

ELECTRONICS AND RADIO ENGINEERING

A Microwave Interferometer for Steady-State Plasma Density Measurements

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Abstract—An interferometer for a wavelength of 8 mm, capable of homodyne frequency conversion for measuring the electron density of a steady-state plasma from a high-frequency ion source, is described. An original method for generating a reference intermediate-frequency signal using a cavity resonator is applied in the interferometer. The unambiguously measured phase shifts range from 1.5° to 360° , and the error in measuring the phase shift is $\sim 5\%$.

Microwave interferometers (MWIs) are conventional devices for measuring electron plasma density. The microwave interferometry technique is now well developed, and there are a variety of designs for such interferometers [1]. The instruments most commonly encountered are MWIs in which the frequency of the microwave oscillator is modulated according to a sawtooth law or a nonequal-arm bridge is used. Among the latter designs, the best characteristics are those of the interferometers in which an additional (reference) waveguide bridge is used to form a reference intermediate-frequency signal [2]. Thanks to this technical solution, the phase difference of the reference and measured signals is virtually independent of changes in the carrier frequency of the microwave oscillator; therefore, such an interferometer is well suited for stationary plasma diagnostics.

It should be noted that a nonequal-arm bridge is formed quite naturally in the interferometer measurement channel, since the microwave circuit of an MWI is usually located far from the experimental setup. The length of the measurement channel waveguide line that connects the interferometer with the antennas on the plasma facility must be >10 m [3]. It is necessary to ensure the same difference in the arms of the waveguide lines in the reference waveguide bridge. This is inevitably involves an increase in the dimensions of the device, higher costs for the waveguide tube, and an rise in the microwave signal power loss.

The MWI described below has none of the above drawbacks, since it has no additional waveguide bridge. However, its design is characterized by a high degree of stability in the initial phase difference (one that compares well with circuits having reference waveguide bridges), thanks to a cavity resonator that is used to form a reference signal.

A block diagram of the MWI is shown in Fig. 1. The interferometer operates as follows: A microwave signal at a wavelength of 8 mm from oscillator Os , the frequency of which is modulated by sawtooth voltage generator SVG , passes sequentially through directional couplers DC_1 and DC_2 , a long waveguide line, antenna system A , and the plasma under study; it then arrives at magic tee MT . A signal from the DC_2 side arm arrives at the second input of MT through attenuator Att and phase shifter PS . These two signals are mixed in microwave detector D_2 . The second MT output is loaded into matched load ML_2 .

The elements connected downstream of DC_2 form a “classical” measuring nonequal-arm waveguide bridge.

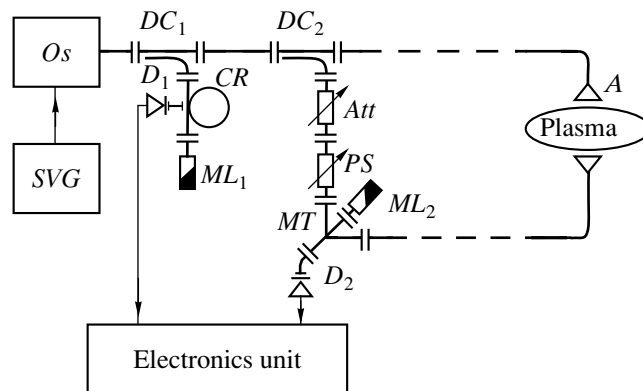


Fig. 1. Block diagram of the microwave interferometer: (Os) microwave oscillator; (SVG) sawtooth voltage generator; (DC_1 , DC_2) directional couplers; (D_1 , D_2) microwave detectors; (CR) cavity resonator; (ML_1 , ML_2) matched loads; (Att) attenuators; (PS) phase shifter; (MT) magic tee; and (A) antenna.

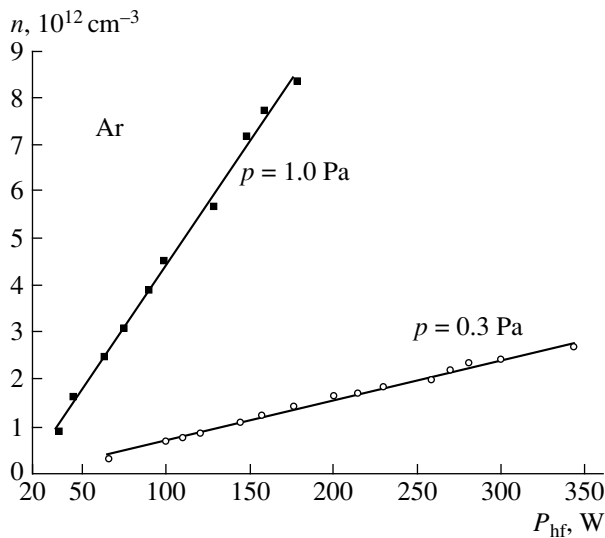


Fig. 2. Density of the plasma produced by the ion source, as a function of the high-frequency power.

Its frequency response is in the form of a sine function. At a sufficiently large deviation in the frequency of the microwave signal, the D_2 output signal takes the form of a sinusoidal segment. When the swing of the modulating sawtooth voltage is selected correctly, the signal is close to sinusoidal, and its first harmonic is used to measure the phase. It should be emphasized that, at a constant difference of the bridge arms, each point of the sinusoidal characteristic is uniquely related to the instantaneous frequency value of the microwave oscillator. As a result, the output signal phase is related to the carrier frequency of the microwave oscillator.

Directional coupler DC_1 , cavity resonator CR , and microwave detector D_1 are used in the circuit to form the reference signal. The CR is tuned so that the operating-type resonance oscillation frequency is close to the carrier frequency of the microwave oscillator. A pulse with a shape determined by the CR resonance curve is then observed at detector D_1 during each forward sawtooth scan. If the CR tuning remains constant, the oscillation peaks at D_1 unambiguously correspond to a certain instantaneous frequency value of the microwave oscillator. The pulses across D_1 follow at the frequency of the modulating sawtooth voltage. Discriminating the first harmonic of the detected signal using a bandpass amplifier allows a reference signal for phase measurement to be obtained.

As was mentioned above, the phases of the measured and reference signals in the absence of plasma are unambiguously determined by the instantaneous frequency values of the microwave oscillator. This means that the phase difference of these signals is independent of slow changes in the carrier frequency of the microwave signal. An important requirement is that the fre-

quency drifts be inferior to the sawtooth deviation; otherwise, the cavity resonator ceases to respond and no reference signal is formed.

The interferometer described above was developed to measure the electron density of the steady-state plasma produced by a high-frequency ion source [4]. The source plasma chamber is a glass cylinder 25 mm in diameter. The expected mean plasma density was between 10^{11} and $5 \times 10^{12} \text{ cm}^{-3}$ depending on the source operating mode. The selected operating frequency of the microwave oscillator (37.5 GHz) both ensured (with a margin) that the plasma transparency condition would be fulfilled and allowed the radiation beam to be guided through the setup chamber with acceptable losses. Since the plasma occupied only a small region, the calculated phase shifts were rather small and ranged from approximately 3° to 40° . This imposed quite stringent requirements upon the stability of the initial phase difference between the reference and measured signal and largely determined the choice of the interferometer layout.

A $\Gamma 4-141$ signal generator operating at a frequency of 37.5 GHz served as the microwave radiation source. The generator was based on a backward-wave tube and allows narrow-band frequency modulation to be accomplished at a minimum level of parasitic amplitude modulation. The frequency of the modulating sawtooth voltage was set equal to 20 kHz; the frequency of the detector output signals was correspondingly the same. The difference between the shoulders of the measuring waveguide bridge was 3.6 m in our case. This determined the swing of the sawtooth frequency modulation (~ 100 MHz) of the microwave oscillator.

The cylindrical cavity resonator of a ЧР-02 wavemeter (from a $\Gamma 4-115$ generator) is used in the reference signal formation channel. All of the elements of the interferometer microwave channel are based on a rectangular waveguide with a cross section of $7.2 \times 3.4 \text{ mm}^2$. The antenna system consists of two conical horn antennas with an aperture of ~ 10 mm.

The signals from the detectors undergo the following processing operations in the electronics unit: discrimination of the first harmonic and its amplification to a level of ~ 10 V, selection of the moments of the amplified signal's transition through zero, and determination of the phase difference between the reference and measured signal by a trigger-type phase detector. Both analogue and digital outputs of the phase detector are provided (the latter for communicating with a computer).

The specifications of the interferometer are as follows: operational wavelength, 8 mm; range of unambiguously measured phase shifts, 1.5° to 360° ; tolerable attenuation of the signal power in plasma, of up to 16 dB; and relative error in phase measurements, $\leq 5\%$.

This interferometer has been successfully operated as one component of a diagnostic complex for the high-frequency ion source. As an example, Fig. 2 shows the mean argon plasma density as a function of the high-frequency power deposited at argon pressures of 0.3 and 1 Pa.

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