OPTICAL PHYSICS LABORATORY MIAPH-OP-69.16

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ABSTRACT

A multiple pass two-beam optical interferometer has been constructed with ~~twenty~~ ten times the sensitivity of a single pass device. Typical applications include measurements of optical density in a gas or plasma sample, and determinations of small changes in figure of optical elements. Double exposure holography is employed to simplify the component requirements. Advantages of the new method are high sensitivity, adaptability to large test regions at low cost, and direct quantitative measurement.

I. Introduction

In the measurement of the figure of optical elements or the index of refraction of a sample of transparent material, it is often of importance to measure extremely small differences in optical path. The sensitivity of the traditional two-beam interferometer has been increased either by utilizing exponentially decreasing multipath interferometry as in the Fabry-Perot or the Fizeau fringe method developed by Tolansky[1] for measuring the figure of crystal surfaces and their films, or alternately by passing the test beam of a two-beam interferometer through the sample to be measured a definite number of times[2].

The first of these methods has the disadvantage that, although the sharpness of the resulting fringes is greatly increased, the <u>shift</u> is exactly the same as in the single pass method. This means that measurements of a very small fraction of a fringe are necessary if high sensitivity is to be achieved. A further disadvantage of this method when applied to index of refraction measurements (of a gas or plasma for example) is the necessity of providing extremely high quality, and often rather large, reflecting elements. The instrument is of course exactly analogous to the traditional Fabry-Perot interferometer as used for the measurement of wavelength. Many plasma devices of practical interest have dimensions of many centimeters, and the cost of the necessary large Fabry-Perot plates, together with their mountings, would be very high indeed.

The second method, that of multiple traversal of the test beam of a two-beam interferometer through the experimental chamber, is perhaps more promising. Here again, however, because the beam traverses the system many times, the optical windows and reflectors must ordinarily be of the highest quality to avoid having their imperfections greatly outweigh the quantities to be measured.

For this reason, we have developed the device described here, which combines a multipass system with the technique of double exposure holography[3]. By this means the demands on the optical system for accuracy are greatly reduced, since the interfering beams traverse precisely the same optical elements, being separated in time instead of in space. Because of the relaxation of the necessity for highly accurate optical elements, it is quite practical to obtain as many as twenty-fold multiplication in sensitivity over the traditional Mach-Zehnder interferometer used in plasma physics diagnostics[4].

II. Description of the Interferometer

A diagram of the optical system of the Holographic Multipass Interferometer (HOMIN) is shown in Fig. 1. The source is a helium-neon gas laser emitting 15 milliwatts of continuous power at 6328 Å. The light from this source is divided into two beams of equal irradiance by the beam splitter B. The microscope objective L1 focuses the test beam through the "beam cleaning" pinhole P1. Lens L2 relays the focus of the beam from the pinhole to a more accessible location and provides for variable beam expansion. This beam is then made to pass several times through the test system, which in this case consists of a 15 cm diameter f/11 collimating lens L_3, an autocollimating plane mirror M5 and the test region (plasma).

The multiple pass arrangement shown in the figure is based upon the Kratz and Mack[5] technique which was developed for an entirely different problem. In our application it is important that any ray passing through a given part of the test region on the first traversal continue to pass through the same part on each succeeding transit. In order to satisfy this requirement it was found necessary to replace the 90° prism used by Kratz and Mack with a 90° Amici roof prism R and a set of individually adjustable mirrors M1, M2, M3 ---, one for each two additional passes through the system. The Amici prism is necessary to provide an extra reflection correcting the reversion which would otherwise be present. The individually adjustable mirrors are needed to superimpose all the passes through the test system.

The second or auxiliary beam emerging from the beam splitter must be superimposed on the test beam at the photographic emulsion in order to make the hologram, H.

III. Design Considerations

To make a successful hologram it is important to ensure high fringe contrast at the photographic plate. The most important points here are:

1. The planes of polarization of the two interfering beams should be parallel.
2. The intensities of the two beams should be as nearly equal as possible.
3. The beams should be coherent with respect to each other.
4. The fringes forming the hologram should be spaced far enough apart to be resolved by the photographic film employed.

5. Temporal stability of the optical path must be maintained.

Points 1 and 2 may be treated together by inserting a linear polarizer (a Polaroid sheet was used successfully) just in front of the photographic film position and rotating it to obtain maximum fringe visibility as observed in the fringe viewing microscope (Figure 1).

The third point, that of coherence, may be treated by adjusting the optical path difference (OPD) between the two beams at the hologram for maximum fringe visibility. With many pulsed lasers this occurs only at or near zero OPD. For well-tuned, single mode continuous lasers, the OPD can have any value up to several meters without significant loss of coherence. For continuous lasers emitting more than one axial mode the OPD should be nearly an even multiple of laser cavity lengths.[6,7]

In anticipation of using the interferometer with a pulsed laser, the auxiliary beam is provided with an optical delay line so that the OPD can be made small. After the appropriate number of passes through the delay line, the auxiliary beam is directed onto the photographic film at H by mirror M4. Lenses L4 and L5 are used, together with pinhole P2, to provide a clear expanded auxiliary beam of appropriate size and irradiance at the hologram.

To insure the satisfaction of the fourth consideration above, the two interfering beams should intersect at a small angle, since the fringe spacing is given by the grating formula

$$t = \lambda \csc\theta. \qquad (1)$$

For small θ, $t = \lambda/\theta$, so that for red light, if θ is 3°, t is about 12 micrometers. The resulting fringes would be easily recorded by an emulsion having a resolution of 100 lines per millimeter.

The constancy of the optical path involves the elimination of vibration of the optical elements and fluctuations in index of refraction of the intervening atmosphere. This was done by suspending the optical system on pneumatic supports and by enclosing it in a wood box to avoid air currents. If the number of traversals is much increased, evacuation of the optical path will become necessary.

A schematic diagram of the system used in reconstruction to obtain the interferogram is shown in Fig. 2. Lens L1 is a microscope objective used to expand the laser beam and P is a "beam-cleaning" pinhole placed at the focus of this lens.

The beam emerging from the pinhole may be considered to be a replica of the auxiliary beam used to make the hologram and its passage through the hologram produces the reconstruction of the two test beams. These superimposed beams correspond to the first positive order of the hologram diffraction grating.

Lens L2 is used to focus the emerging beams behind the hologram. The desired pair of superimposed test beams may then be selected by passage through the iris diaphragm. The interference fringes produced by the two superimposed interfering reconstructed test beams may then be recorded as an interferogram on photographic film at I.

It also is desirable to have in the interferogram a background of nominally straight fringes whose departure from straightness is a measure of the change in the test wavefront between the two exposures. This is accomplished most easily and reproducibly by simply translating the photographic film a small amount parallel to its own plane between exposures.

IV. Results

In order to test the operation of the interferometer so as to exhibit its sensitivity and accuracy a gas cell was used as a test object, the construction of which is indicated in Fig. 3. This cell was placed in the region between lens L3 and mirror M5 of Fig. 1. The interferometer was set up for 2, 4, 6, 8, and 10 passes of the test beam through the cell. For each of these a calibration hologram was made with the cell containing air at ambient pressure during both exposures. A set of straight vertical fringes was made to appear in the interferogram of each calibration hologram by translating the hologram through 0.5 millimeter between exposures, as mentioned above.

A second hologram was made for each step. For these the cell contained air during the first exposure and carbon dioxide during the second. Since CO_2 has an index of refraction somewhat greater than air, the wedge-shaped lower half of the cell provides a gradient in optical path, while the parallel-sided upper half does not. This results in tilted fringes for the lower half of the field and straight ones for the upper.

The greater the number of passes through the system, the greater should be the tilt of the fringes in the lower half. The number m of fringe-tilt is given by the expression

$$m = \frac{n\Delta\mu d}{\lambda} \tag{2}$$

where $\Delta\mu$ is the difference in index of refraction between air and CO_2, d is the geometrical depth of the wedge shown in Fig. 3, λ is the wavelength of light, and n is the number of passes through the cell.

We notice that the expected deflection is proportional to n, the number of passes.

The interferograms obtained from this series of holograms are shown in Fig. 4. It can be seen that the deflections average about 1.2 fringes per pass, in accordance with the proportionality shown in Eq. (2). Because of the preliminary nature of these experiments no attempt was made to monitor the actual temperature and purity of the gasses involved, so that no absolute measurements were made.

In order to exhibit the quality attainable by HOMIN without the presence of optical imperfections in the gas cell, the cell was removed and the calibration interferogram of Fig. 5 was made with ten passes. The 15 cm diameter aperture of the collimating lens is here limited at the top and bottom by the retro mirror whose height is only 12.5 cm.

V. Conclusion

We have demonstrated a very simple multipass interferometer suited to quantitative measurements of extremely small changes in optical path. It is not severely limited by demands for accurate optical elements, and can therefore be adapted to very large test regions. Twenty passes have been realized, and there seems no reason why this number cannot be greatly extended, especially if air is excluded from the optical path and vibrations are eliminated.

VI. Acknowledgements

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FIGURE CAPTIONS

Figure 1. Holographic Multiple Pass Interferometer (HOMIN).

Figure 2. Reconstruction configuration used to obtain interferograms from holograms made on HOMIN.

Figure 3. Drawing of the gas cell used to illustrate the use of the interferometer.

Figure 4. Interferograms showing fringe deflections.

Figure 5. Interferogram showing the quality attainable with ten passes if the gas cell is not used.

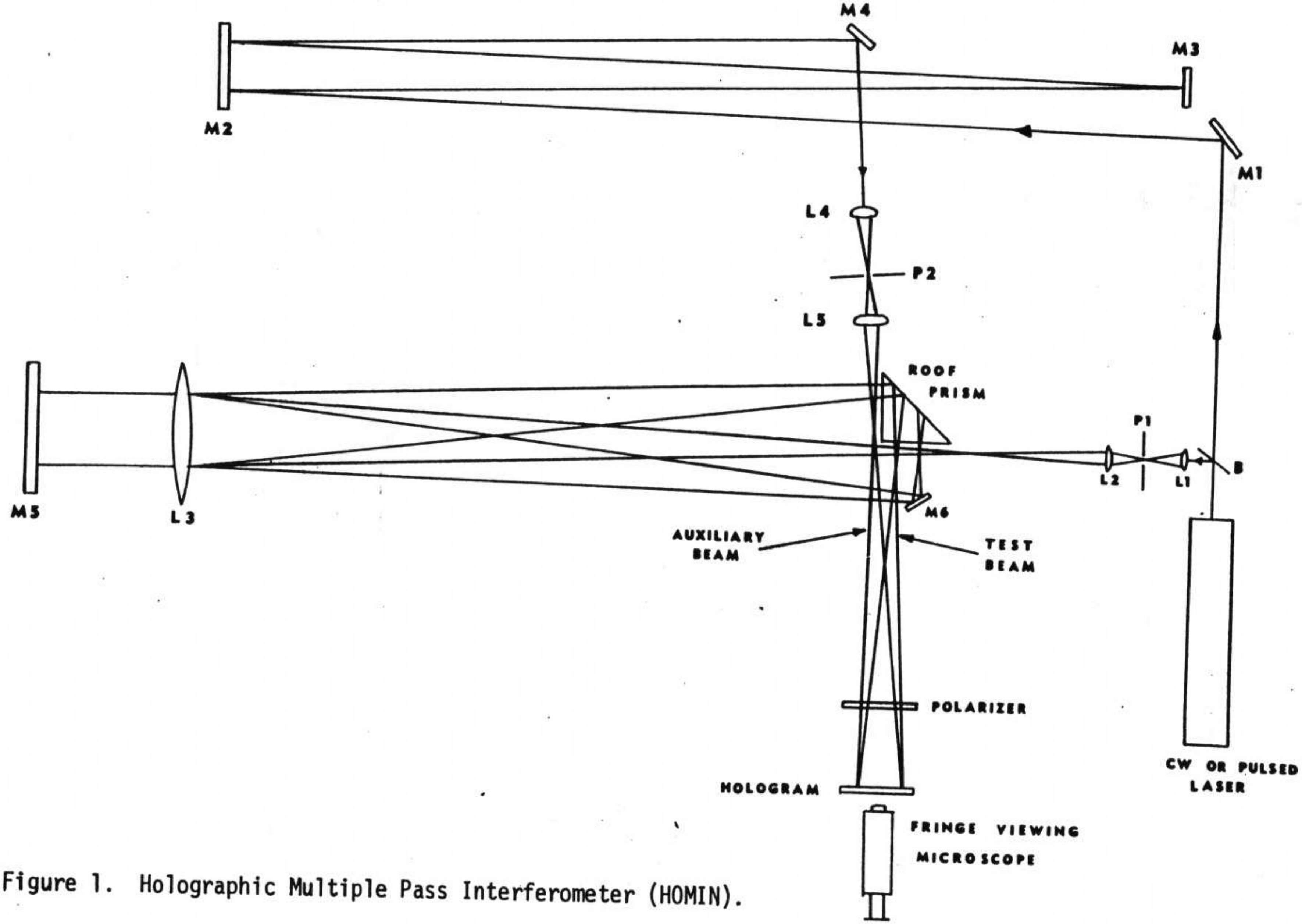


Figure 1. Holographic Multiple Pass Interferometer (HOMIN).

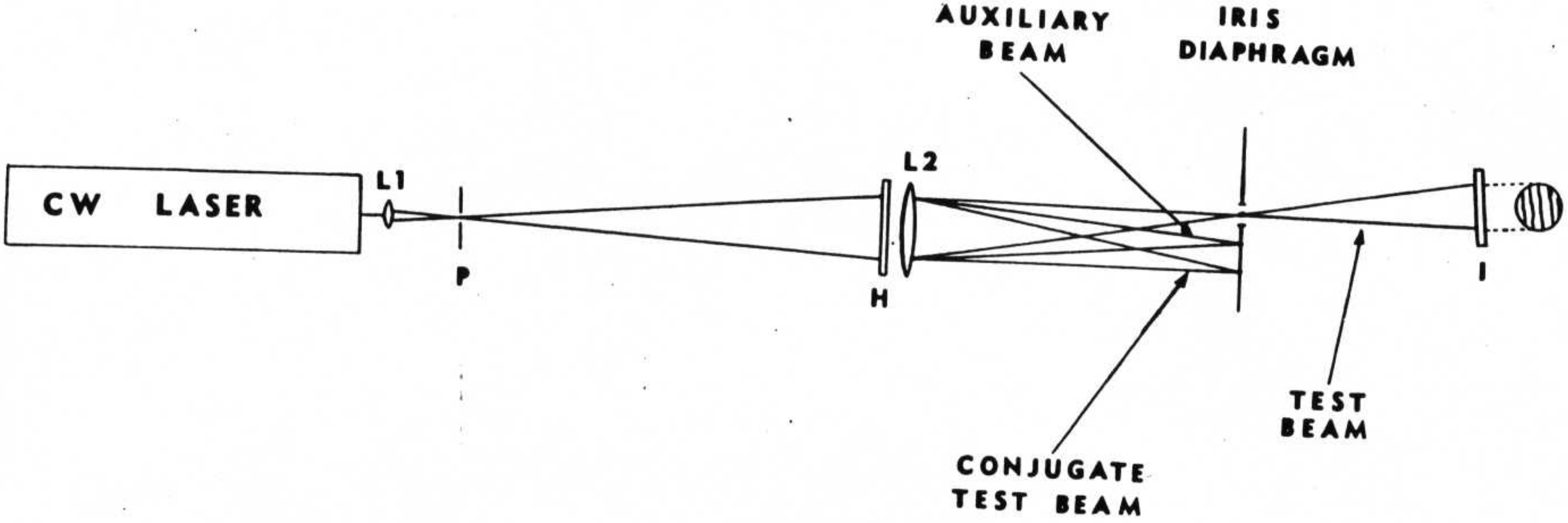


Figure 2. Reconstruction configuration used to obtain interferograms from holograms made on HOMIN.

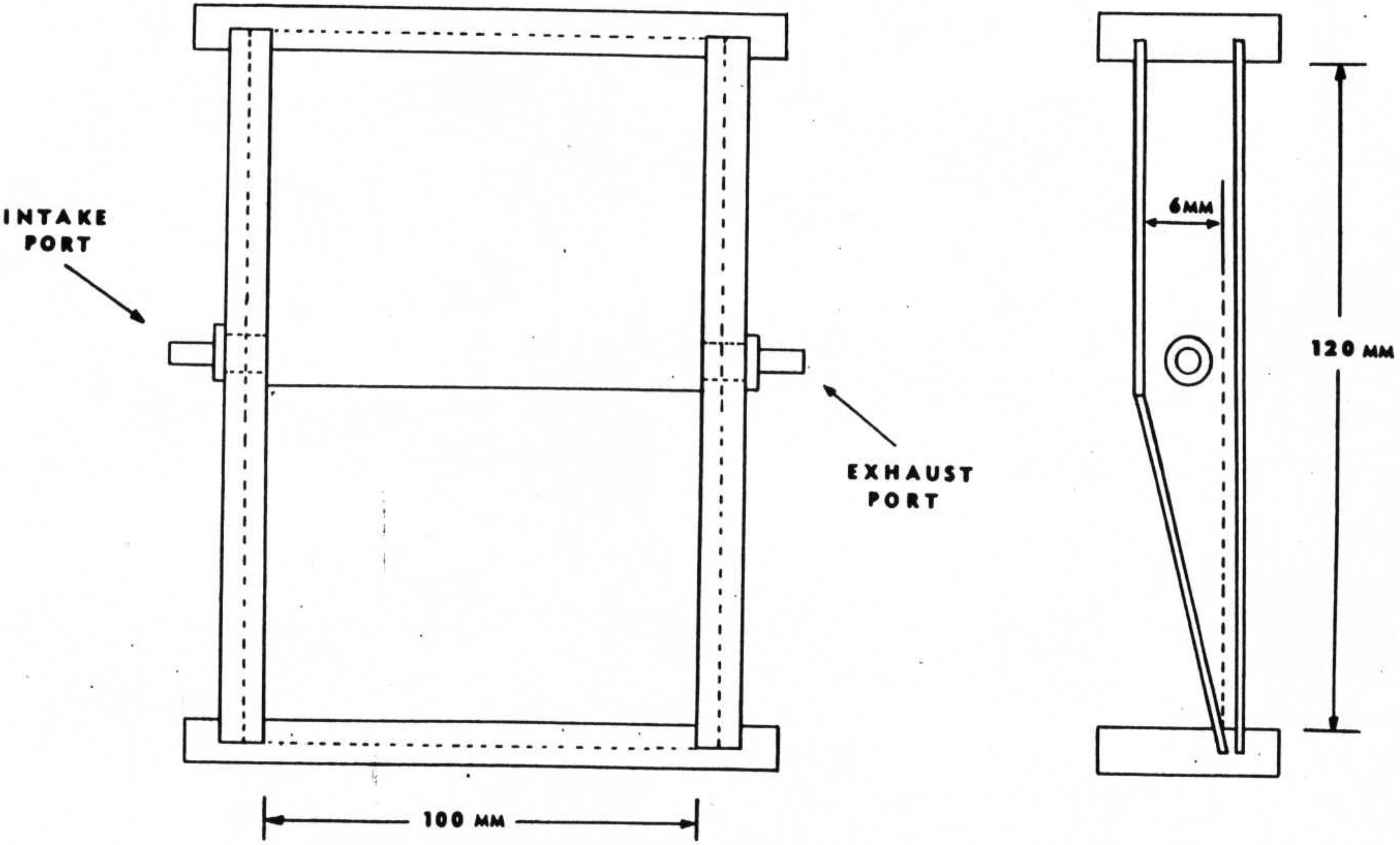
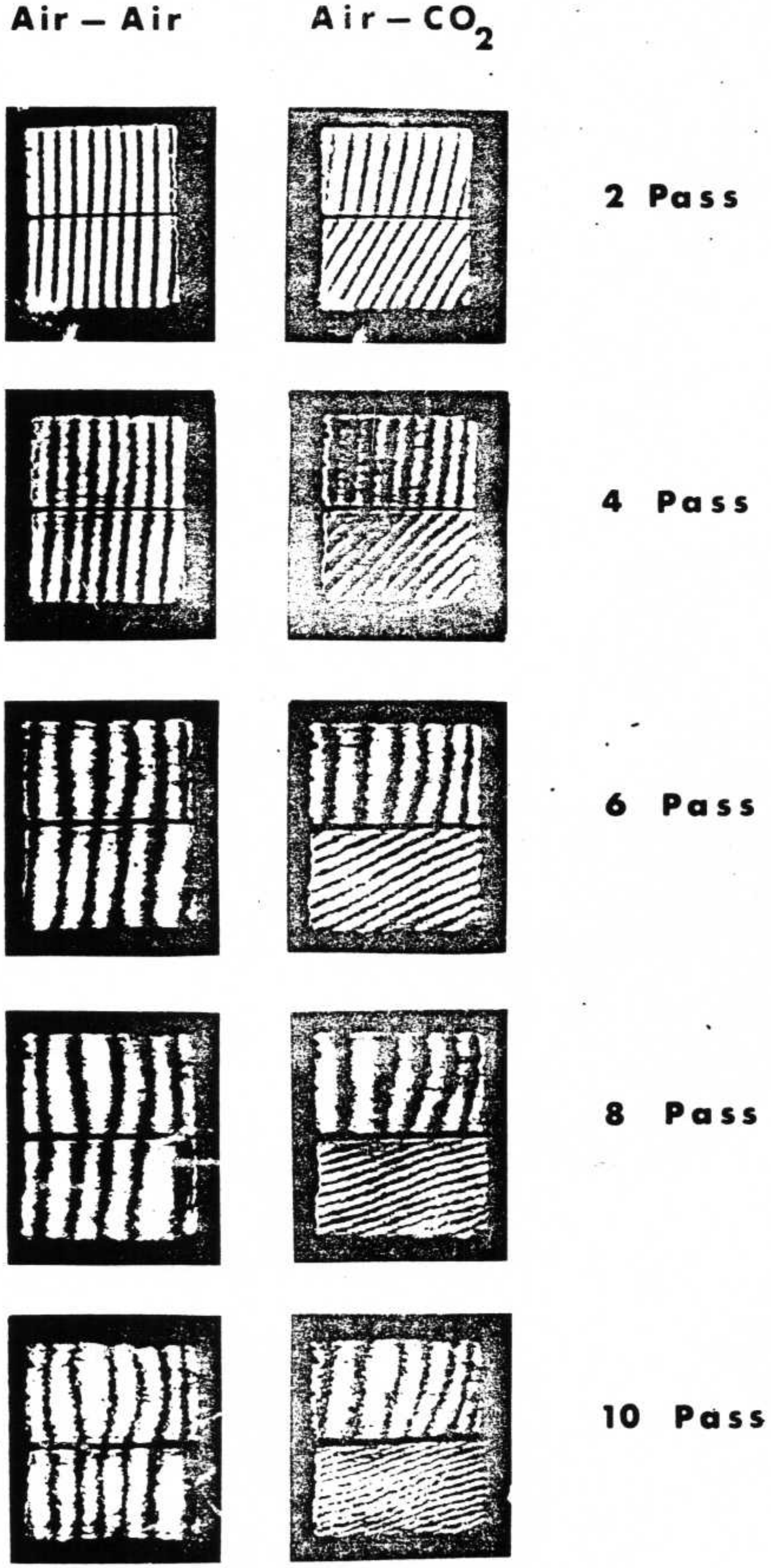


Figure 3. Drawing of the gas cell used to illustrate the use of the interferometer.



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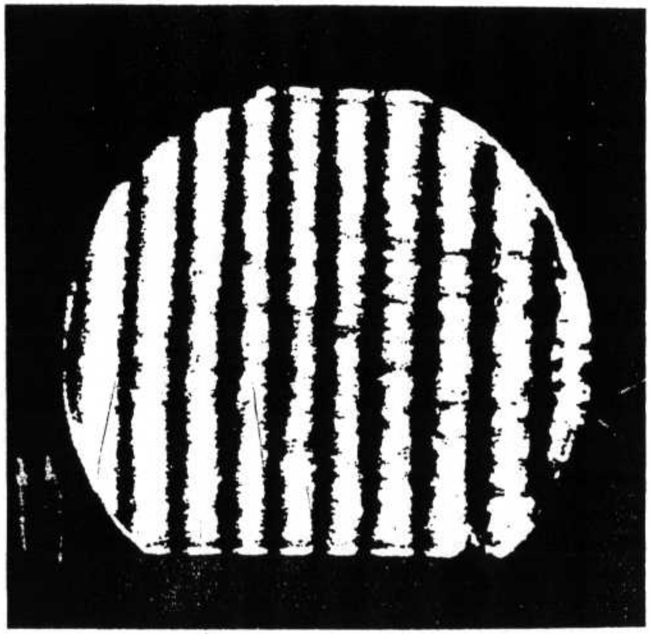

Air — Air

10 Pass

Figure 5. Interferogram showing the quality attainable with ten passes if the gas cell is not used.