Dual-Fiberoptic Microcantilever Proximity Sensor

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ABSTRACT

Microcantilevers are key components of many Micro-Electro-Mechanical Systems (MEMS) and Micro-Optical-Electro-Mechanical Systems (MOEMS) because slight changes to them physically or chemically lead to changes in mechanical characteristics. An inexpensive dual-fiberoptic microcantilever proximity sensor and model to predict its performance are reported here. Motion of a magnetic-material-coated cantilever is the basis of a system under development for measuring magnetic fields. The dual fiber proximity sensor will be used to monitor the motion of the cantilever. The specific goal is to sense induction fields produced by a current carrying conductor. The proximity sensor consists of two fibers side by side with claddings in contact. The fiber core diameter, 50 microns, and cladding thickness, 10 microns, are as small as routinely available commercially with the exception of single mode fiber. Light is launched into one fiber from a light-emitting diode (LED). It emerges from that fiber and reflects from the cantilever into the adjacent receiving fiber connected to a detector. The sensing end is cast molded with a diameter of 3-mm over the last 20-mm, yielding a low profile sensor. This reflective triangulation approach is probably the oldest and simplest fiber proximity sensing approach, yet the novelty here is in demonstrating high sensitivity at low expense from a triangular microstructure with amorphous magnetic coatings of iron, cobalt, permalloy, etc. The signal intensity versus distance curve yields an approximate gaussian shape. For a typical configuration, the signal grows from 10% to 90% of maximum in traversing from 6 to 50 microns from a coated cantilever. With signal levels exceeding a volt, nanometer resolution should be readily achievable for periodic signals.

1.0 INTRODUCTION

The development of microcantever-based sensors began with the atomic force microscope (AFM). In that application, a micron-scaled silicon cantilever (microcantilever) is moved across a surface and the interactions with the surface cause the microcantilever to deflect[1]. The rapid development and commercialization of this technology has lead to the commercial availability of microcantilevers mass produced by photolithography. These cantilevers are typically sold with several variations. The typical classifications of these microcantilevers are based on whether they are direct optical readout or piezoresistive and if they are fabricated from silicon nitride or silicon.

In the proper application these mass-produced microcantilevers can be used as the basis for a variety of sensors. [2-4] These microcantilevers have already been used to detect chemical species and infrared radiation. In most cases all that is required to make these cantilevers sensitive to different stimuli is a material coating. If the coating material is matched to the chosen stimulus then the motion of the microcantilever will show the changes made by the stimulus.

The goal of the present effort is the development of a magnetic field sensor by coating a magnetic material onto a silicon nitride cantilever and monitoring its motion as indicative of magnetic field strength and temporal dependence. In a laboratory situation, motion of the cantilever can often be detected by an optical beam deflection technique wherein path distances are on the order of a meter or more. While this is a very sensitive approach, such optical path distances are not viable in field deployable applications. Described here are initial tests of a simple method for determining microcantilever position or deflection that, while not as sensitive as the optical beam deflection, will be viable for some applications.

2.0 APPROACH

The main factor in selecting an optical approach for this effort is the potential for low cost. A variety of optical sensing approaches for sensing cantilever flexure were considered initially. Interferometric methods are generally the most sensitive since the light intensity is modulated by distance changes of half a wavelength. Fiberoptic Fabry-Perot sensors are commercially available; however, data acquisition and analysis requirements are sophisticated and render interferometric methods more expensive than simple reflective approaches. In addition, surface preparation and fixturing for the limited working distance are more critical. The experiments described here are for two optical fibers placed side-by-side. One fiber delivers light to the surface of interest and the other accepts the reflected light, transmitting it to an attached detector, such as a photomultiplier tube (PMT) or photodiode. This general scheme is several decades old [5,6] but it is important to demonstrate it for the microcantilever application. A microcantilever will intercept a small fraction of the emitted light. The reflected light from this interception will be dependent on nonuniform and nonspecular reflection properties of the surface as well as the distance between the sensor the reflective surface. Figure 1 shows the geometry. Light is launched into one fiber from a LED. It emerges from that fiber and reflects from the cantilever surface into the adjacent receiving fiber connected to a detector.

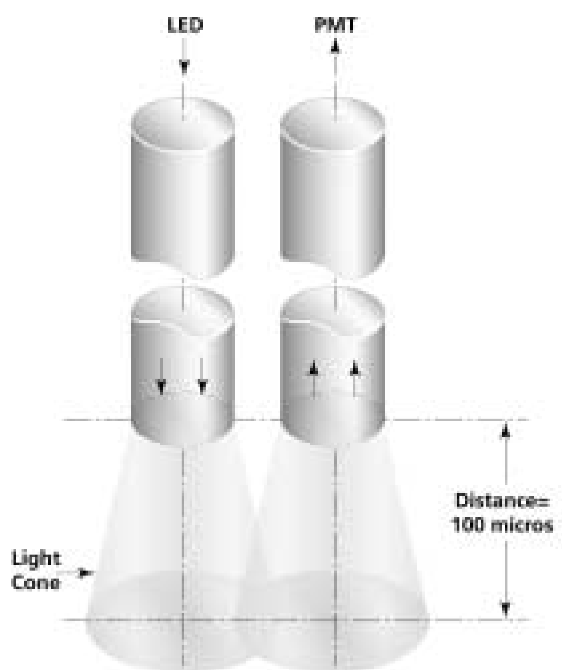

Figure 1: Dual-fiber reflective probe.

Figure 2 shows a view in the plane of a representative cantilever with the axis of the delivery fiber perpendicular to the lever. The approximate diameter of the light emerging from the fiber, in the plane of the lever is depicted by the dotted lines for two sizes of fiber, with 200 and 50 micron core diameters respectively. This assumes the manufacturers specification of an NA=0.22 and that the fiber is 50 microns from the lever. It is seen that the lever only intercepts a fraction of the light from either fiber. And, that fraction decreases with increased distance between fiber and cantilever.

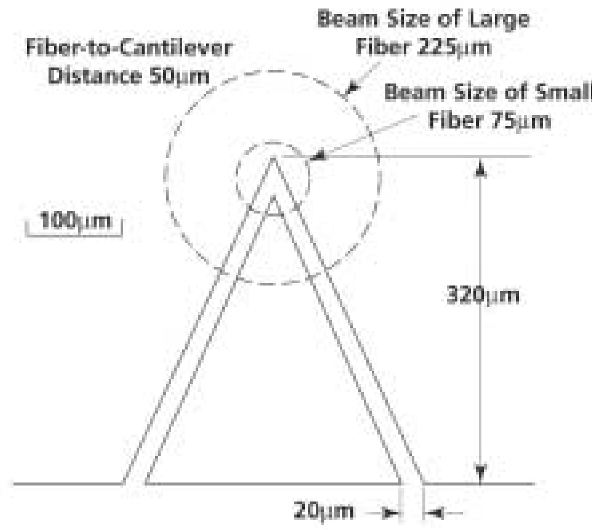

Figure 2: Microcantilever in relation to beam profiles.

Figure 3 is a schematic of the experiment performed. For calibrations, the fiber is moved along the line perpendicular to the plane of the stationary cantilever. Two nearly orthogonal cameras view the fiber and cantilever and are used for initial positioning of the fiber relative to the cantilever. The dual fibers are contained in the same sheath except for the last twelve inches where they are separated to allow for the light delivery from an LED and monitoring of the reflected light by a PMT.

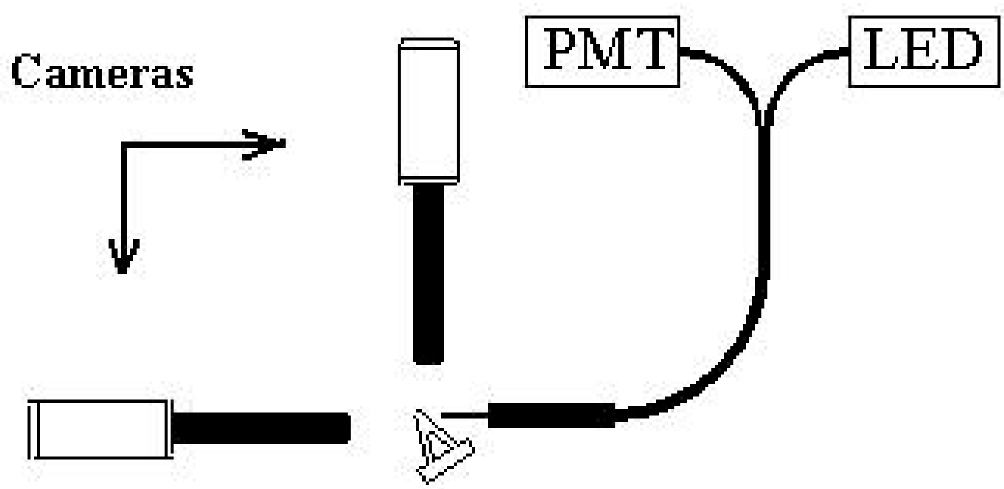

Figure 3: Schematic of Experimental Arrangement.

A blue LED with luminous output specified between 0.6 and 1.2 mW was butt-coupled to the delivery fiber. The spectrum of this LED (Ledtronics BP280CWB1K-3.6Vf-050T) peaks at 450 nm. A pulsed power supply delivered typically 5 to 25 volts to the LED and a 25 ohm load resistor. A large amount of optical loss occurs at the LED/fiber interface since the fiber touches the LED on its dome, after most of the light has diverged significantly. Better coupling would increase light delivery. While a wide variety of higher power LEDs are readily available, for the current application the present LED is more than adequate. For the tests described in this work, a Hamamatsu model H5783-01 photomultiplier with a current gain of about 10^5 was used.

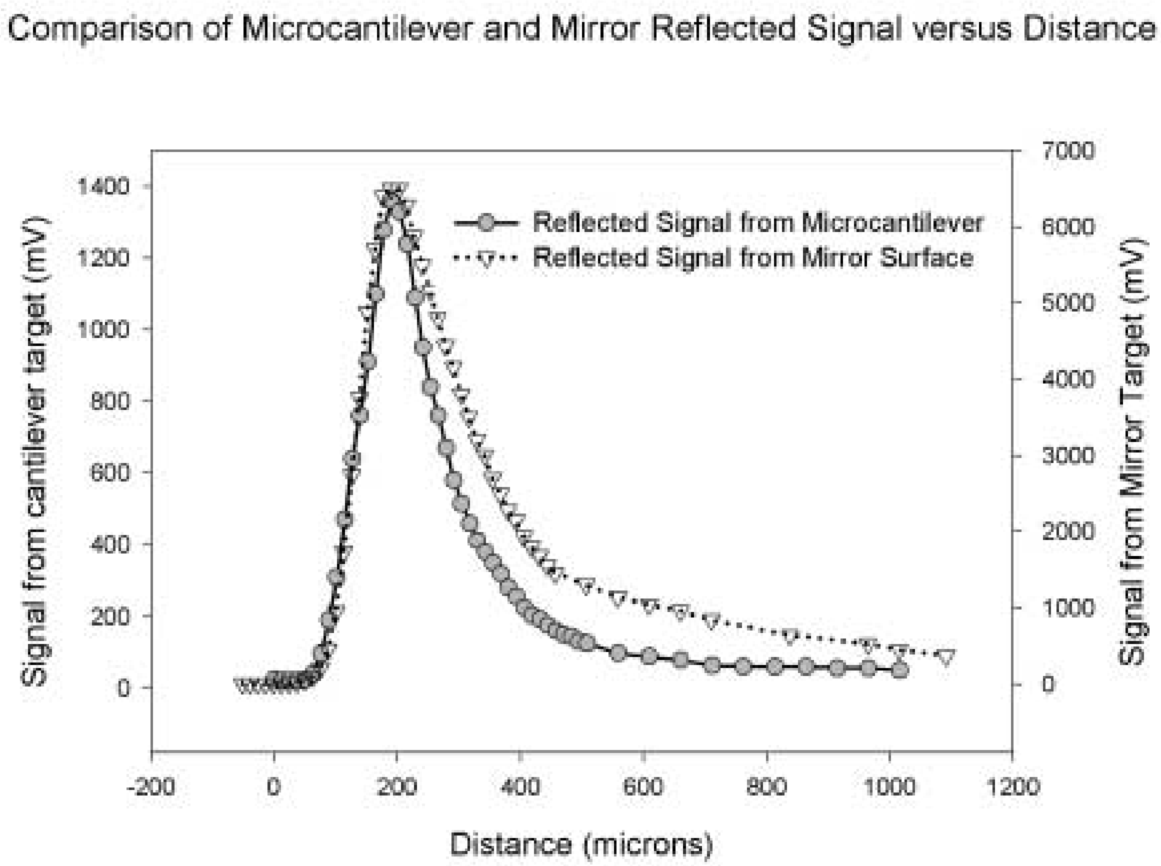

Figure 4: Comparison of Microcantilever and Mirror Signal vs Distance.

Figure 4 shows the received signal as the dual fiber is translated relative to a permalloy-coated microcantilever and to a mirror surface. As expected, the signal is stronger for the mirror surface for two reasons. First, the mirror should have a higher quality surface that is specular. Second, the cantilever obviously does not intercept the entire emitted light beam from the delivery fiber as can be seen in Figure 2.

Figure 5 shows a linear regression fit to the rising portion of the curve for two separate experimental runs. For these test runs a microcantilever coated with permalloy was used as the reflective target. The only difference between the two sets is due to repositioning of the fiber relative to the position of the cantilever. Figure 5 shows the repeatability of the dual fiber position sensor as well as the importance of alignment.

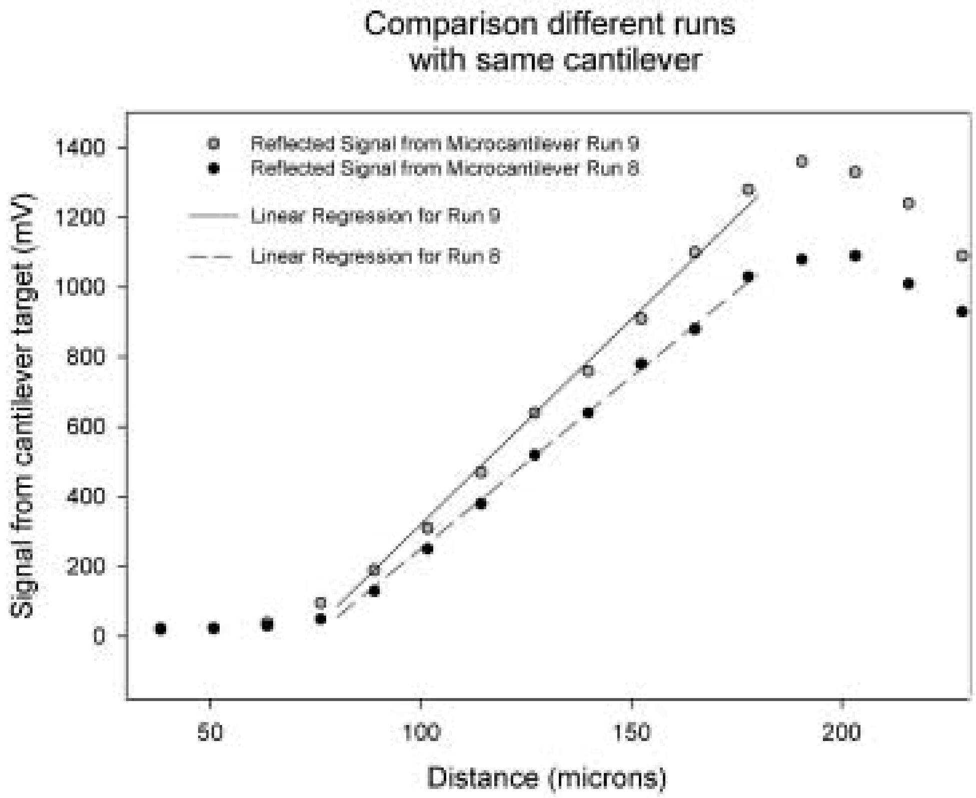

Figure 5: Results of separate data runs and linear regression.

3.0 MODEL

To better understand the results seen in Figures 4 and 5, a discrete geometric model based on a finite number of photons emanating from the delivery fiber was developed. To simplify the model, several assumptions were made. First, it was assumed that all of the photons exiting the delivery fiber were equally spaced resulting in a flat distribution rather than a Gaussian distribution. Second, no provision was made for multiple reflections. Third, the reflective surface was assumed to be 100% reflective and infinite in size. Finally, due to symmetry only one quadrant of the delivery fiber was analyzed to determine the performance of the system. With these assumptions in place, delivery fiber was divided into discrete point sources in both the x and y directions. The angle of each photon exiting the delivery fiber was defined by the numerical aperture of the fiber and the ratio of the position in the x direction to the radius of the fiber. For a given distance to the reflective surface, the angle defined above was used to determine the position where the light strikes the plane of the reflector, and the position that the reflected light crosses the plane of the capture fiber. Once all of these points had been calculated a routine defined which points struck the capture fiber and summed them. This process was then repeated for other distances to the reflective surface to produce the curve seen in Figure 7. Although, a more complex model could have been developed, or a commercial ray trace program could have been procured and exercised, the simple model described here is sufficient for the present needs.

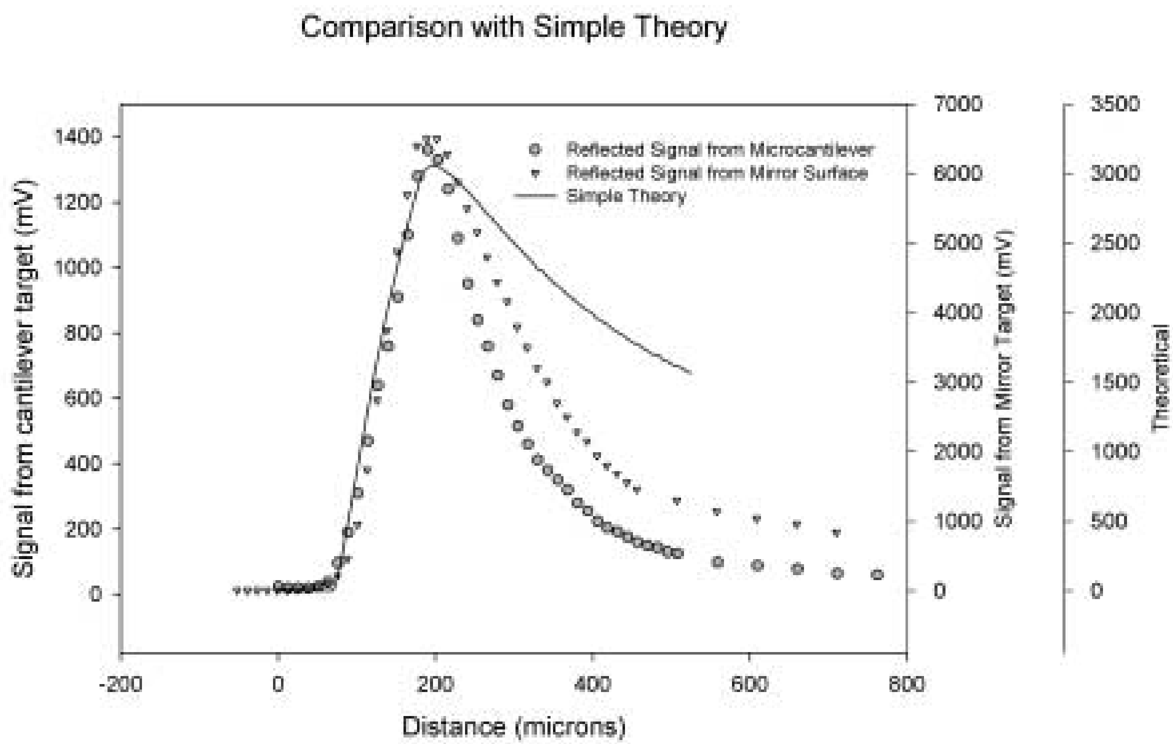

Figure 6: Comparison with a simple model.

Figure 6 includes the prediction of the simple model with the results from Figure 4. The model appears to function fairly well on the rise portion of the curves as can be more clearly seen in Figure 7. The empirical data falls more rapidly after the peak than that predicted by the model. This drop in the empirical data may be caused by 1) the fraction of light beam intercepted by the cantilever decreases with distance and 2) there may be a slight misalignment between the reflective surface and the fiber.

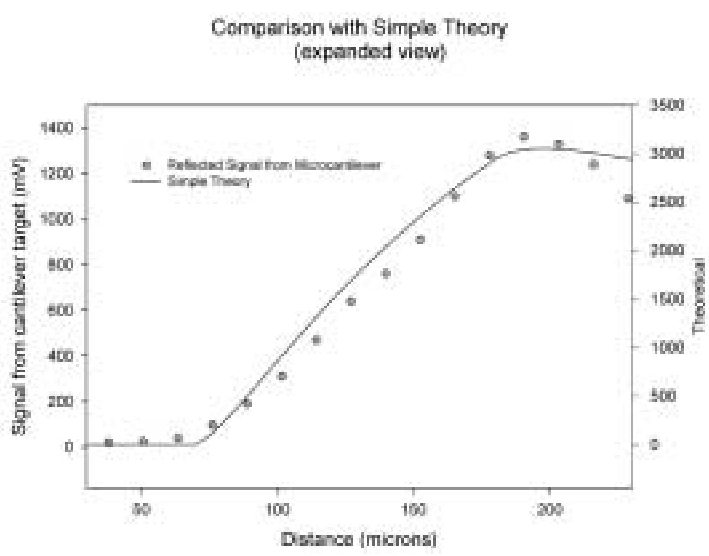

Figure 7: Expanded view of cantilever and model data.

Since the model had been justified for the rising portion of the experimental data, it may be used to find ways to increase the sensitivity of the dual fiber sensor. Since the behavior of the 50 micron core dual fiber with the numerical aperture of 0.22 is known, it is instructive to see how changing the numerical aperture effects the sensitivity. The change in sensitivity with respect to the numerical aperture is shown in Figure 8. As can be seen increasing the numerical aperture increases the slope of the linear region and thus the sensitivity. For this increased sensitivity the dual fiber must be moved closer to the reflective surface.

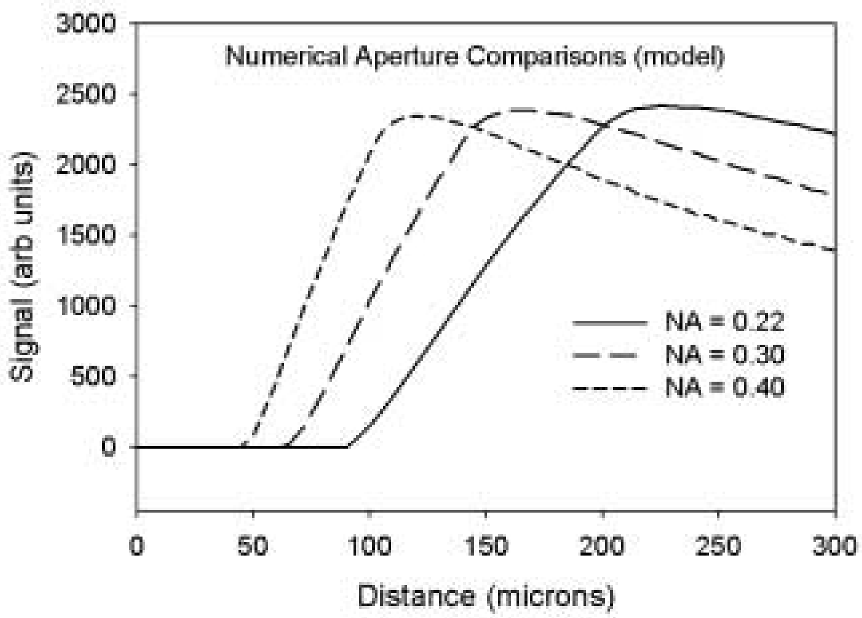

Figure 8: Comparison of model results for differing numerical aperture.

Another possible method to increase the sensitivity is to change the diameter of the fiber. For a second attempt in the design of the dual fiber sensor a pair of 200 micron core fibers were placed side-by-side as close as possible to each other. This configuration is similar to that used with the fifty micron core fibers except that the ultra thin 20 millimeter section was not used. Figure 9 compares results from a permalloy-coated microncantilever using 50 and 200 micron fibers. For comparison, the gain on the detector was turned down when using the larger fiber in order to keep the signals to the same approximate scale. As can be seen in Figure 10 the linear region of the signal using the 200 micron fiber set reaches a higher peak and traverses a longer distance. For the 200 micron fiber set the slope of the linear region is approximately 2.8 mV/µm. For the linear region of the 50 micron fiber set the slope is 11.8 mV/µm. Thus while the 200 micron fiber set has a greater signal strength the 50 micron fiber set has the higher sensitivity.

An alternative reflective method would be to use a single fiber to emit and collect the light. This requires extra optical components for injecting light into the fiber and an appropriate beamsplitter with associated optics to direct return light to a detector. Spatial filtering for stray light rejection should also be evaluated depending on conditions. On the other hand, for a dual fiber system, connection to the light source and detector can be effected by simple butt-coupling to the respective fiber with no intervening optics. It would therefore seem that a single fiber system might lead to greater cost because of greater number of discrete components required. However, thanks to economy of scale, the optics and electronics contained in a consumer compact disc player are inexpensive and may be used with a single optical fiber. This was demonstrated by During[7] where an optical fiber was placed at the focal plane of compact disc readout optics. Photodetector current was observed as a mirror was translated to and from the output end of the fiber, similar to the experiments described here. Of course the signal is a maximum when the fiber is in contact with the mirror and it decreases as the mirror retracts. In Figure 2 of reference 7 intensity, I, is plotted versus distance for a 100 micron fiber with NA=0.29. In order to compare sensitivity of the dual fiber versus the single fiber method, one minus this intensity from the single fiber method is plotted along with the results for the 50 and 200 micron core dual fiber in Figure 10. The data from the two methods is normalized to the same peak value.

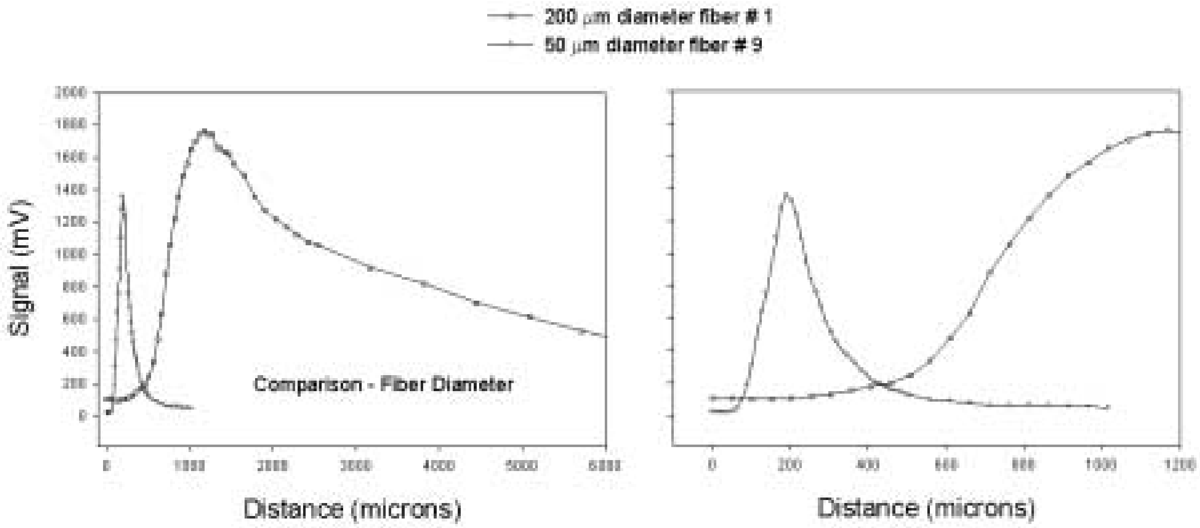

Figure 9: Comparison of 50 and 200 micron diameter fibers.

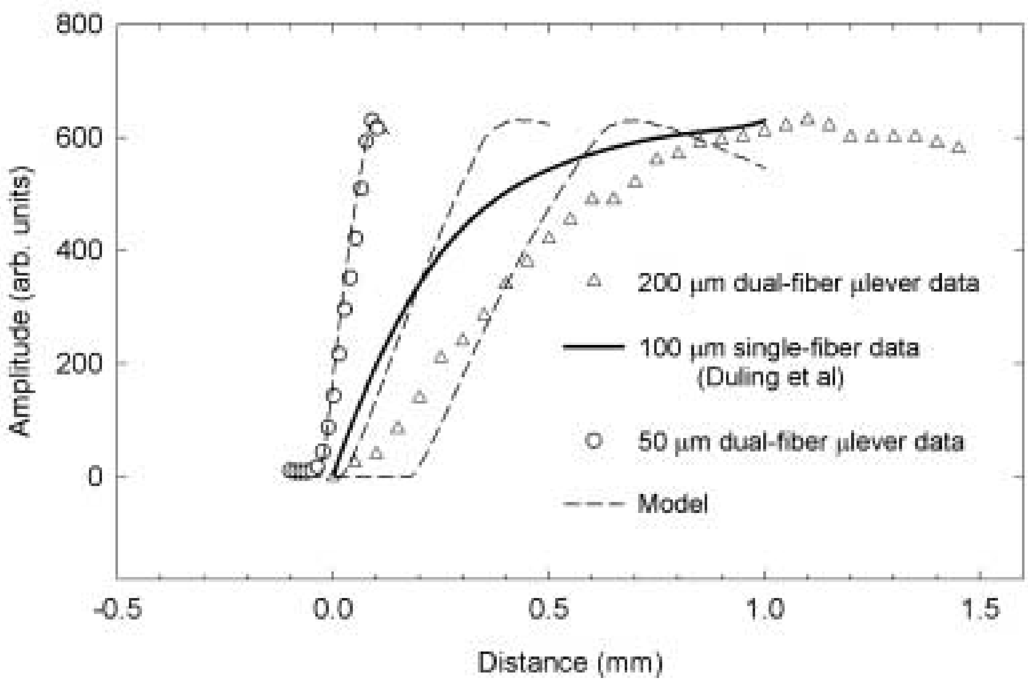

Figure 10: Comparison data for 50, 100 (single fiber), and 200 micron fiber.

Figure 10 shows model results for three different dual fiber configurations with 50, 100, and 200 micron core diameters. These results are used for comparison to the data presented here as well as in reference 7. As Figure 10 shows, the model predicts a better match with decreasing fiber diameter. This is not surprising since the reflective surface used in the model is assumed to be infinite, and therefore no light can go around the reflective surface. Since the reflective surface is not infinite, as seen in Figure 2, less light will be reflected and the amplitude of the signal will be smaller. As might be expected, the 100 micron fiber sensitivity falls in between the 50 and 200 micron data. The overall consistency of the data and modeling is satisfactory.

Regarding achievable sensitivity, in a test with 50 micron core fiber, a sensitivity of about 400 mV per micron of motion was achieved with a shiny but not specular surface. The light source was a laser attenuated to about 1 microwatt. The captured reflected light was measured with a photomultiplier tube. Assuming a 1 mV measurement resolution, this would imply a distance resolution of about 2½ nm. Economics would dictate replacing the photomultiplier with a less expensive and less sensitive photodetector. However, an avalanche photodiode with a gain of a few hundred in conjunction with a 1 mW light source could still yield a similar resolution based on this scenario.

4.0 CONCLUSIONS

The experimental data shows a consistent linear optical response versus probe-surface distance for both the 50 and 200 micron fiber core diameter sets. As expected, the amplitude of the reflected signal increases with increasing core diameter. This trend is also confirmed by the simple model developed. The results also show that increasing the core diameter from 50 to 200 micron increases the working distance, where the working distance is defined as the distance between the probe end of the fiber set and the reflective surface at the center of the linear region of the calibration curve, from 140 µm to 660 µm. Along with the increased working distance the working range, the length of the linear portion of the calibration curve, increases from 100 µm to 500 µm with the increase in the core diameter. From these results a simple rule of thumb can be defined for both the working distance and working range. The working distance tends to be approximately two times the core diameter and the working range tends to be approximately three times the core diameter. If a 1 mV measurement resolution is assumed, then the current results show an obtainable resolution of 2 ½ nm for a 50 micron core fiber set from a nonspecular reflective surface. The resolution for the same fiber set was found to be 84 nm when used with a permalloy-coated cantilever. Increasing the fiber core diameter to 200 microns increased the minimum resolution to 357 nm. As can be seen increasing the core diameter increases the working distance, the working range and the sensor throughput, but does not increase the sensitivity or the resolution of the system.

This work has also proven that a discrete geometric model is very capable of predicting the performance of the dual fiber position sensor. The model can approximate the sensitivity and working range of the dual fiber position sensor. The model also predicts relative changes in the working distance based on changes in the fiber parameters.

The results also establish that sufficient light is reflected from a cantilever for useful distance measurements. The signals are consistent and adequately predictable. The light source used, a blue LED, is comparatively dim and brighter LEDs could be easily substituted. A laser diode could also present a better alternative since it could be more efficiently coupled to a fiber. It appears feasible that resolutions considerable less than one micron are achievable.

ACKNOWLEDGEMENTS

Oak Ridge National Laboratory is operated for the U.S. Department of Energy by Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725. The work performed by Oak Ridge National Laboratory was supported by the U.S. Department of Energy and the Defense Advanced Research Projects Agency (DARPA). The work performed by the University of Tennessee was supported by the National Science Foundation grant ECS-9727208.

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