading calibrated phase shifter. The plasma arm, on the other hand, consists of a y-junction circulator, an attenuator, and a remote control phase shifter. The microwave beam is injected vertically into an EBT cavity through a standard gain horn. Port 2 of the circulator (Fig. 1) has the FPS with a terminated end. The incoming signal from port 1 traverses the FPS twice before it comes out of port 3. Therefore, a circulator and FPS combination can provide twice the phase-shift change to the beam that the FPS alone delivers. With this arrangement, the dynamic range of the system for phase-shift measurements (and, in turn, density) can easily be extended by 4π (two fringes) for every FPS cascaded.

The signal from the receiving horn is mixed with the reference signal in the balanced mixer. A pair of crystal diodes that are located at the summing and at the difference ports of the balanced mixer perform the usual square law detection[2] of the signal. With the help of the selective preamplifiers, each signal is then filtered and applied to the tuned (50-kHz) differential amplifier, which has an output voltage[3] of $V_d \sim \cos\phi \cos\omega_m t$, where $\phi = \phi_R - \phi_P$ is the phase-shift difference between the arms. Before the measurement, the system is nulled by bringing the plasma and the reference arms into quadrature with the remote control phase shifter so that V_d is zero. This initial null in V_d is independent of the relative signal amplitudes of the arms. The phase-sensitive detector (PSD) basically consists of a multiplier and a low-pass filter[4] and performs an amplitude demodulation by means of synchronous detection.[3] The output signal of the PSD is proportional to the phase difference ϕ (i.e., $V_{PSD} \sim \cos\phi$). Introducing plasma into the cavity causes a phase shift $-\Delta\phi_P$ in the plasma arm since the refractive index of the plasma is less than that of the vacuum. Having maintained the null in the system (i.e., keeping the initial value of ϕ_P constant), by means of the FPS, the value of $\Delta\phi_P$ can be determined since $\Delta\phi_P = \Delta\phi_{FPS}$. The nulling process is continuously and automatically achieved by the ferrite servocurrent driver (FSD) that follows the phase-sensitive detector via a feedback control loop, as shown in Fig. 1. Any small phase-shift deviation from the initial quadrature setup induces a nonzero PSD output voltage that provides an input current to the driver. This input current changes (in-

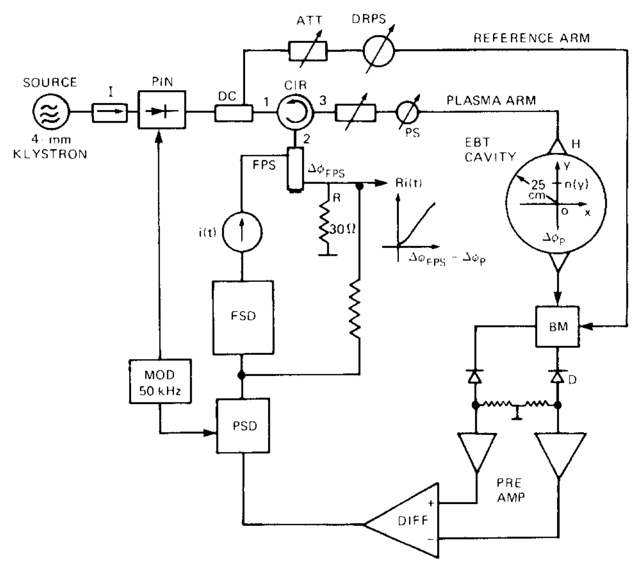

FIG. 1. Schematic of the direct reading 4-mm fast microwave interferometer. I–isolator; PIN–pin diode; DC–directional coupler; ATT–attenuator; DRPS–calibrated direct reading phase shifter; CIR–circulator; FPS–ferrite phase shifter; PS–remote control phase shifter; H–standard gain horn; BM–balanced mixer; PRE-AMP–selective preamplifier; DIFF–tuned (50-kHz) differential amplifier; PSD-phase-sensitive detector; FSD–ferrite servocurrent driver; MOD–50-kHz modulator.

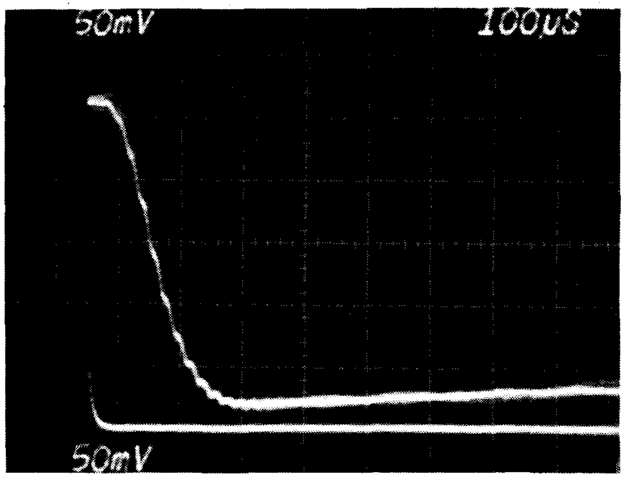

FIG.2. The time response of the fast interferometer ($\sim 100\ \mu$s) to 0–$\pi/2$ phase-shift change.

creases or decreases)until the phase-sensitive detector output becomes zero with the help of servocontrol of the FSD. The $\Delta\phi_P$ is related to the plasma density as

$$\Delta\phi_P = \alpha \int dy\, n(y),$$

where α represents the interferometer operating parameter,[2] related to ω, and $\int dy\, n(y)$ is the electron line density along the beam path length.

The overall system response time to a step phase-shift change (0 to $\pi/2$) has been measured, and the result is given by the lower trace of Fig. 2. The upper trace represents the step phase-shift change of the second FPS that was inserted into the reference arm and energized with a pulse generator. The amplitude of the second trace corresponds to a $\pi/2$ phase shift, and its rise time is about $100\ \mu$s. The amplitude difference between the traces is due to not having a perfectly matching pair of FPS's for the operating frequency used. The rise time of the system can be improved by choosing a higher modulation frequency and by making the PSD low-pass filter an active one that operates with a larger bandwidth.

The fast interferometer described here can successfully be utilized on other plasma devices as long as their densities have few fringes at 70 GHz, like the EBT plasma. At these low densities ($\sim$few 10^{12} cm^{-3}), a minimum number of FPS's are used in conjunction with the circulator. The low-density limitation of the system is due only to the insertion losses of the circulator–FPS combination ($\sim$6–7 dB in V-band).

A number of advantages of this interferometer can be summarized as follows: (1) The system is simple and inexpensive. (2) The time evolution of the density can be observed and measured "instantaneously." (3) The absolute value of the phase shift measured is readily obtained from the ferrite control current. (4) *in situ* calibration is carried out easily with a direct reading calibrated phase shifter, which is inserted into the reference arm that simulates the plasma. (5) The maximum measurable phase shift, or dynamic range, of the system can easily be extended by using a number of FPS's in series.

This system is presently part of the horizontally scanning interferometer[5] on EBT so that it is possible to measure the time evolution of the density profile $n(x, t)$ during the pulsed operation of the device.

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