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Comprehensive Final Report for the Period 5/31/1998-5/30/2002

NAG3-2189: "Optical Electronic Bragg Reflection Sensor System with Hydrodynamic Flow Applications"

This project, as described in the following report, involved design and fabrication of fiber optic sensors for the detection and measurement of dynamic fluid density variations. These devices are created using UV ablation and generally modified transverse holographic fiber grating techniques. The resulting phase gratings created on or immediately underneath the flat portion of D-shaped optical waveguides are characterized as evanescent field sensing devices. The primary applications include the sensor portion of a real-time localized or distributed measurement system for hydrodynamic flow, fluid density measurements, and phase change phenomena. Several design modifications were implemented in an attempt to accomplish the tasks specified in our original proposal. In addition, we have established key collaborative relationships with Dr. Keith Jackson, Associate Director in the X-ray Optics Division of Lawrence Berkeley Radiation Laboratory at UC Berkeley, Dr. Donnell T. Walton, Senior Research Scientist at Corning Incorporated, and Dr. Giovannae Anderson of Agilent Incorporated, and, more recently, Lawrence Livermore Nat'l labs/U.C. Davis and Stanford University.

Final Objectives
(1) Fabricate a distributed sensor employing D-type fiber that will be capable of responding to quasi-static hydrodynamic fields (with a primary orientation toward fluid density and temperature sensing applications);

(2) Interface a tunable solid-state IR laser system for readout of a 5 to 20 point sensing unit. The sensor is to be incorporated into the inner surface wall of an ampoule in order to acquire dynamic fluid density readings with initial experiments demonstrating simple solution density fluctuations at a single location;

(3) Consider the placement of D-fiber Bragg sensors in NASA specified aerospace structure where the evaluation of hydrodynamic parameters is of interest and deliver sensing devices with readout specifications to Glenn Research Center (with necessary technical assistance),

(4) Use the resulting efforts and appropriate resources to increase the number of underrepresented minorities and women in the sciences by establishing current research topics and projects in which they receive encouragement to participate.

(5) Develop related technologies that are of possible use to the Microgravity and Fluids Branch or other NASA programs (where appropriate) assuming time and resources permit while maintaining the overall grant objectives.

Accomplishments
(1) In order to start the project, we prepared D-fibers for writing multiple gratings through the flat portion of their cladding. This included the development of fabrication

techniques involving repeatability in D-fiber orientation. The preparation of samples also included careful de-cladding of the fiber in the sensing regions and precise polishing of fiber-units with noise-suppressing inputs to less than .3 microns surface smoothness in their input/output regions.

(2) Our sensor designs use a narrow linewidth laser to demonstrate the capability of wavelength tuning to achieve nulled outputs (for periodically perturbed evanescent field sensors). In addition, we established reliable analytical systems to characterize the wavelengths, linewidths, and reflectivities of these holographic gratings device.

(3) An empirical method for etching D-fiber samples to within several microns of their cores was devised due in-house theoretical calculations suggesting strong interactions only for physical patterns spaced within a few microns of the core. One such photomicrograph is shown at the end of this report.

(4) The University filed a patent entitled "Apparatus for and Methods of Sensing Evanescent Events in a Fluid Field" that incorporates techniques and models developed under this and other grants. This patent is presently pending and we anticipate its acceptance during the current year. Supplemental funding for further development of this technology has been acquired from DARPA. Finally, we have secured the assistance of Lawrence Berkeley Radiation Laboratory and their micro-fabrication facility as well as Lawrence Livermore Nat'l Lab as alternative micro-patterning facilities. These contacts have been made through Dr. Keith Jackson, Associate Director in the Center for X-ray Optics who uses e-beam lithographic methods and Dr. Kennedy Reed, Staff Physicist at LLNL.

(5) For completeness, a short theoretical excerpt is included at the end of this report exploring regions of applicability (liquid and gas phases) of the sensor using slight modifications of the original hydrodynamic design. A hydrodynamic sensors paper entitled "Design of Fiber Optic Sensors for Measuring Hydrodynamic Parameters", upon which the theoretical portion of this work is based, has been submitted to the xxx.lanl archives (lanl.arXiv.org) and is included with this report in PDF format. The work includes analytical solutions for a previously unsolved group of nonlinear integral-differential equations of the Navier-Stokes type describing the fluid dynamics for compressible and incompressible flow in the boundary layer of aerospace structures and will be subsequently submitted to a mainstream journal upon completion of the experimental verification.

(6) I have graduated the third of my Ph.D. students, a former **NASA Glenn GSRP Fellow**, who is an African-American female and who is recently completed a **Post-Doctoral Fellow** position (as well as a **Merck Fellow**) in the Department of Chemical Engineering at California Institute of Technology. Her current position is a **Senior Process Engineer** at **Intel Corporation**. Her Ph.D. thesis was entitled "A Novel Fiber-Based Refractive Index Sensor".

(7) The short theoretical excerpt, at the end of this report exploring regions of applicability (liquid and gas phases) of the sensor using slight modifications of the original hydrodynamic design, is extracted from a Masters thesis entitled "Design of Fiber Optic Sensors for Measuring Hydrodynamic Parameters". This student, partially supported under this grant, derived analytical solutions for a previously unsolved group of nonlinear integral-differential equations of the Navier-Stokes type describing the fluid dynamics for compressible and incompressible flow in the boundary layer region of the fiber optic sensors developed during this research.

(8) Additionally, we published a paper entitled "Realization of a Bragg Reflection Filter Wavemeter" describing our automated UV/VIS double interferometer comparator for writing highly predictable fiber filters. This device was introduced to the public as the singular metrological standard for fiber gratings allowing Bragg grating-based dense wavelength division multiplexing (DWDM). The paper made the November 1, 2000 **Front Cover** of Applied Optics

(9) Our paper entitled "Modeling and Observations of Phase Mask Trapezoidal Profiles with Grating-Fiber Image Reproduction" was also featured on the **Front Cover** of the March 1, 2000 issue of Applied Optics. The paper details the modeling and experimental evaluation of commercial phase masks and has 2 associated patents for phase mask optimization and cost reduction.

Summary of Our Research
(1) Certain experimental designs employing both a narrow linewidth tunable laser and the Bragg grating Wavemeter were chosen due to their usefulness for creating multi-point fiber sensors for the measurement of fluid densities. These D-fiber based devices are included in the Fluid Sensor patent. All are non-intrusive and several are non-fragile allowing their insertion into tight spaces without breakage. The original physically patterned device has been included in the patent but was not used for this project due to its limited ability to endure bending. The several details of these designs are included in this report with their implementation to occur at a future date.

(2) Small-scale chemical species detection studies have continued in cooperation with Dr. G. Y. Yan at Stanford and have resulted in the development of simple non-intrusive fiber optic probes. We have solicited funding from DARPA and the EPA for non-intrusive remote chemical sensors based on this and other related fiber technologies.

Principles of Optical Sensor Operation
In a single fiber and for certain optical configurations holographic gratings act independently to reflect a predetermined number of wavelengths at preset static amplitudes. The dynamic amplitude and the wavelength of the reflections are proportional to the induced strains and strain locations respectively. The sensor responses to hypersonic flow conditions are related to the induced periodic boundary conditions imposed on the D-fiber structure during the fabrication process whereby its light throughput is dynamically governed by Bernoulli conditions for the pressure above and within the boundary layer. Thus, the ensuing relationship between pressure and fluid

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density within the boundary layer affect the evanescent field coupling between the guided and unguided modes of the fiber. Consequently, for a filter of nearly 100% reflectivity, small deviations away from the null imply related pressure differentials.

During the course of the funding we completed building a prototype for multiple sensor fabrication. This prototype consists of a high resolution, automated writing system containing a double interferometer setup (one visible and the other UV). A schematic of the actual prototype is shown in Figure 2. This device allows registration of large numbers of evenly spaced gratings in samples such as our distributed Bragg sensors planned for the next funding cycle.

Summary Information for Optical Hydrodynamic Sensors Theory:

The modeling developed during this grant uses geometric perturbations in an optical fiber to induce coupling between modes that are sensitive to the external optical properties of the local environment. The parameters investigated were optimized to emphasize the sensor sensitivity in particular desired nominal ranges, especially with regards to chemical species concentrations and measurable hydrodynamic properties. Since the sensors were designed to be ultra-sensitive, the resultant structure permits sufficient flexibility for tuning within a range of sensed parameters and environmental factors. Several variables were explored with regards to developing the most efficient devices. Geometrical variables include the size and shape of the sensors, as well as the geometrical corrugation parameters. The desired range of optical measurements significantly affects the required material properties of the sensor, as well as the qualitative behavior of its responses. Use of a tunable laser to drive the device considerably enhances the flexibility and range of usefulness of a given sensor. At the present, several designs have been developed which demonstrate the desired ultra-sensitivity and tunability within various optical ranges. The computational effort determined optical modes and couplings within a given geometrical design.

We have developed equations that approximate the behavior of viscous fluid flow within the boundary layer in order to parameterize the optical properties of the fluid and develop suitable sensor designs. The effort involved examining the Navier-Stokes and continuity equations and developing a boundary layer differential-integral equation which was defined in terms of a parameterizable viscous flow which approaches laminar flow outside of the boundary layer. Analytic equations were develop for the flow velocity and fluid density expanded in terms of the ratio of the transverse coordinate to the boundary layer thickness $y/\delta(x)$ and small variations in the boundary layer thickness $d\delta/dx$. These direct expressions of the flow fields and densities permit the investigators to optically model the sensors more directly without the need of excessive numerical computations, and provide a more intuitive feel for the required design parameters.

The design of a sensor, which would perform a direct optical measurement of the optical parameters of the flow field, required a representation of the optical density of the hydrodynamic system. The optical density is related to the fluid density to the order needed by the expression

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$$n = 1 + \beta \frac{\rho}{\rho_o}$$

where for instance β is of the order of 0.0003 for nitrogen gas. Near the sensor surface, the density has been found to satisfy the equation

$$\rho(x,0) = \rho_\infty \left[1 - \frac{3}{4} \frac{u_\infty}{c} \frac{\Lambda_o}{x} \right] \quad where \quad \Lambda_o = \frac{\eta}{\rho_\infty c}$$

In these equations, ρ_∞ and u_∞ represent the density and flow field far from the flat sensor (outside of the boundary layer), c represents the speed of sound in the far region, η the viscosity, and Λ_o is a characteristic length associated with the viscous flow. A sensor that will directly measure the optical properties at a position x along the flow will therefore require a resolution given by

$$\frac{\delta n}{n} \approx -\frac{3}{4} \beta \frac{\Lambda_o}{x} \frac{\delta u_\infty}{c}$$

Substitution of values for the desired hydrodynamic systems gives direct design constraints for the optical sensors. For example, in air at $0^{\circ}C$ the constant Λ_o has the value 40 nanometers, in air at 25°C we find that $\Lambda_o = 45$ nanometers while in water at 25°C, Λ_o has a value given by $\Lambda_o = 0.6$ nanometers and in water at 100°C $\Lambda_o = 0.2$ nanometers. Direct measurement of optical property changes due to speed variations will therefore be difficult, both because of the size of the opto-mechanical coupling β as well as the requisite proximity to flow onset for the presently available optical sensitivity. Coupled mode optical sensors have been designed which can theoretically measure relative optical variations on the order of 0.01% to 1%, which is not sufficient for direct optical speed measurements in most systems of interest.

The design of a less direct shear stress sensor requires the calculation of the flux of the stress tensor

$$T_{jk} = \rho v_j v_k + P \delta_{jk} - \eta \left(\frac{\partial v_j}{\partial x_k} + \frac{\partial v_k}{\partial x_j} - \frac{2}{3} \delta_{jk} \vec{\nabla} \cdot \vec{v} \right) - \xi \delta_{jk} \vec{\nabla} \cdot \vec{v}$$

For the rectangular sensor design with length L and width w, the calculated stress force is given by

$$f_x = -\frac{3}{2} \rho_\infty u_\infty^2 w \sqrt{\frac{13}{70} \Lambda L}$$

The effect was predicted to be sufficient to measure using available Bragg gratings, and has been experimentally observed by the investigators.

Finally, the dominant alternate sensor design is shown in the diagram below. The detector's response is related to dynamic fluid index changes in the region of interest via the amount of back-reflected light.
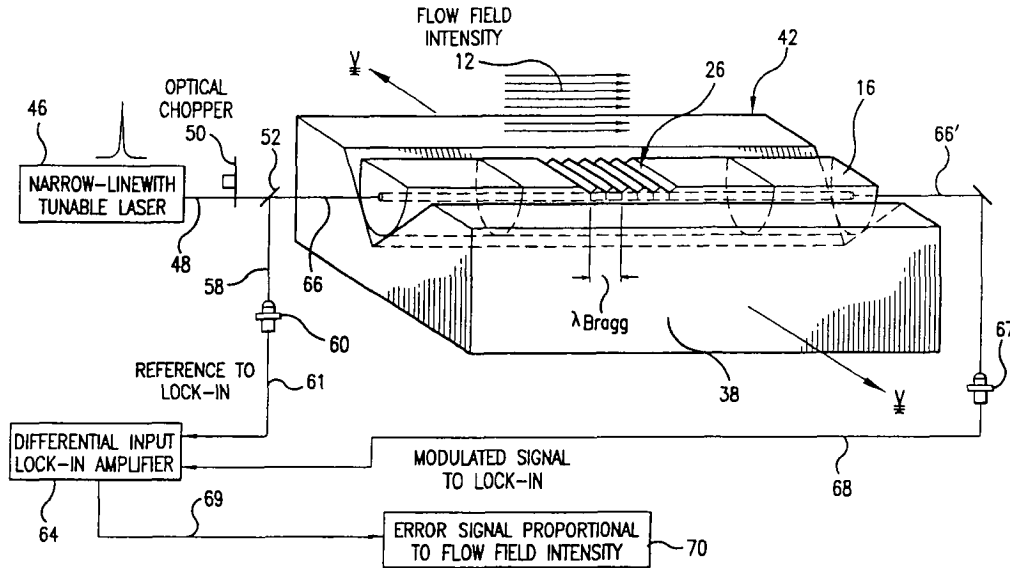

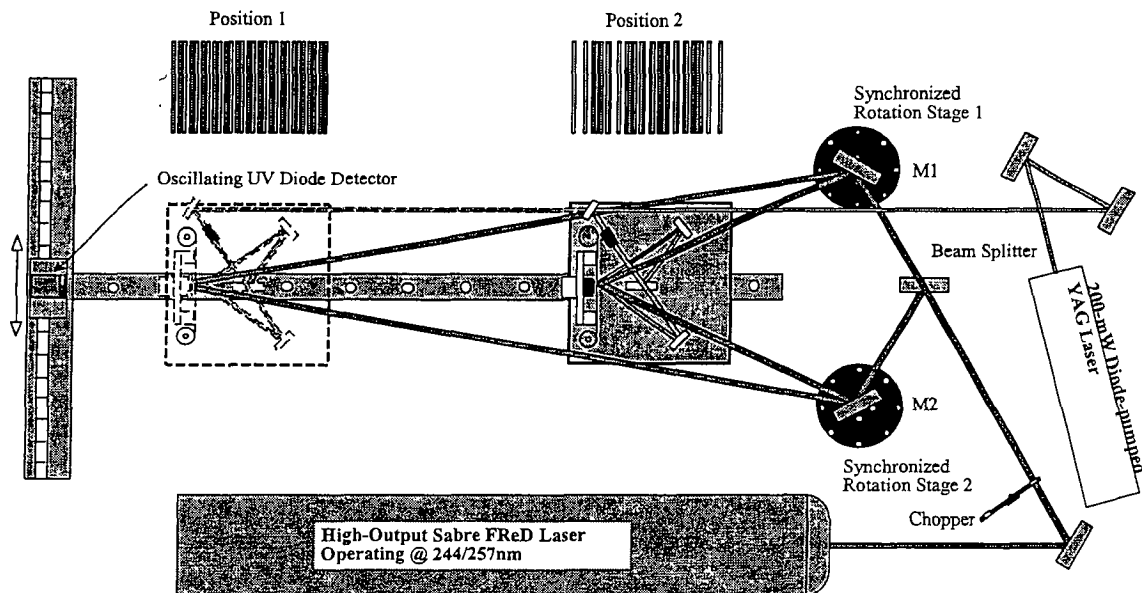Figure 1. Version 1 of the fluid density fiber optic sensor from Fluid Sensor patent

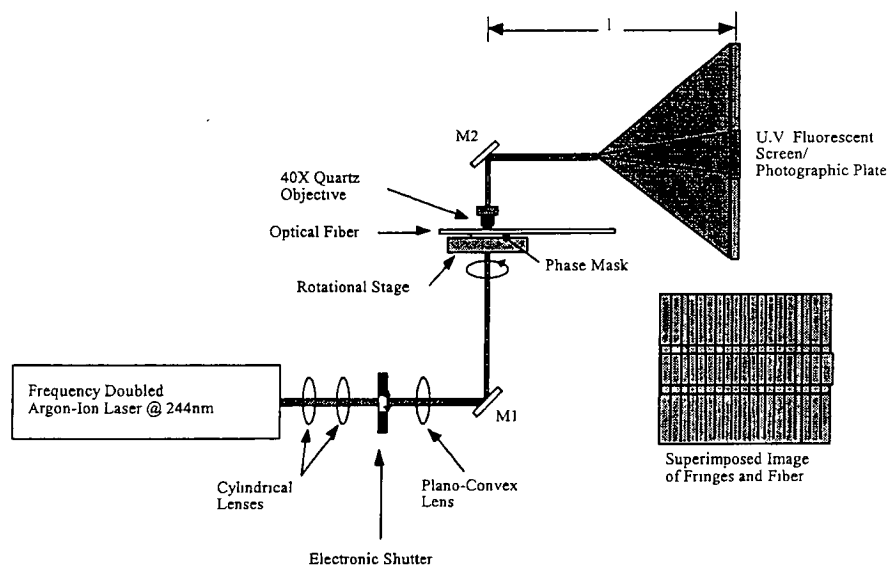Figure 2. Wavelength comparator full layout (Top View)

Figure 3. Experimental arrangement used to create UV ablated corrugations on top of D-fibers

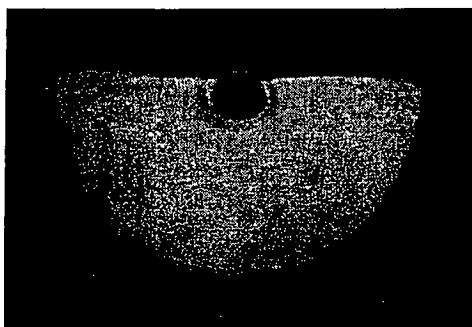Figure 4. Long coherence length excimer laser for ablating phase grating patterns on fibers

Figure 5. Acid-etched D-fiber used to enhance coupling of guided and unguided modes

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