NON-INVASIVE PRESSURE SENSING IN MICROFLUIDIC CHIPS USING LASER INTERFEROMETRY

Asm Kamruzzaman[1], Yusuf A. Koksal[2], Xiaolong Yin[1], Hossein Kazemi[1], Erdal Ozkan[1], Necati U. Kaya[2]

[1]Petroleum Engineering Department, Colorado School of Mines, Golden, Colorado, USA.

[2]Kaia Corp., Denver, Colorado, USA.

RESEARCH SUMMARY

- We propose a laser interferometry technique capable of sensing fluid pressure change in lab-on-a-chip applications noninvasively.
- Similar approaches have been proposed in the past [1]; however, we have used a different laboratory setup.
- In our study, we were able to detect fluid pressure change in a microfluidics chip; however, we are in the process of quantifying the pressure change.
- The use of laser interferometry for fluid pressure measurements in lab-on-a-chip is a viable and promising method.

[1] Fultz, D. W., and Allen, J. S., "Nonintrusive pressure measurement in microfluidic systems via backscattering interferometry," Experimental Fluids, 55, 1754 (2014).

OUTLINE

- Research background
- Laboratory procedure
- Air pressure sensing in microfluidic model
- Experimental results
- Discussion
- Conclusion

RESEARCH BACKGROUND
MICRO- AND NANO-SCALE POROUS MEDIA

- Micro- and nano-scale **pores and fractures** exist:
  - Across the earth, biological, and material sciences disciplines.
  - Soil, organic tissues and membranes, natural and synthetic materials, and **petroleum reservoir rocks.**
  - **Critical locations** for fluid storage, transport, and chemical reactions.

- In these small pores, **fluid(s) pressure determination is difficult**:
  - Impedes the quantification of **chemical behavior** and fluid conditions.
  - Integration of on-chip pressure sensors in **small space** is challenging.
  - In-situ pressure determination or **pressure mapping** hard to achieve.

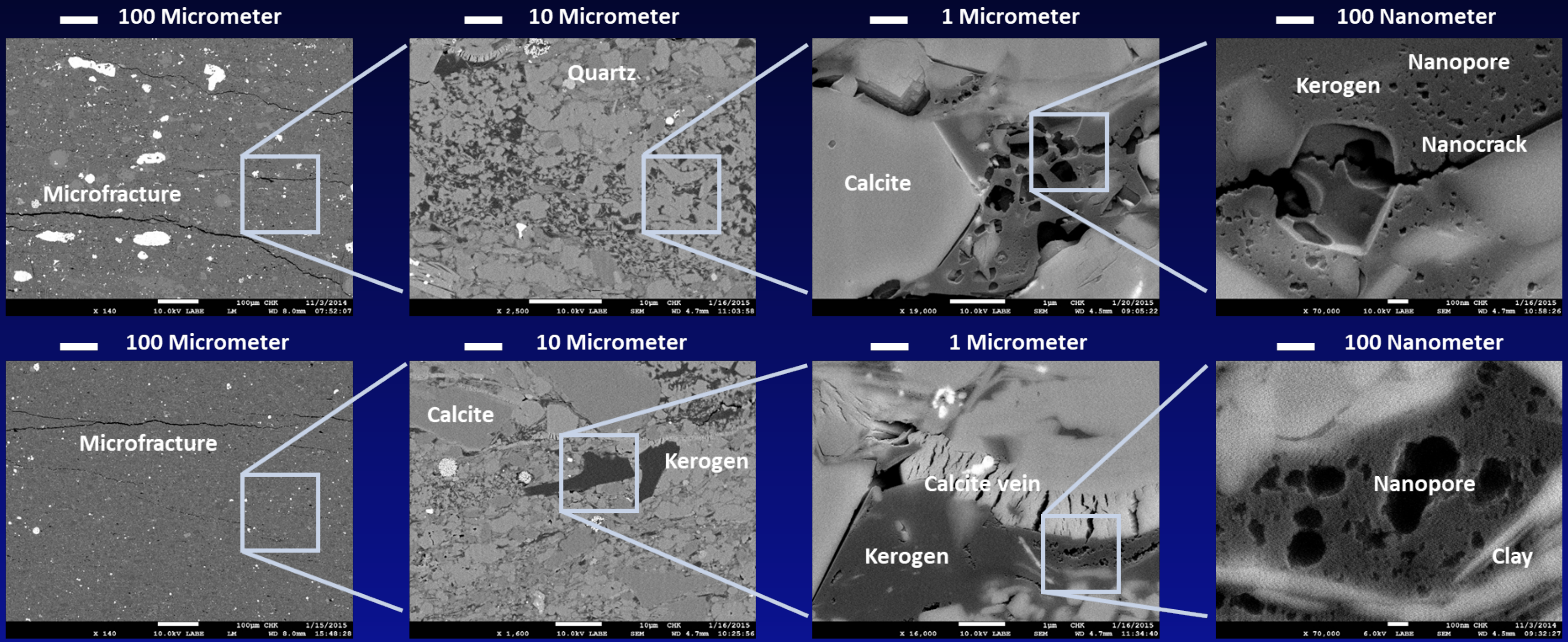


Figure: Electron microscopy images showing micro-and nanoscale pores and flow networks in petroleum reservoir rocks.

RESEARCH BACKGROUND
LASER INTERFEROMETRY PRINCIPLES

- **Adapted laser interferometric technique:**
  - **Helium-neon laser** impinges on microfluidic chip with plane-parallel plates with varying optical properties.
  - Microchannels are etched on adhesive substrate and sealed with glass cover.
- At any fluid pressure (Pressure 1), light reflects off the outer and inner surfaces of the microchannel:
  - As two spherical wavefronts.
  - Waves superposition in space to **produce interference fringes**; constructive vs. destructive interference.
  - Fringes are captured by a sensor.
- With increase in fluid pressure (Pressure 2):
  - Origin of spherical wavefront moves.
  - **Fringes shift position** in response to this fluid pressure change.
- The fringe shift is a **strong function** of:
  - Change in fluid density and pressure.
  - Wavefront geometry.

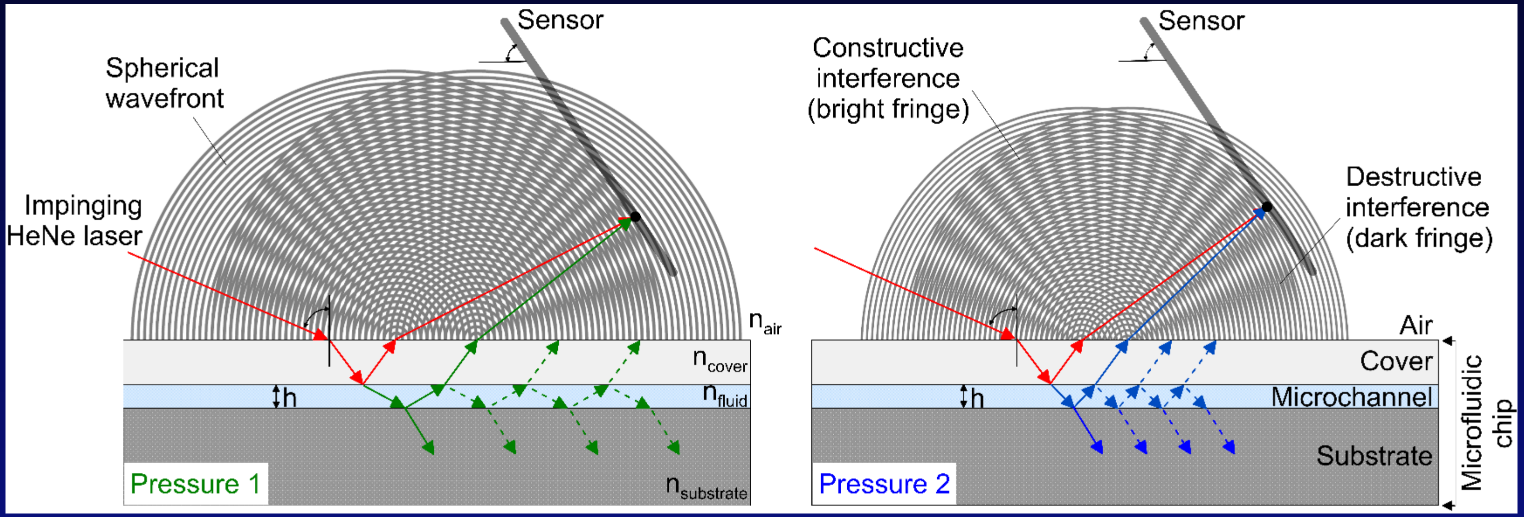


Figure: A simplified illustration of the working principle of optical interferometry and its microfluidic application.

LABORATORY PROCEDURE
INTEGRATION OF INTERFEROMETRY AND MICROFLUIDICS

- HeNe beam impinges on microchip:
  - Has 632.8 nm wavelength and 0.48 mm beam diameter.
  - Directed by a laser quality mirror.
  - Oblique incidence angle of 40° - 60° from surface normal.
- Transparent, air-filled microchannel:
  - Etched on 1.02 mm thick Norland Optical Adhesive 81 (NOA81) substrate; has attractive optical and physical properties.
  - Sealed by an 1.07 mm thick glass cover.
  - Characteristic dimension of 100 μm.
- Reflected beams:
  - Passed through a laser filter and a linear polarizer.
  - Interference fringes were captured by a CMOS sensor.
  - The sensor sends digitized images to a computer.

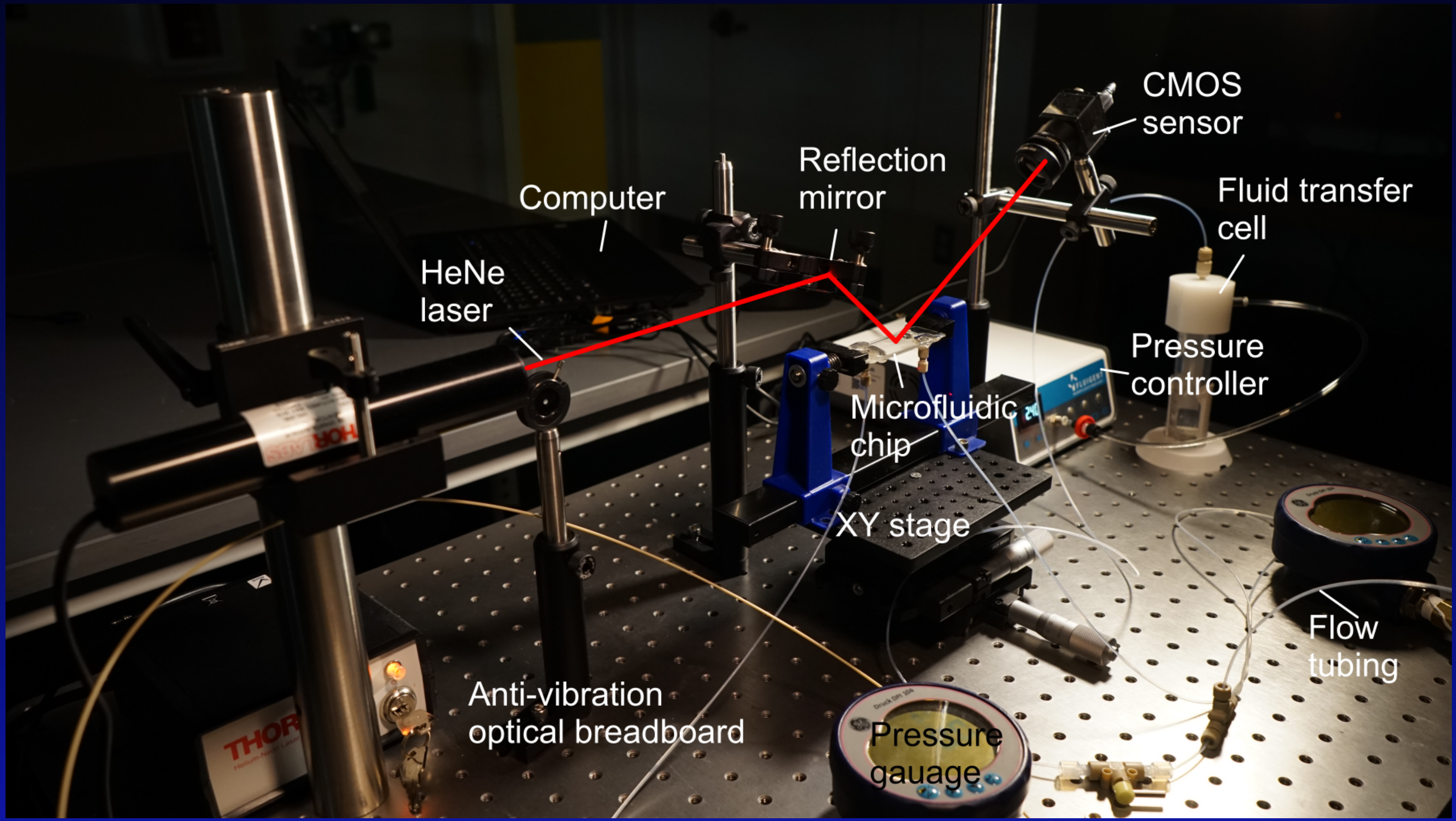


Figure: A photo of the laser interferometry laboratory setup used in this study.

LABORATORY PROCEDURE

INTEGRATION OF INTERFEROMETRY AND MICROFLUIDICS (CONT.)

- The pressure control system includes:
  - An automated pump.
  - Digital pressure gauges.
  - A back-pressure regulator.
  - An air compressor.
- In the future, fringe images will be processed using custom-built image processing algorithm.

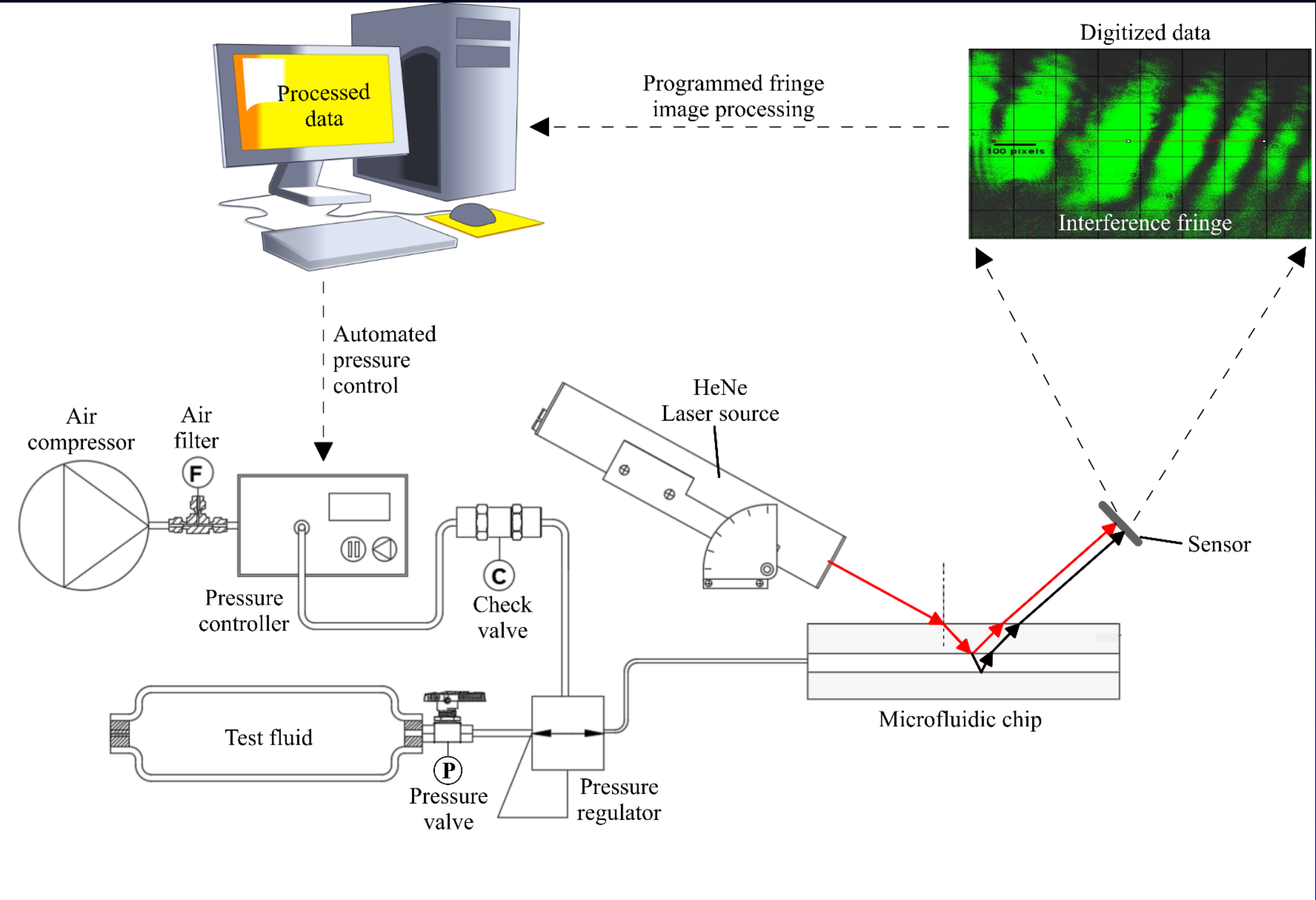


Figure: A simplified schematic of the laboratory setup.

AIR PRESSURE SENSING IN MICROFLUIDIC MODEL
INTERFERENCE FRINGE AND RAY-TRACE GEOMETRY

- The ray-trace geometry describes:
  - The propagation history of the reflected waves before and during pressurization of air in the microchannel.

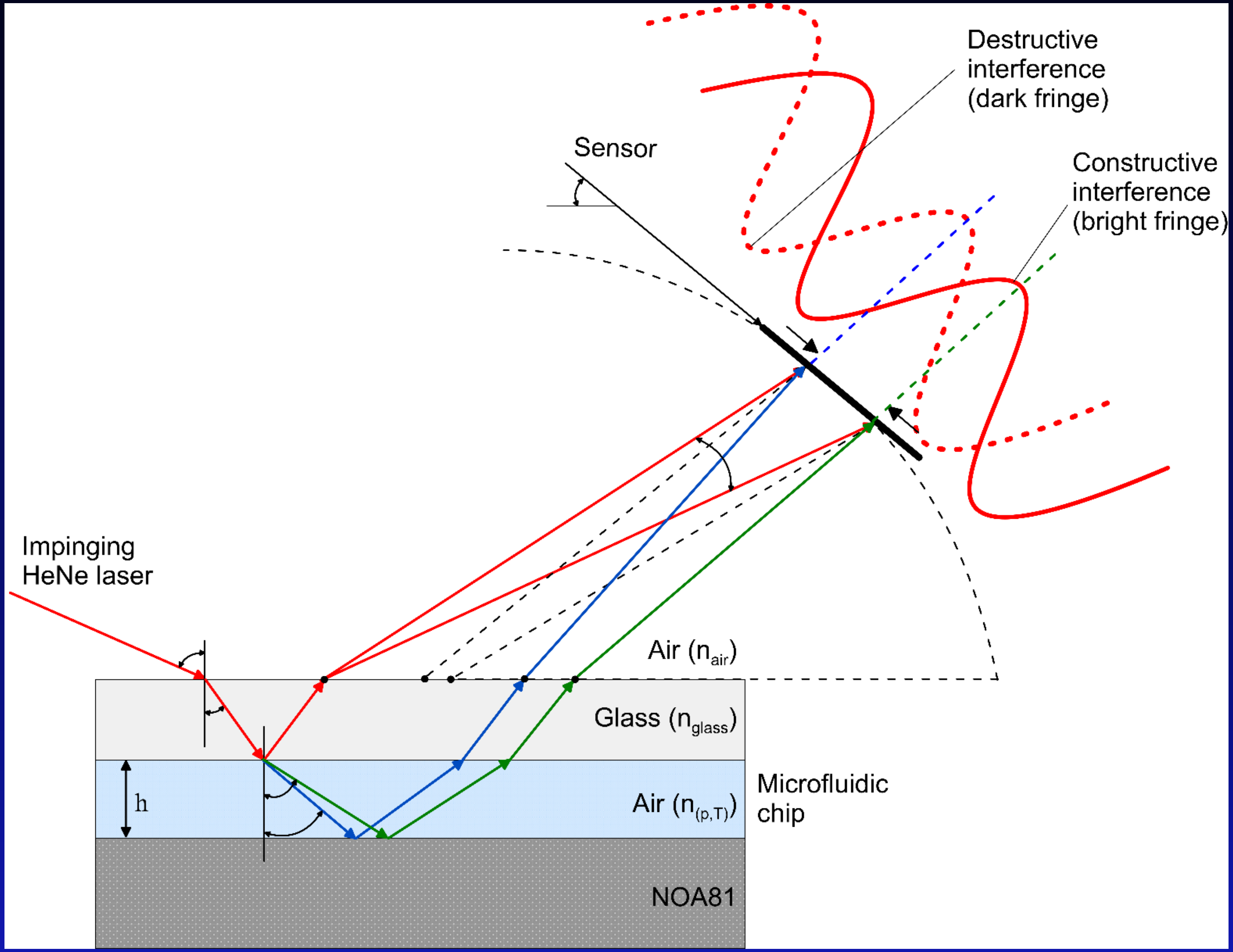


Figure: An exaggerated illustration of the laser interferometric ray-trace geometry.

AIR PRESSURE SENSING IN MICROFLUIDIC MODEL
ANALYSIS OF FRINGE MORPHOLOGY AND SHIFT

- Interference fringes were captured at **1-10 psi**:
  - Fringe images were processed by image processing software.
  - Images were grayscaled and thresholded.
  - Fringe shift was quantified using fringe intensity profiles.
  - Constructive fringes seen as bright green on black background.

- Interpretation of fringe intensity:
  - First fringe is reflected off external glass surface and 180° out of phase.
  - Other microchannel reflected fringes are reduced in intensity.
  - First in-phase fringe has highest intensity and width.
  - Fringe shift is estimated in pixel at the sensor.

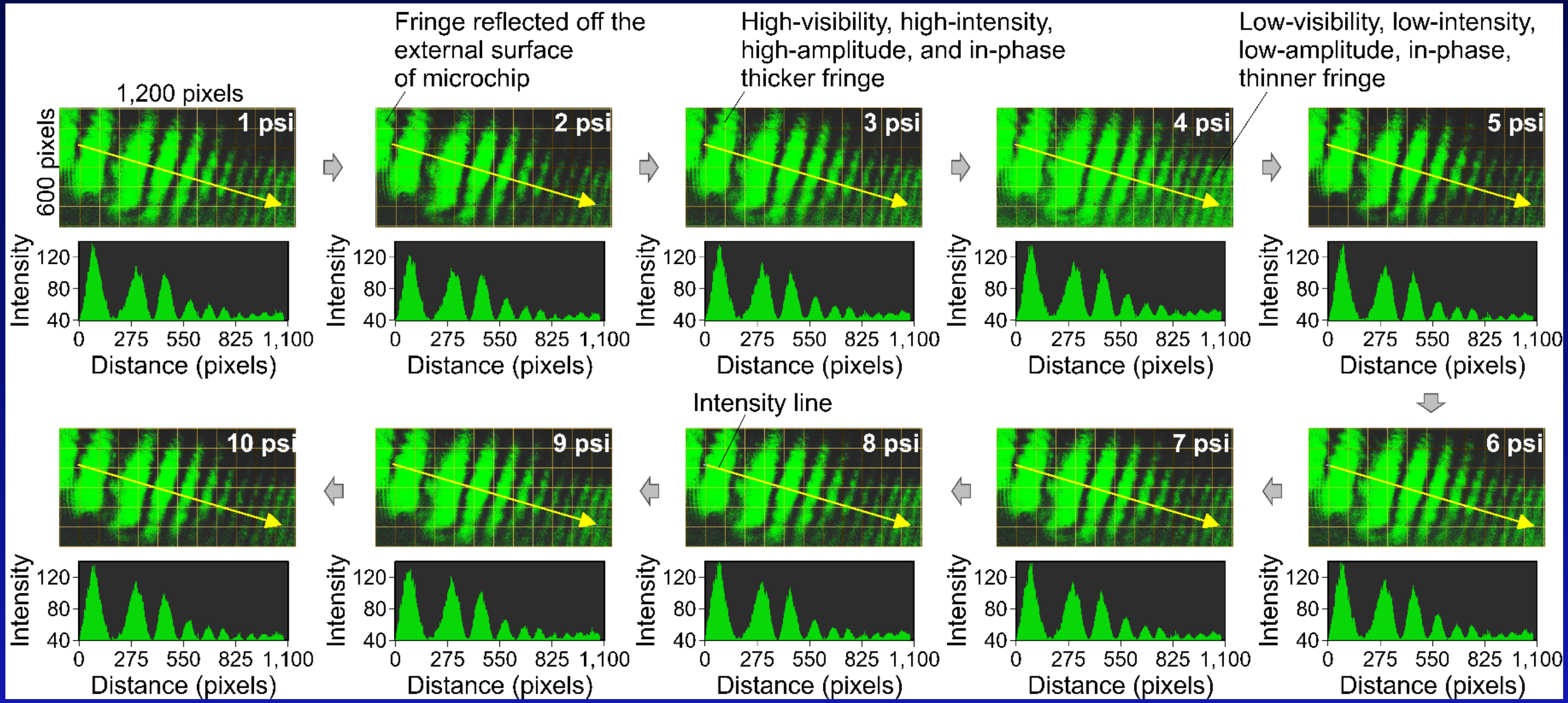


Figure: Analysis of air fringe images for fringe shift estimation.

EXPERIMENTAL RESULTS
DETERMINATION OF FRINGE PROPERTIES

- **Results:**
  - (Figure a-b) For 1-10 psi, fringe intensity and width decrease for all fringe indices along the forward arrow direction of the intensity profile line, and are largely unresponsive to the pressure change.
  - (Figure c) Fringe shift from one pressure to the next is fairly independent of pressure (about two pixels in average), except a small episodic spread.
  - (Figure d) Consecutive bright fringe peak distances from the first out of phase fringe change parabolically since the radial fringe spacing decreases away from the source.
  - (Figure e) The index of refraction increases with increasing air density.
  - (Figure f) Laser wavelength decreases with increasing pressure.

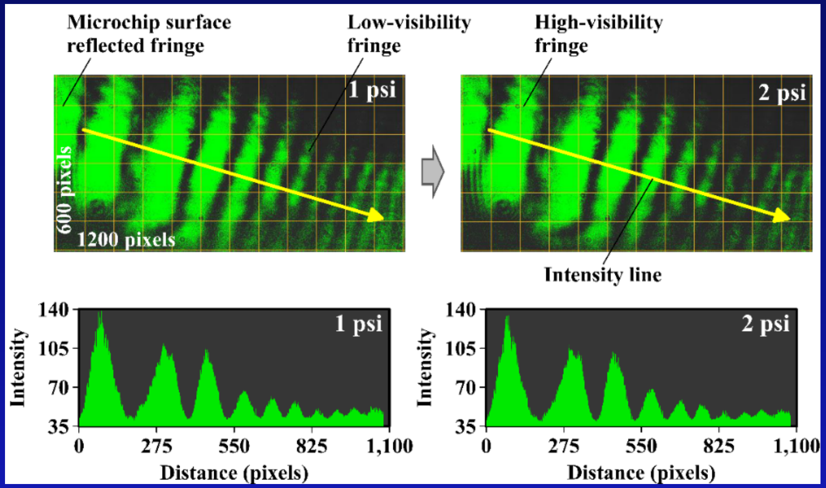
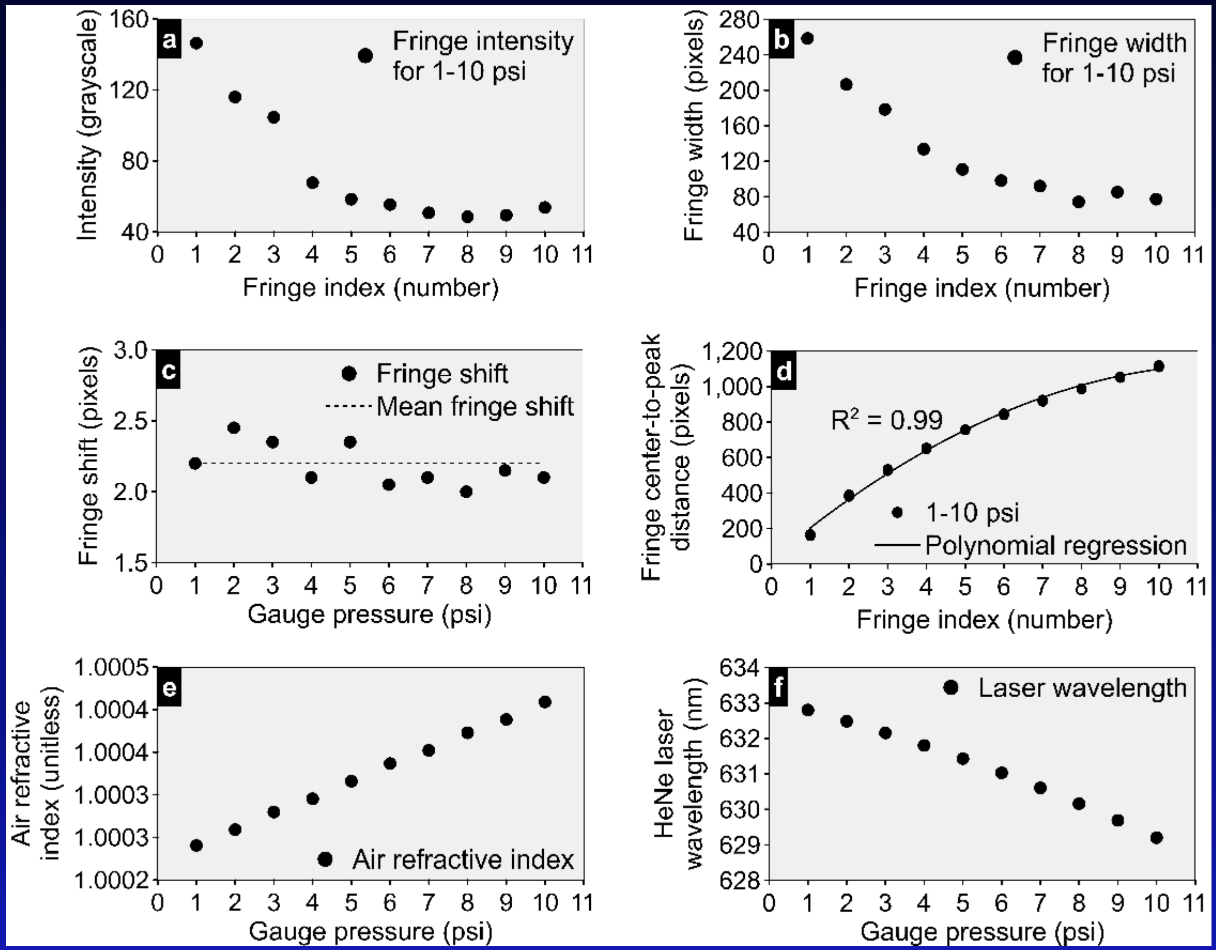


Figure: Observed fringe properties.



DISCUSSION

SENSING AIR PRESSURE VS. MEASURING AIR PRESSURE

- **Challenges** in the experimental observations:
  - **The decrease in fringe intensity** gives rise to successively thinner fringes.
  - **The fringe intensity varies** from the average value; thus, a need to target only a single fringe for fringe shift calculation purposes.
  - **Image processing software** cannot readily detect low-intensity fringes. However, fringe shift of the **highest intensity peak** can be reliably measured.
- Perspectives:
  - **As of now, we do not have a reliable mathematical theory** to relate fringe shift to fluid pressure.

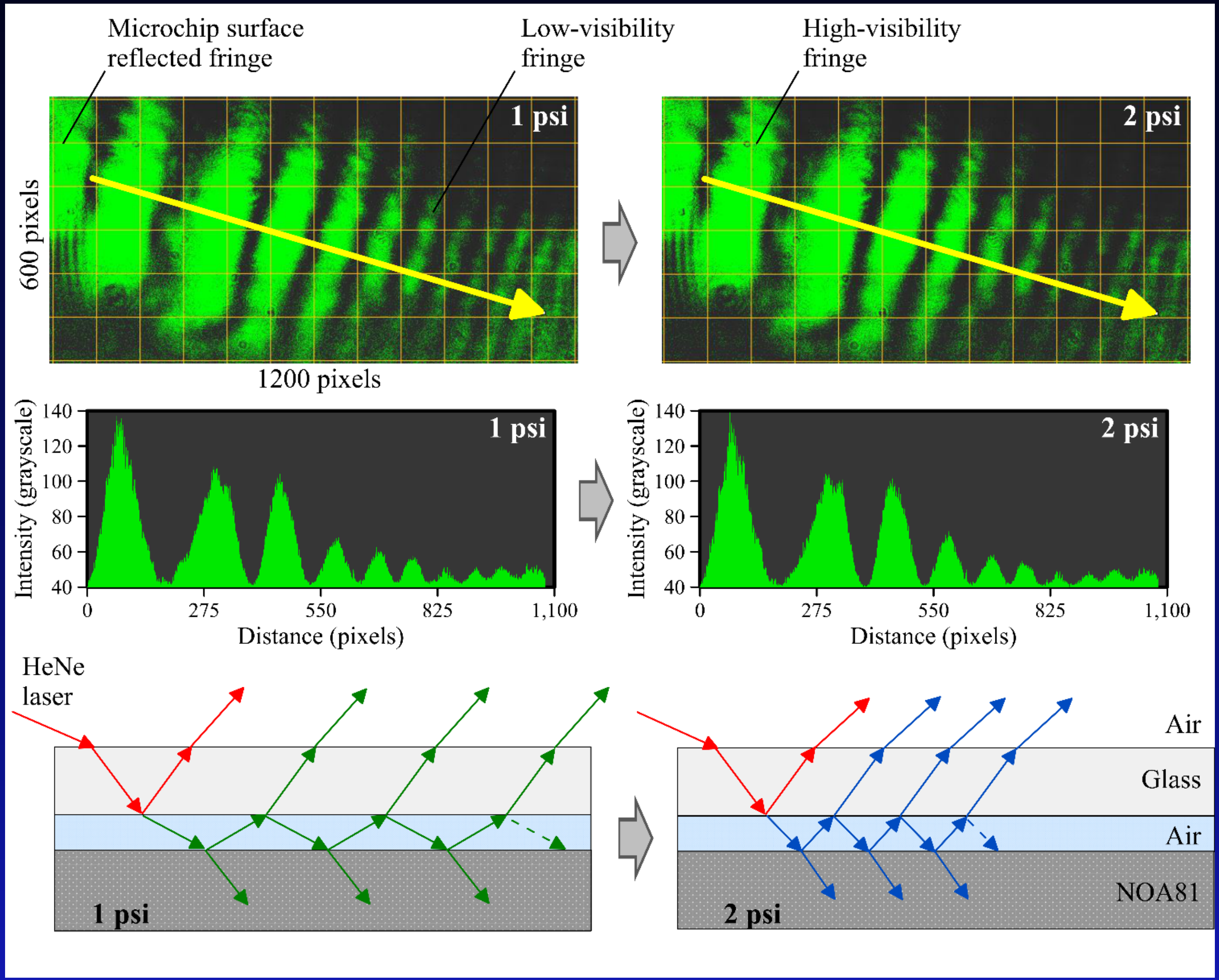


Figure: Analysis of air fringe images for fringe shift estimation.

DISCUSSION
MEASUREMENT REPEATABILITY

- Practices that have improved repeatability:
  - **Reducing microchannel wall deformation** with robust chip materials
  - **Eliminating backscattering** by making microchannel dimensions larger than the laser wavelength.
  - Incorporating an automated pressure control system that **minimized pump output fluctuations.**
  - **Incorporating anti-vibration breadboard.**

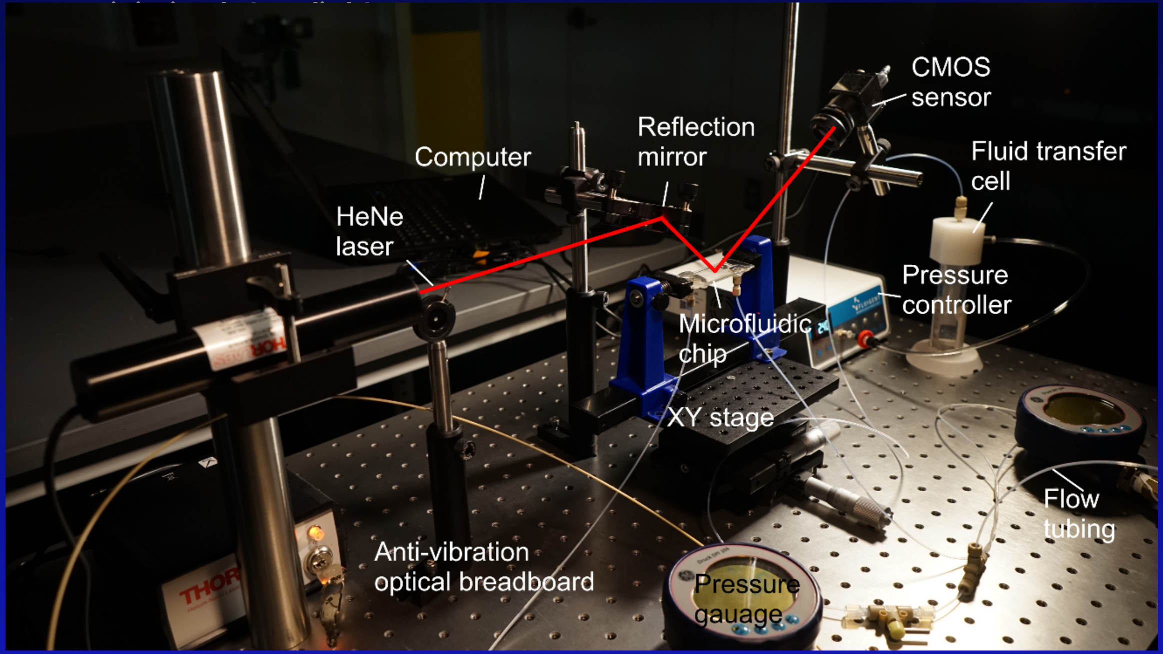
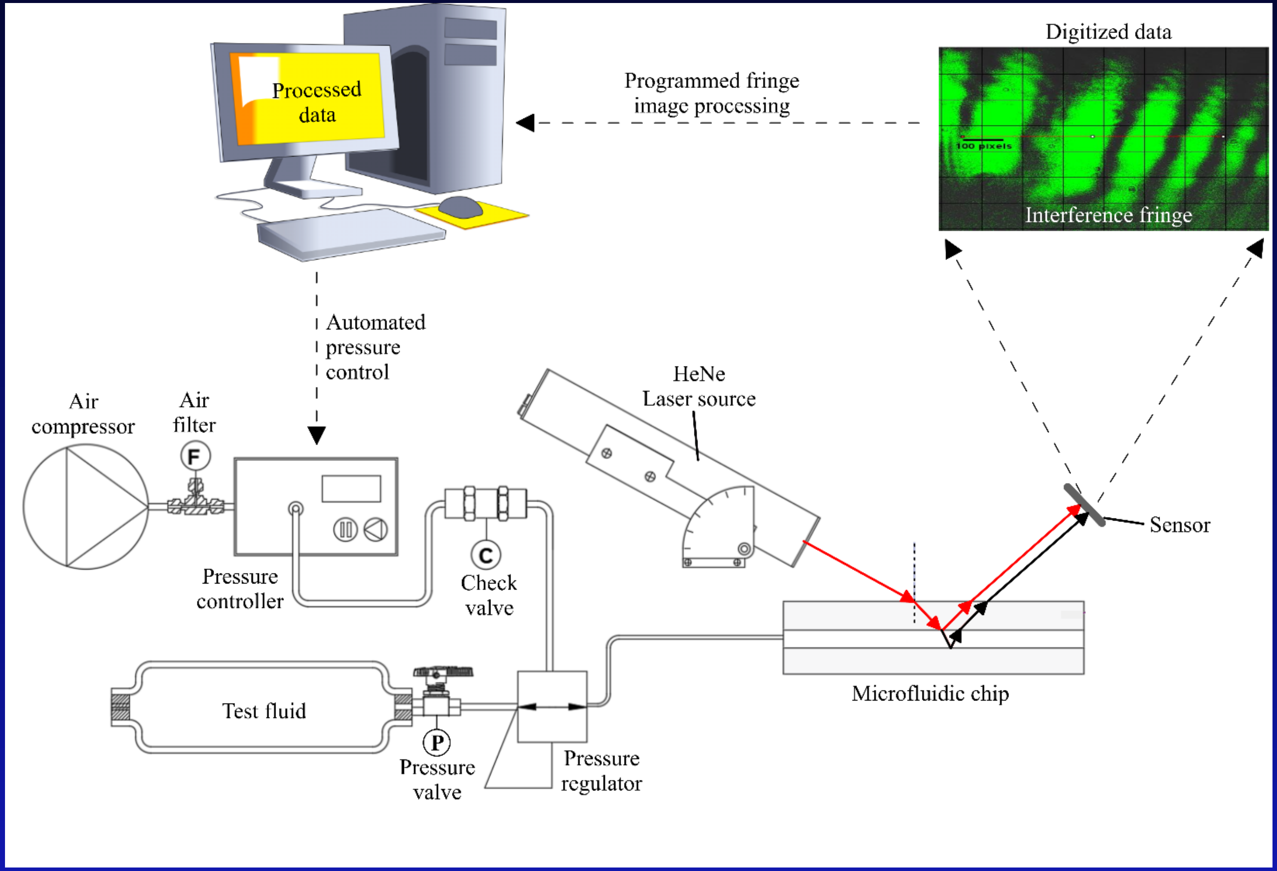


Figure: A simplified schematic of the laboratory setup.



CONCLUSION

- We presented a non-invasive, laser interferometry-based pressure-sensing procedure for use in measuring pressure in microfluidic chips.
- We established a verifiable relationship between optical interference and fluid properties in a microfluidic device.
- We identified that fringe shifts, resulting from air pressure change, can be detected; however, many critical challenges remain.
- Our proposed technique is a novel method to detect fluid pressure in micrometer pores, useful for thermodynamic phase shift analysis of fluid(s).

ACKNOWLEDGEMENT

We thank

- The Unconventional Reservoir Engineering Project (UREP) Consortium at Colorado School of Mines.
- The US Department of Energy: Award Number STTR DE-SC0017941.

Thank you