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Fractional-Fringe-Shift Laser Interferometer

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by

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FRACTIONAL-FRINGE-SHIFT LASER INTERFEROMETER*

by

J. E. Hammel and D. L. Rode[†]

ABSTRACT

The 3.39- μ radiation from the He-Ne laser has been used extensively in the measurement of electron densities in pulsed plasma experiments. The lower limit on density measurements over long paths has been of the order of 10^{15} cm⁻² along the beam. The sensitivity of the method has been increased by about one order of magnitude in a singly-pulsed plasma where the chamber requires a beam path of many meters. Some of the features of the technique are similar to those used by Hooper and Bekefi in a small repetitively-pulsed plasma. A known fractional fringe modulation is applied to the interferometer cavity by a sinusoidal motion of the cavity mirror driven by a speaker coil. The infrared amplitude change due to the fast plasma pulse is then compared with the slow continuous modulation given by the known displacement of the oscillating mirror. The method is checked with a known fast injection of gas. The increased sensitivity is providing information on plasma densities in gun plasma experiments.

A laser interferometer suited to the measurement of transient plasma density fluctuations has been constructed through the modification of an Ashby-Jephcott interferometer.¹ The plasma density relates linearly to the data for changes in the

optical length of the external cavity of less than one-tenth wavelength, and the range of measurable densities is 10^{13} to 10^{16} cm⁻³. External cavity modulation is applied at such a frequency that ambient vibration does not appreciably disturb the interferometer over the time of measurement even when the length of the external path is several meters. To increase sensitivity, the 3.39- μ emission from a He-Ne gas laser is used as the interference wavelength, and the visible 6328-Å line provides ease of alignment. The instrument has been used on a one-shot neutral hydrogen fast-injection experiment

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and on a gun plasma experiment.

The interferometer schematic is shown in Fig. 1. An RF discharge laser (Model 112, Spectraphysics) acts as the source and phase-sensitive detector for the interferometer. The coherent output from the hemispherical cavity at the $6328\text{-}\text{\AA}$ and $3.39\text{-}\mu$ lines is 5 mW and 1 mW , respectively. The portion of the beam transmitted through the plane mirror traverses the external cavity and is reflected back onto itself. Depending upon the phase of the reflected beam, the intensity of the beam within the laser cavity is increased or decreased from that corresponding to none of the beam being returned. Because of the double pass across the external cavity length, one period of the interference pattern results for each $\lambda/2$ change in the optical length where λ is the wavelength of the interfering radiation.

Even though the intensity of the laser can be monitored with a photomultiplier detector which senses $6328\text{-}\text{\AA}$ radiation, an indium-arsenide infrared detector (KH-33, Block Engineering, Inc.) is used to enhance frequency response.^{2,3} Since a high-Q cavity is needed to sustain the visible line, this intensity cannot be modulated at the rate of the higher gain infrared line which can be sustained in a much lower Q cavity. Working entirely in the infrared removes this limitation on the interferometer response time.

The filter indicated in Fig. 1 is a germanium flat (Semi-Elements, Inc.) which excludes visible radiation from the external cavity. When both lines are present in the external cavity, the interference patterns for $3.39\text{-}\mu$ radiation have superposed on themselves the interference patterns for $6328\text{-}\text{\AA}$ radiation.

Laser infrared output versus the optical length of the external cavity is shown in Fig. 2. Rather than modulate the external mirror over many fringes,²

Fig. 1. Schematic of the interferometer placed on a large plasma device.

the sinusoidal movement of the external mirror has been limited to less than one-tenth fringe. Thus, the response of the interferometer is linearly proportional to the mirror displacement for a range of phases of the operating point. Random ambient vibration changes the length of the external cavity, and this will vary the amplitude and phase of the IR signal in random fashion. For our particular environment, the ambient vibrations cause fluctuations in the interferometer output which occur with periods greater than 10 msec . Therefore, if the phase is fixed for a linear response at a given time, it will remain very nearly stationary for the succeeding millisecond. For this reason, the frequency of the mirror modulation was chosen to be 1 kHz . By adjusting the trigger level of the oscilloscope from which the patterns are photographed, up to about 80% probability for achieving a constant amplitude linear response for a few periods of modulation has been attained. An experiment is timed to induce a shift in the pattern $500\text{ }\mu\text{sec}$ after the beginning of such a trace so that the experimental shift falls at a maximum or a minimum of the sinusoid. A comparison of the amplitudes of the two shifts then provides knowledge of the change in optical length of the external cavity due to the plasma experiment.

Three possible designs were considered for the external modulator:

Fig. 2. Laser infrared output for a small change in the external cavity length.

- 1) acoustic transducers
- 2) piezo-electric transducers
- 3) coil-driven transducers

The first involves driving a sound wave across the beam path as done by Hooper and Bekefi.⁴ With the anticipation of modulating at higher frequencies, this method was not attempted.

Second, a mirror attached to a stack of three ceramic-wafer transducers served as a modulator, but this transducer required a high amplitude driving voltage (1 kV peak-to-peak) to produce movements of one-tenth wavelength at 1 kHz. The resonant frequency was 12 kHz. Off resonance, the equivalent circuit was a parallel RC circuit of 200 k Ω and 1700 pf so that sufficient power was dissipated in the transducer to cause overheating and deterioration in the amplitude after 30 seconds of continuous operation.

A coil-driven transducer was chosen and tested with acceptable success. A 6-in., 5-W audio speaker was mounted with its acoustic cone removed. A $\frac{1}{2}$ -in.-diam aluminum front-surface mirror was attached to a lucite block which was fastened to the suspension diaphragm of the speaker. The assembly resonated at 73 Hz -- far below any expected operating frequency. Well-behaved movements of 1700 Å at 1 kHz can be produced over long periods of time. The mirror responded linearly to the sinusoidal driving voltage for these small amplitudes.

A record of the phase shift of the modulator response against frequency allows one to determine whether the external cavity length is increasing or decreasing with a given polarity of the driving voltage. For the 6-in.-speaker transducer, the response lagged by a few degrees at frequencies below 30 Hz. The lag increased rapidly to 90° at resonance (73 Hz) and remained near 180° for frequencies near 1 kHz. Data of this sort served to verify whether or not experimentally-induced shifts reduced the refractive index along the external beam path, as would be the case for plasma experiments. Since the operating point on the response curve of the interferometer is determined by random vibrations, the shift induced by plasma may be positive or negative depending on the slope of the response curve. This fact helps to identify noise signals due to ground loops as well as spurious radiation from the plasma which may be incident on the detector. (The germanium fil-

ter helps to attenuate this signal.)

The amplitude of the modulation due to ambient vibrations is comparable to that of a full fringe and, hence, is ordinarily more than five times the amplitude of the desired small shift response. Since the spectrum of this coarse noise falls below about 100 Hz, it is easily excluded by an amplifier whose lower cutoff frequency is above 100 Hz but well below 1 kHz.

To estimate the accuracy of the interferometer in an experiment, a fast-injection hydrogen gas cell was inserted in the external cavity. The cell consisted of a 19-cm³ cylinder with quartz endplates so positioned that the beam traversed 5.5 cm of gas. An electromagnetic fast-valve connected to the cylinder through a tee allowed room temperature hydrogen to be injected into the cell to pressures of about 15 mm Hg. This valve is driven open for approximately 50 μ sec by a 200-J capacitor bank. Figure 3 shows the history of the filling. A capillary tube connects the cell to a differential pressure gauge from which is obtained the steady-state pressure indicated on the curve.

The neutral hydrogen test provides a pessimistic estimate of the interferometer performance. The instrument is better suited to the measurement of small changes in optical path length which occur in less than about 400 μ sec and which do not persist after this interval. Otherwise, as in the hydrogen-gas test, the operating position is moved to a different slope and the sinusoidal calibration response changes slightly during the measurement. Furthermore, for the slower fringe shifts, one must extrapolate the remainder of the sinusoidal response as it would have proceeded if undisturbed (judged from

Fig. 3. Observed fringe shift for the injection of hydrogen gas in the beam path.

that preceding the arrival of gas) to obtain the fringe shift due to the gas.

The interferometer was arranged to observe the plasma density on-axis of a mirror field. A deuterium plasma of kilovolt energy was injected transversely into a 5-kG magnetic mirror field by a coaxial Marshall gun. Because the plasma experiment was contained in a large vacuum tank, the work path of the interferometer was about 4 m long. Plasma radiation did not disturb the infrared detector since a germanium filter was placed in the beam path. The data of Fig. 4 show the one-tenth fringe shift, the gun current, and the sinusoidal calibration response. The sinusoidal response is set to one-tenth fringe peak-to-peak and the gun is timed to fire near a peak of this response. The integrated density for

Fig. 4. (Top) I.R. signal from the interferometer for a coaxial gun plasma injected across the beam path. (Bottom) Expanded time scale for the same plasma taken at the time of first arrival of the plasma.

one-tenth fringe is $3.3 \times 10^{15} \text{ cm}^{-2}$, and the spatial extent of the plasma is about 10 cm. Hence, there is appreciable plasma ($10^{13} - 10^{14} \text{ cm}^{-3}$) present in the mirror for 100 μsec. A record of the density is obtained by comparing the amplitude of the fringe shift due to plasma with that due to the known calibration.

The present technique provides a method of measuring plasma densities with a sensitivity of about 1/100 fringe and with a frequency response sufficient to measure plasma events taking place faster than 1 μsec. In addition to the increased sensitivity, the method provides for greater ease in set-up and reduction when compared with the previous fringe-counting techniques.

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