MINIATURE AND MICRO-DOPPLER SENSORS

by

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Abstract

Recent advancement has resulted in the miniaturization of laser Doppler sensors for the measurement of flow velocity and wall shear stress. In particular, the design and the performance of a Miniature laser Doppler anemometer, a miniature particle sizing sensor, and an optical shear stress sensor based on micro-optical electromechanical systems (MOEMS) is reviewed.

The Miniature LDA (See Figure 1) uses a diode laser, diffractive optical element and miniature optics resulting in a rugged, small and self- contained backscatter LDA with frequency shifting. It has a fixed probe distance, and except for a rotating diffraction grating, has no moving or adjustable parts. It has a dimension of 50 mm in length and 25 mm in diameter. Sensors with different fringe sizes and sensor f-numbers have been fabricated.

By incorporating a second laser and modifying the collection optics of the miniature LDA, a miniature particle sizing probe for spherical and non-spherical particles was fabricated. The particle sizing is achieved by the "IMAX" technique. The sensor is capable of sizing particles from a micron to 100's of microns. The dynamic range is limited by the dynamic range of the linear or log detector. Addition of a second detector allows the sensor to measure droplet size using the "Phase Doppler" technique.

Further miniaturization of the laser Doppler sensor was achieved by the fabrication of integrated optics on a single substrate. Micro-Devices technology was used for the integration of curved diffractive optical elements on a single substrate. As an initial demonstration of the technology, an optical shear stress sensor was fabricated. In this sensor, four optical elements were printed on a single silicone substrate. Using a diode laser, an optical fiber, and the substrate, an optical shear sensor was fabricated. The sensor has a dimension of 15 mm in diameter and 20 mm in length.

Figure 1. Photograph of a miniature laser Doppler anemometer.

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INTRODUCTION

Laser Doppler anemometry (LDA) has been in use as a research tool for over three decades. Since its inception in 1964 (Yeh and Cummins, 1964) the LDA technique has matured to the point of being well understood and, when used carefully, providing accurate experimental data. LDA's unique attributes of linear response, high frequency response (defined by the quality of the seed particles) and non-intrusiveness have made it the technique of choice for the study of complex multi-dimensional and turbulent flows (Modarress and Johnson, 1979, Lemann et al., 1996). It has also been modified for use in multi-phase flows (Modarress and Tan, 1983), particle sizing (Bachalo, 1980), remote sensing (Dopheide et al., 1990), and wall shear stress measurement (Naqwi and Reynolds, 1987) to cite a few examples. Advancement in the areas of laser performance, fiber optics and signal processing has enhanced the utility of the technique in the fluid mechanics and related research areas.

The overall configuration of LDA systems has, however, not been altered over the period of its existence and as such, its use has been limited to laboratories, experimentally unique events and a modest number of industrial applications. To expand the utility of the LDA to many other applications with a need for speed measurement, we need to develop Doppler-based sensors that are smaller, integrated, easier to use and less expensive. The results of our on-going efforts in this direction are briefly described here.

The miniature-LDA

The miniature LDA[3] sensor developed by the authors is the precursor to the micro-systems under development. An example of the mini-LDA is shown in Figure 1. The optical head contains the light source, miniature optics, receiving optics and detection system. In our present design, the diode laser does not require temperature stabilization. This portable device works in backscatter mode with a probe volume distances from 3 to 12 cm. The sensor includes frequency shifting. Figure 2 shows the calibration data for the LDA sensor. The frequency shift has a range of 10 KHz to 10 MHz. The overall dimension of the sensor head is 3 cm in diameter and 5 cm in length. Except for frequency shifting mechanism, it has no moving parts and requires no on-site alignment and calibration.

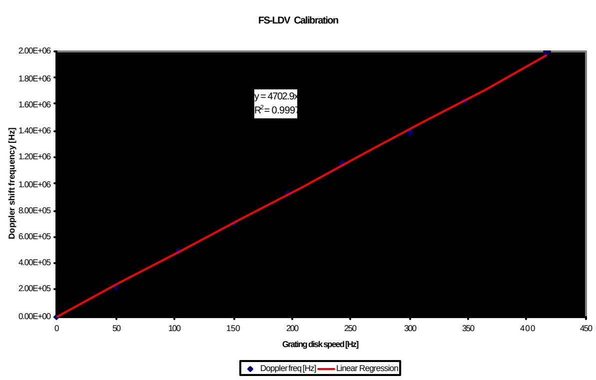

Figure 2. Frequency shifting calibration data

The micro-LDA

Efforts are under way to develop and fabricate LDA transmitters/receivers[1] using MOEM technology. A preliminary design of an LDA transmitter is shown in Figure 3. The substrate has a dimension of 5 x 10 mm^2. The light exiting from a single mode fiber or an embedded laser is allowed to diverge on a beam splitter. The light diverges beyond the beam splitter onto curved gratings. The curved gratings direct the light upward away from the substrate and focus the beams. The beams intersect at their waist forming a fringe pattern.

[3] Patent pending

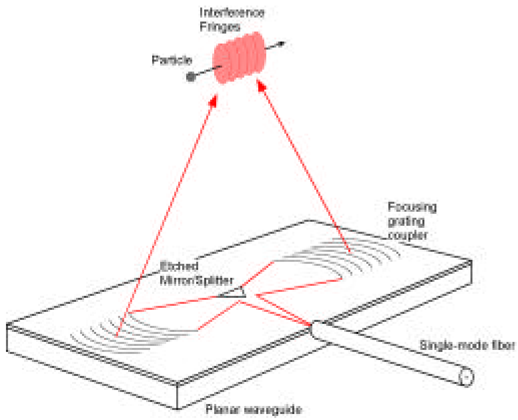

Figure 3. Conceptual design of the integrated optics micro-LDA.

As a proof of concept, a first generation of the micro-LDA transmitter is in the fabrication phase. A schematic of this first generation LDA is shown in Figure 4.

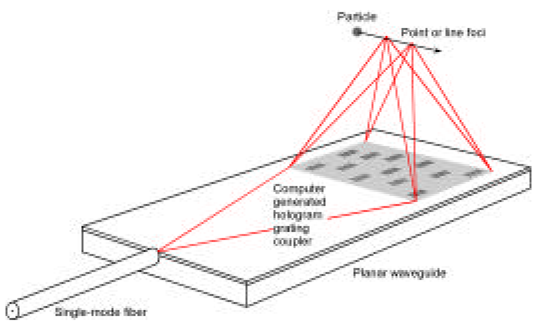

Figure 4. Time-of-flight device under fabrication.

This transmitter is designed to produce two spots (fringes) and as such can be treated as a time-of-flight device. The light output of a single-mode fiber is allowed to diverge onto a computer-generated hologram grating coupler. The grating coupler diffracts the incident light into two focal points in space. For practical applications, the autocorrelation of the detector signal (not shown) is processed for instantaneous measurement of velocity component. Figure 5 shows a modeling of the optical pattern generated with the hologram. The high intensity regions are 400 microns long and 10 microns wide. The two spots are approximately 60 microns apart.

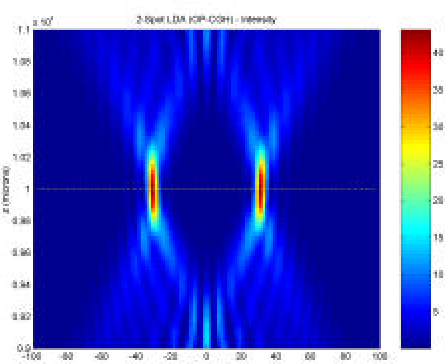

Figure 5. Modeling results of the fringe pattern generated by computer-generated-hologram grating coupler.

Wall shear stress sensor[4]

This diffractive optical micro-sensor generates a diverging fringe pattern within the first few hundred microns of the wall. Close to the wall, the velocity gradient is linear, $u ? ? y$, where u is the velocity, $?$ is the shear stress, and y is the vertical coordinate. Our diffractive optical micro-sensor generates a linearly diverging fringe pattern as illustrated in Figure 6. The fringe spacing can be expressed as $? ? ky$, where k is slope of the first non-vertical fringe.

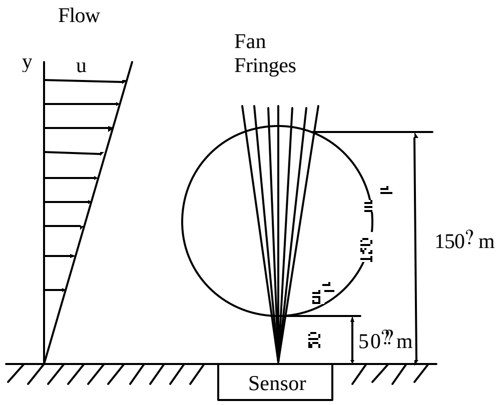

Figure 6. Schematic of the shear stress sensor principle.

As particles in the fluid flow through the linearly diverging fringes, they scatter light to a detector with a frequency f that is proportional to the instantaneous velocity and inversely proportional to the fringe separation at the location of particle trajectory, $f ? u / ?$. Using the relations for u and $?$ above, the measured frequency is directly proportional to the wall shear,

$$f ? \frac{? \ y}{k \ y} ? \frac{1}{k} ?$$

Knowing k from the geometry of the optics, the measured frequency directly provides for the gradient of the velocity at the wall. The signal conditioning and processing required for the shear stress sensor is identical to those used for standard LDA instrument. This technique was first presented by Naqwi and Reynolds(2) with conventional optics.

1. Design and modeling

A conceptual drawing of the micro shear stress sensor is shown in Figure 7. The diverging light from a diode laser is focused by a diffractive optical element (DOE) to two parallel line foci. These foci are coincident with two slits in a metal mask on the opposite side of a quartz substrate. The light diffracts from the slits and interferes to form linearly diverging fringes to a good approximation. The light scattered by particles traveling through the fringe pattern is collected through a window in the metal mask. Another DOE on the backside focuses the light to an optical fiber connected to a detector.

[4] Patent pending

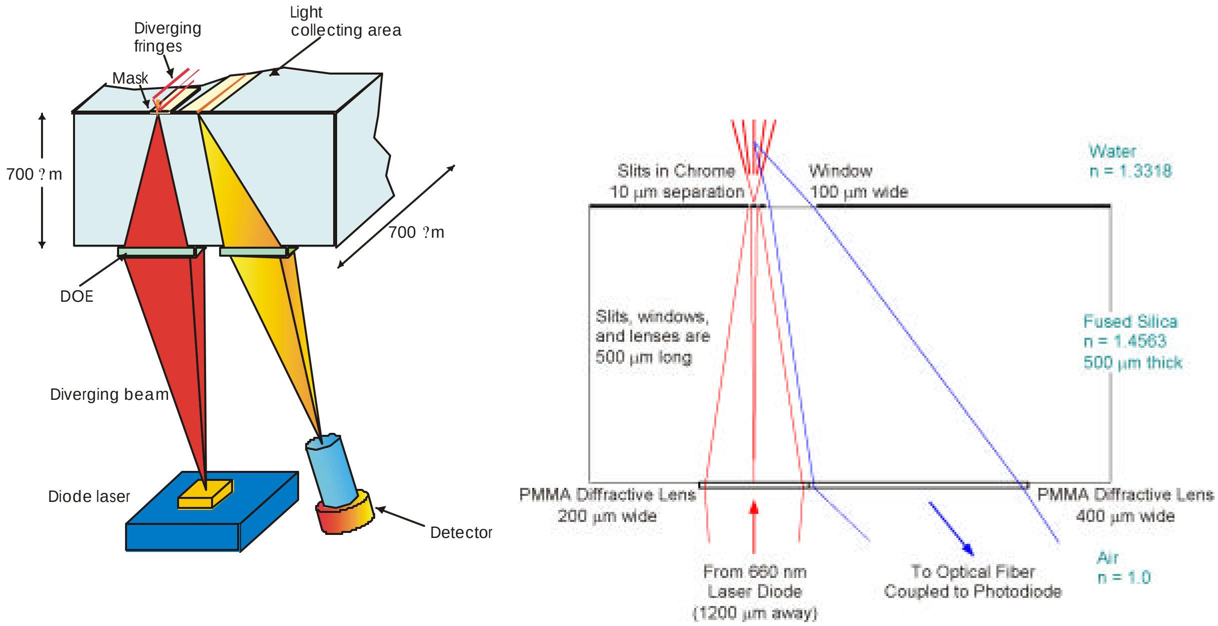

Figure 7. Schematic of the shear stress sensor assembly.

A series of simulations were performed to aid in the design of the sensor. A finite-difference simulation of the fringe pattern for 2 ?m wide slits separated by 10 ?m is shown in Figure 8. The fringe pattern displays a suitable number of fringes for adequate measurements. The number of high-contrast fringes is determined by the slit width and the divergence of the fringe pattern is determined by the slit separation.

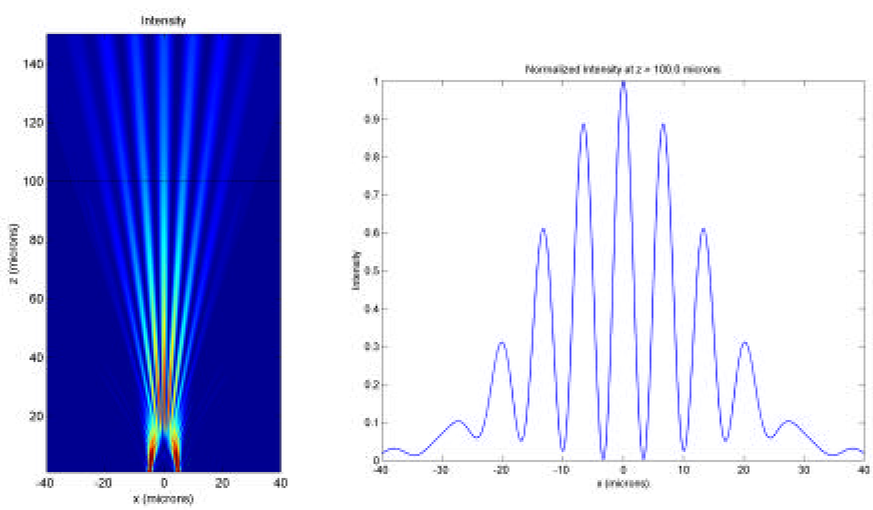

Figure 8. Fringe pattern resulting from 2 ? m slits separated by 10 ? m (propagation of a finite-difference solution of slit diffraction when illumined by the dual-line-focus laser lens).

2. Fabrication and testing

The main sensor element was fabricated by two-sided lithography on a 500 ?m thick quartz substrate. The slits and collecting window on the front were fabricated by direct-write electron-beam lithography followed by wet etching of evaporated chrome. The polymethyl methacrylate (PMMA) diffractive optical elements on the back were fabricated by analog direct-write electron-beam lithography followed by acetone development (Maker et.al., 1996). A photograph and atomic force microscope scan of the dual-line focus-laser lens are shown in Figure 9.

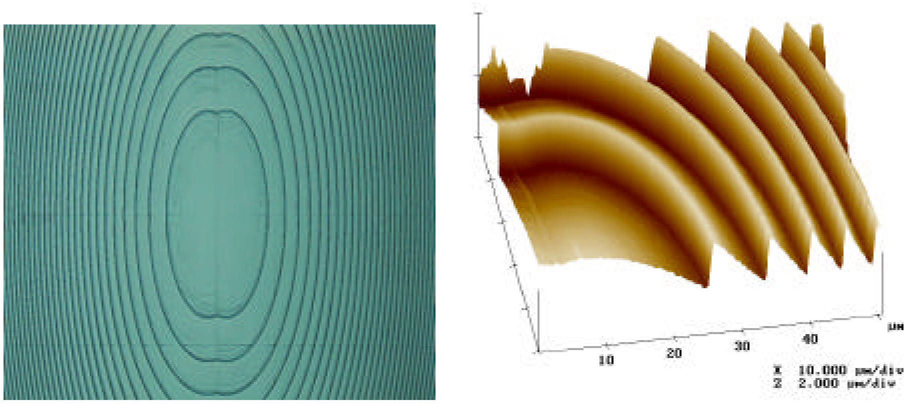

Figure 9. Photograph (left) and AFM scan (right) of the center of the dual-line-focus laser lens

The shear stress sensor's elements were assembled into a package with a diode laser (660 nm) and a port for the collection fiber. The overall size of this prototype is 15 mm in diameter and 20 mm in length. A photograph of the shear stress sensor is shown in Figure 10.

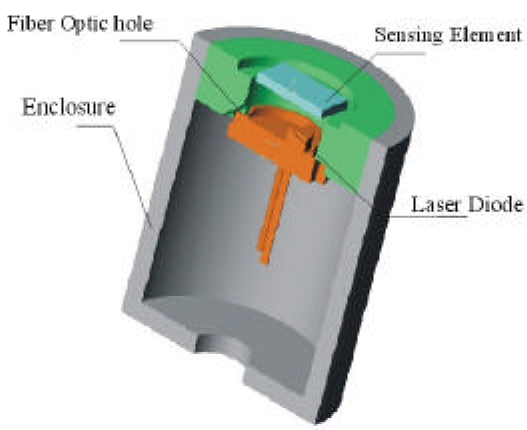

Figure 10. Shear stress sensor assembly.

The fringes were imaged with a CCD camera using a microscope objective and are shown in Figure 11. The fringe divergence was measured to be linear with a slope in close agreement with theory. The contrast is very satisfactory and preliminary tests using a moving surface through the fringe pattern yield a clear signal. Testing of the receiver side of the sensor element is currently underway.

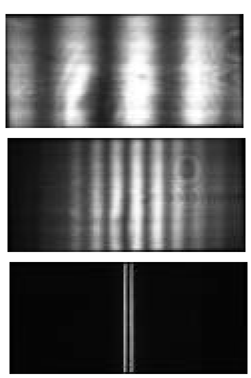

Figure 11. Photographs of the fringes at different heights above the surface.

Particle sizing

A particle sizing device based on the mini-LDA with an associated scattering intensity measurement known as the Imax method has been developed. Photograph of the sensor head and sample traces are shown in Figure 12. This probe measures both the speed and the size of the particles. The particle sizing for non-spherical particles is based on the "Imax" technique (Hess, 1985). It uses a third laser beam, co-located with the LDA probe volume. The peak intensity is recorded only during a successful detection of a Doppler burst. The device is 10 cm long and 3 cm wide.

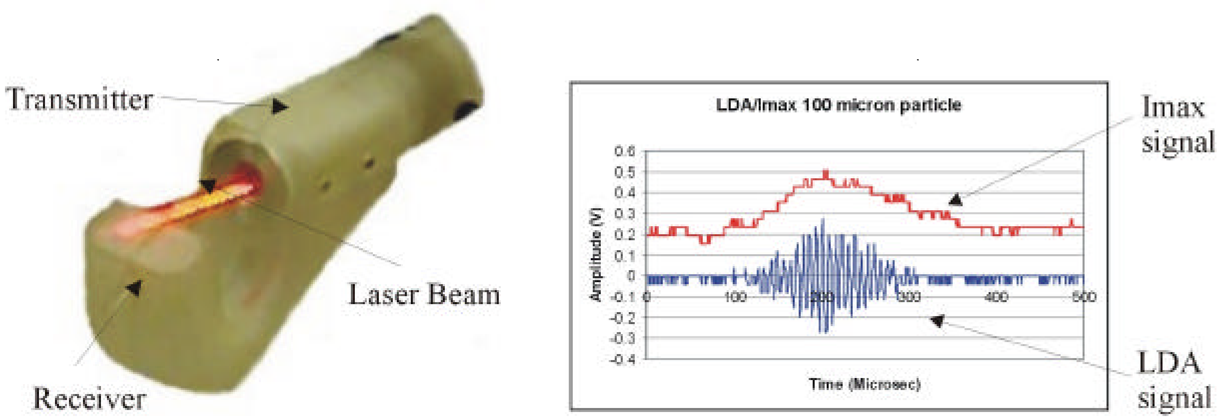

Figure 12. Particle sizing device and sample signal trace.

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