FLUORESCENT OPTICAL LIQUID-LEVEL SENSOR

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ABSTRACT

An optical method of detecting liquid level is presented that uses fluorescence radiation generated in an impurity-doped glass or plastic slab. In operation, the slab is inserted into the liquid and pump light is coupled into it so that the light is guided by the slab-air interface above the liquid and escapes into the liquid just below its surface. Since the fluorescence is generated only in that section of the slab above the liquid, the fluorescence power will monotonically decrease with increasing liquid level. Thus, a relationship can be established between any signal proportional to it and the liquid level. Because optical fibers link the pump source and the detector of fluorescence radiation to the sensor, no electrical connections are needed in or near the liquid. Their absence vastly decreases the hazard associated with placing a liquid-level sensor in a potentially explosive environment. A laboratory prototype, consisting of a methyl styrene slab doped with an organic dye, has been built and successfully tested in water. Its response to liquid level when pumped by a tunable argon-ion laser at 476, 488, and 496 nm, and by a blue LED, is presented and shown to be consistent with theory. The fluorescence spectra are also presented and discussed.

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1 INTRODUCTION

There is a need for continuous liquid-level measurements in numerous commercial and military arenas, such as the fuel, oil, and water tanks of aircraft, rockets, and automobiles. Less mobile applications include storage tanks for fuel-dispensing, wastewater, chemical, and food-processing purposes. In many cases, electrical sensors are inappropriate because of the hazards posed by sparks in potentially explosive environments. The crash of the TWA-800 flight several years ago, where the suspected cause was an explosion in the fuel tank, underscores this issue. Since then, the FAA has mandated a re-examination of the wiring leading to the fuel tanks in certain commercial aircraft. Electrical sensors will also be undesirable when electromagnetic interference can overwhelm the signals generated by them. This situation is likely in a high EMI environment where space or weight limitations do not allow for adequate shielding. Visual inspection will, of course, be inconvenient or impossible when the level must be remotely and continuously monitored. An optical liquid-level sensor with all electrical components for optoelectronic conversion far removed will overcome all of these problems. In this paper, we present the operating principle of such a sensor and the test data on a laboratory prototype. For simplicity, water was used in these experiments.

2 BASIC DESCRIPTION OF THE OPTICAL SENSOR

Figure 1 schematically illustrates the essentials of the fluorescent optical liquid-level sensor. Inserted into the liquid and serving as the basic sensor element, is a glass or plastic rectangular slab that is uniformly doped with a fluorescent impurity. Light that

excites or pumps the impurity is guided by a fiber from a remote source, is collimated, and enters the slab through a section of clear material, referred to as an optical coupler. For simplicity of construction, the collimated beam is normal to the beveled face of the coupler. To avoid unwanted refraction and reflection at the coupler-slab interface, the refractive index of the coupler should be as close as possible to that of the slab. The pump light enters the slab such that its angle of incidence, θ_i , at the slab-air interface is greater than the critical angle, θ_c . Thus, the pump light undergoes a zig-zag path down the slab until it reaches the liquid level, where essentially all of it escapes into the liquid if the angle of incidence is substantially less than the critical angle at the slab-liquid interface. Since the pump light only generates fluorescence radiation while in the slab, the total optical power associated with it will monotonically increase with decreasing liquid level. The relationship between the fluorescence power and the liquid level is the basis of this sensor.

Also shown in the Figure 1 is a bundle of optical fibers abutting the top face of the coupler. These collect whatever fluorescence radiation travels in their direction and within their numerical aperture, and guides it to a remote detector. For signal maximization, it is thus advantageous to use fibers with as high a numerical aperture as possible, particularly since bandwidth is no issue in this application.** The bottom face of the slab is shown as reflecting in order to reverse the direction of whatever fluorescence is heading away from the fibers. Aside from increasing the signal at any liquid level, the reflecting face also produces another benefit. At very low liquid levels, when the pump beam encounters the bottom of the sensor, this surface will reflect it and cause the

** This statement might have to be modified if some time-division multiplexing scheme were used involving several sensors.

generation of more fluorescence as the pump beam heads in the upward direction. The resulting sudden rise in the signal can serve as an alarm that one will soon be "flying on empty"!

For a narrow pump beam, a dead zone exists in which the sensor will not respond to changing liquid level because, within this zone, the pump beam is not impinging upon either wall. This region has length Z , as indicated in Figure 1. From simple geometry, it is given by:

$$Z = W \tan \theta_i - B/\cos \theta_i, \quad (1)$$

where W is the width of the slab and B is the width of the beam. Therefore, this dead zone disappears when:

$$B \geq W \sin(\theta_i). \quad (2)$$

When the equality holds, the pump beam covers the top face of the slab upon entering it.

Unfortunately, the fluorescence signal is not exactly zero even when the liquid level is at the top of the sensor because the pump beam still makes one diagonal pass through the slab. However, by forcing the pump beam to cross the top face of the slab on the right in Figure 1, one minimizes the length of this pass and, thus, the size of the residual signal.

3 CONSTRUCTION OF THE PROTOTYPE SENSOR

The prototype sensor was constructed of a slab of methyl styrene doped with a proprietary organic dye from BICRON¹, a manufacturer of scintillators for nuclear detection. Methyl styrene is a clear polymer very similar to polystyrene. The dye absorbs heavily in the blue region of the spectrum and fluoresces primarily in the green, although the fluorescence spectrum does extend out to 600 nm. Based on data provided by BICRON, Figure 2 shows a plot of the absorption coefficient of this impurity-doped slab vs. wavelength. The fluorescence spectra for the particular excitation sources used in this experiment will be presented later. These sources were: spectral lines at 476 nm, 488 nm, and 496 nm, from a tunable argon-ion laser, and a blue LED, whose emission spectrum is shown in Figure 3.

The slab's width was 1.27 cm (0.5"); its depth, D, was 5.08 cm (2"); and its height was 45.7 cm (18"). The depth was chosen to make it easy to keep the beam away from the side walls of the slab because these surfaces were not as optically smooth as its primary surfaces. It was feared that diffuse scattering off the sidewalls would have degraded the performance of the sensor. In hindsight, the depth could have been made smaller, perhaps 1.27 cm, thereby reducing the size of the fiber bundle by a factor of four.^{***} In addition, if all four walls were of sufficient optical quality, then side reflections would not have been a problem.

The optical fiber leading from the pump source to the collimating lens was a step-index, multimode fiber having 140 μ core and a numerical aperture of 0.66. Thus, light emerged from it unpolarized. If its numerical aperture were substantially filled, the collimated pump beam would have been wider than necessary to avoid dead zones (0.9

^{***} For this prototype, the cross-section of the bundle coincided with that of the slab. The use of a lens may have reduced the size of the bundle.

cm). However, the laser light was well collimated and a beam expander followed by a focusing lens would have been necessary produce a well-filled numerical aperture. The fiber, optimally aligned, simply intercepted a portion of the laser beam, while still resulting in very usable signals. However, since this arrangement resulted in predominantly low-order modes being excited within the fiber, it produced a collimated pump beam of only ~ 0.45 cm in diameter. Tilting the fiber with respect to the laser broadened the pump beam, but now the paucity of excited low-order modes caused an "intensity hole" to appear in its center. Light from the LED, however, had to be focused into the fiber to produce usable signals. It also produced a pump beam wide enough to avoid dead zones. This digression on dead zones has been included for completeness; their presence will be shown to have essentially no impact on the main thrust of this paper. As for the other set of fibers, those constituting the bundle had a core diameter of $50\text{ }\mu$ and a numerical aperture of 0.55.

Regarding the angle of incidence, methyl styrene has a refractive index ~ 1.58 ,¹ resulting in a critical angle between it and air of 39.3° . The critical angle between it and water is 57.6° . For convenience, the angle of incidence was chosen to be 45° . For these parameters, the percent transmission of unpolarized light from the slab into the water is 97.7, a value very close to the ideal of 100. For jet fuel, which has a refractive index of about 1.45,² the percent transmission would be even higher at 99.6. The important issue of how well methyl styrene resists chemical attack by jet fuel has not been investigated.

The optical coupler was made of polystyrene, a material with a refractive index of ~ 1.60 .¹ The coupler was bonded to the slab along the two faces shown in Figure 1 with an optical epoxy from BICRON, which was specially designed for adhesion to plastics.

Since the epoxy has a refractive index of ~ 1.56 ,¹ the entire top assembly approaches the ideal of being optically homogeneous.

The optical coupler not only allows light to pass between the fibers and the slab, it also isolates the external optical components, like the collimating lens, from the liquid. The prototype was constructed with the sensor slab protected in a PlexiglasTM tube containing holes for the passage of liquid. Attached to the top end of this tube was the coupler, whose design contained features for this purpose that are not shown in Figure 1. Thus the coupler also isolated the slab from the outside world. It also served as an assembly for the lens and the fibers attached to it. A Plexiglas cap was bolted onto the bottom end of the tube. This cap contained a shallow rectangular groove into which the bottom of the slab was inserted and stabilized through slight compression. A metal foil, the reflector, also resided in this groove. The tube containing the sensor was inserted into a larger Plexiglas tube that acted as the "fuel tank" for these experiments.

Figures 4 and 5 are photographs of the prototype with the tank empty and partially filled with water, which clearly show the fluorescence radiation "zig-zagging" down the slab and, in the latter case, escaping into the water at the top of the liquid column. The fluorescence appears greener to the eye than presented in these photographs. The "tank" was lined with two strips of black velvet to absorb the pump light that escaped into the water. Otherwise, it totally internally reflected off the tank-air boundary and re-entered the slab further down. Since they were rotated out of the way for these photographs, some scattered 488-nm pump light may be visible below the liquid level. The narrow tube diagonally approaching the top of the sensor assembly contains the "pump-beam" fiber, whose connection to the argon laser is seen in the background. The large black tube

encloses the fiber bundle and connects to a box behind the stand containing the silicon detector and associated electronics.

Parenthetically, if this sensor were used to monitor liquid hydrogen or liquid oxygen, the tolerance on the angle of incidence would be tighter than the 18.3° for water. This is especially true of hydrogen. At their one-atmosphere boiling points, their refractive indexes are ~ 1.11 and ~ 1.22 , respectively.³ These values result in critical angles between the slab and these two liquids of 44.6° and 50.5° . Thus, the range of acceptable angles of incidence is reduced to 5.3° and 11.2° . Additionally, the percent transmission across the interface drops somewhat. In the case of oxygen, for example, the percent transmission at an angle of incidence of 45° is 91.4. It increases to 96.3 right at the minimum acceptable angle of 39.3° . For hydrogen, one cannot use 45° because the light would be guided by the slab-liquid interface. Right at 39.3° , the percent transmission is 89.9. The situation improves for these cryogenic liquids if impurity-doped fused silica were used instead of methyl styrene. The fused silica could be doped with neodymium, pumped in the near IR, and fluoresce in the spectral regions around 900 nm, 1060 nm, and 1350 nm.⁴ Assuming a refractive index of 1.46 for this material, the maximum permissible transmission for oxygen and hydrogen are 97.8% and 92.2%, respectively. Therefore, sensors could be made to monitor these liquids, but not quite as easily as for either water or jet fuel. (The fluorescence efficiency at cryogenic temperatures and the differential thermal contractions among the various mechanical components must also be considered.)

4 CALCULATION OF THE SENSOR RESPONSE

This sensor is an outgrowth of a fiber-optic shock wave position sensor that the author invented several years ago.⁵ It involved an impurity-doped fiber that fluoresced when pumped from one end and was progressively shortened by a shock wave approaching it from the other. It was shown that when the fiber has a length L , the power associated with the fluorescence radiation traveling back to the pump source is of the form:

$$I = K (1 - \exp(-\alpha L)), \quad (3)$$

where I is the fluorescence power and α is the total absorption coefficient of the pump beam and the fluorescence. The constant K depends on pump power, coupling efficiencies, etc. Ideally, α is caused by the fluorescers acting on the pump beam, rather than any bulk absorption of the pump or fluorescence. Since the fiber had a small numerical aperture, all light was assumed to travel essentially along its axis. Also, no reflection of any consequence was assumed or observed from the fiber end hackled by the shock.

We expect this liquid level sensor to behave similarly to the shock position sensor, with the relevant length L_a above the liquid. A few differences do exist, however. First, the beam is traveling at an angle $(90 - \theta_i)^\circ$ with respect to the vertical axis of the slab. Thus, the effective path length is not L_a , but $L_a/\sin \theta_i$. This difference produces only a change in scale. Second, not all of the beam necessarily travels the same length in the slab, for a given liquid level. The lower portion of it may escape into the liquid, while the remainder will reflect off the wall and make one additional pass through the slab before

escaping into the liquid. This situation would be illustrated in Figure 1 if the liquid level were drawn straddled by the pump beam. Third, the length of the first pass and, at low liquid levels, the last pass will vary across the beam. The fourth difference is the reflector on the bottom face, which enhances the signal when at least a portion of the pump beam strikes it. Fifth is the existence of dead zones if the pump beam is too narrow.

For the purpose of this calculation, let us assume that the beam enters the slab at the extreme right, as in Figure 6, so as to minimize the offset signal when the liquid level is at the top of the sensor. This was not the case in our experiments; the beam entered the slab near the center of its top face. Let us also assume that the sensor's length L is such that the pump beam makes an integral number of passes through the slab before reaching the bottom. This was the situation in our case, where that integer was 36. Finally, let us assume that the cross section of the beam is rectangular and of uniform power density. In our case, the pump beam was circular and, most likely, non-uniform. These simplifications produce modifications only in the fine structure of the response curve; they have no effect on its basic character.

Referring to Figure 6, when the height H of the liquid is such that

$$0 \leq H \leq (W - W_1) \tan \theta_i, \quad (4)$$

then the entire pump beam reaches the bottom of the sensor, undergoes reflection, and generates additional fluorescence traveling back up the sensor. Aside from irrelevant constants, the fluorescence signal, $\text{Sig}(H)$, is

$$\text{Sig}(H) = W_1 \tan \theta_i [1 - \exp(-2 \alpha L / \sin \theta_i)], \quad (5)$$

where the ideal α has been assumed. Data from BICRON justify this assumption, if the absorption characteristics of methyl styrene are similar to those of polystyrene. These data indicate that the bulk absorption of clear polystyrene is essentially a constant .0007/cm in the spectral range relevant to these experiments. Figure 2, on the other hand, indicates that the absorption coefficient of the doped methyl styrene is: .005/cm, .014/cm, and .029/cm at 496 nm, 488 nm, and 476 nm, respectively.

For H such that

$$(W - W_1) \tan \theta_i \leq H \leq W \tan \theta_i, \quad (6)$$

the portion of the pump beam between $(W - W_1) \tan \theta_i$ and H escapes into the liquid without undergoing the last pass to the reflecting bottom of the slab. As illustrated in Figure 6, the portion of the beam between H and $W \tan \theta_i$ does make the final pass. We also note that the length of the final pass is $y / \sin \theta_i$ for that portion of the beam that reflects off the vertical wall of the slab at a distance y from the bottom. Thus, for this range of H the signal can be written

$$\begin{aligned} \text{Sig}(H) = & (W_1 \tan \theta_i - H) [1 - \exp(-2 \alpha L / \sin \theta_i)] + \\ & \int_{(W - W_1) \tan \theta_i}^H dy [1 - \exp(-\alpha(L - y) / \sin \theta_i)]. \end{aligned} \quad (7)$$

After performing the integration and a few rearrangements, we obtain

$$\begin{aligned} \text{Sig}(H) = & W_1 \tan \theta_i + (\sin \theta_i / \alpha) \exp(-\alpha L / \sin \theta_i) [\exp(\alpha H / \sin \theta_i) \\ & - \exp(\alpha (W - W_1) / \cos \theta_i)] + \\ & (W_1 \tan \theta_i - H) \exp(-2 \alpha L / \sin \theta_i). \end{aligned} \quad (8)$$

For H such that

$$W \tan \theta_i \leq H \leq (2W - W_1) \tan \theta_i, \quad (9)$$

the sensor is in a dead zone; thus

$$\text{Sig}(H) = \text{Sig}(W \tan \theta_i). \quad (10)$$

For H such that

$$(NW - W_1) \tan \theta_i \leq H \leq NW \tan \theta_i, \quad (11)$$

where $N \geq 2$ but $NW \tan \theta_i \leq L$, we can divide the beam into sections above and below the liquid level, as was done in deriving Eqns. 7 and 8. Similarly, after accounting for path lengths (including the partial pass at the top of the slab) and integrating over the beam cross section, we obtain:

$$\text{Sig}(H) = W_1 \tan \theta_i - (\sin \theta_i / \alpha) \exp(-\alpha L / \sin \theta_i) [\exp(\alpha H / \sin \theta_i) (1 - \exp(-\alpha W / \cos \theta_i) + \exp(NW\alpha / \cos \theta_i) (\exp(-\alpha W / \cos \theta_i) - \exp(-\alpha W_1 / \cos \theta_i))]. \quad (12)$$

For H such that

$$NW \tan \theta_i \leq H \leq ((N + 1)W - W_1) \tan \theta_i, \quad (13)$$

where the same conditions apply to N, the sensor is again in a dead zone. Thus,

$$\text{Sig}(H) = \text{Sig}(NW \tan \theta_i). \quad (14)$$

These formulas were used to calculate the sensor response at the three argon-ion pump wavelengths: 496 nm, 488 nm, and 476 nm. For reasons mentioned below, an additional curve involving an absorption coefficient of .075/cm has also been included. (Not performed was the more complex calculation involving the integration over wavelength that would be required for the response to the LED pump beam.) Figure 7 illustrates the normalized results using a slab having the same dimensions as that used experimentally, for $\theta_i = 45^\circ$, and for $W_1 = W$. The last condition means that the beam was assumed to be just wide enough to avoid dead zones. Figure 8 shows the results for a beam half that width at 488 nm. Between the dead zones the signal rises more or less linearly to the next plateau, but the basic behavior is no different from the 488-nm curve in Figure 7. If the beam were wider than that needed to avoid dead zones, the response

curve would have been a superposition of a curve similar to the one in Figure 8 and the one in Figure 7.

5 PRESENTATION OF DATA

5.1 *Sensor Response*

In Figures 9-12 are the results of the liquid-level measurements for the three laser lines and the LED as pump beams. The filter referred to is a long-pass optical filter having its 50% transmission point at 509 nm and a maximum transmission of ~ 92 % starting at ~ 570 nm. Its transmission at 476, 488, and 496 nm is 12%, 35%, 52%, respectively. Each set of measurements was made with and without this filter in front of the silicon detector in order to check for backscatter or reflection of the pump beam into the detector. We see from these figures that filtering out a substantial fraction of the pump wavelength produced very little change in the character of the curves. Furthermore, the effects of filtering were inconsistent; the filtered 488-nm and 496-nm curves lay above their unfiltered counterparts and below only one of the two unfiltered curves in the case of 476 nm, despite the fact that the filter was the most effective at that wavelength. In the case of the LED, virtually no effect can be observed.

Most likely, the apparent effects of the filter were caused by the variable output of the argon-ion laser. Neither its output nor that of the LED was monitored during the measurement. However, both were monitored for much longer periods on separate occasions. The LED output was perfectly constant to within the precision of the measurement (~ 0.1%). The laser output, on the other hand, gradually varied by several percent during certain periods equal to the measurement period of the liquid level, but was

constant during others, with no obvious pattern. Therefore, the apparent effect of the filter probably depended on the laser's behavior during the whole set of measurements at a particular wavelength. Laser variability can also explain any apparent hysteresis, since this sensor has no moving parts and the water "sheeted" nicely off the surface of the slab. We thus conclude that any level-independent reflection of the pump light into the detector was negligible, or that any return of the pump to the detector had the same level dependence as the fluorescence.

Regarding the characteristics of the measured response, it is encouraging that they basically agree with calculation. The initial rise at high liquid level, the flattening out of the response at intermediate levels, the very rapid rise at low liquid level, and the trend in all of these characteristics with pump wavelength are basically compatible with the curves in Figure 7. For example, the theoretical and experimental curves at 496 nm and 488 nm look very similar. Qualitatively, the trends in the calculated curve for 476 nm agree with measurement. The initial drop in signal at low liquid level is smaller than for the other two wavelengths; the region of intermediate level is flatter; the drop in signal at high levels is faster; and the offset on full is greater. However, quantitative agreement between theory and experiment, which is not as good as for the other two wavelengths, would be markedly improved if an absorption coefficient of $\sim 0.075/\text{cm}$ were chosen, rather than $0.029/\text{cm}$. This is apparent from the additional plot in Figure 7. In the absence of proof that the absorption data from BICRON are incorrect in the immediate vicinity of 476 nm, we have no explanation for the disagreement. The LED curve was not calculated, but from Figure 3 we note the presence in its emission spectrum of a considerable amount of energy at wavelengths where the absorption by the slab is relatively high. This contribution to the

response tends to produce considerable flattening at intermediate liquid levels and a large offset at the highest level. The latter occurs because of the high level of fluorescence generated by the first pass.

The most desirable pump wavelengths for a sensor of this length are 488 nm and 496 nm. Each produces a response with low offset (i.e., large dynamic range), a rather linear response over the entire range of liquid level, and a large rise near empty. The other two, especially the LED, produce undesirable responses. However, this situation could be rectified by reducing the concentration of fluorescent dye in the slab to whatever level is required for the particular application (i.e., the length of the sensor). Within limits, a sensor can be tailored to the desired pump source. At one extreme, the limit is determined by the solubility of the fluorescers within the matrix; if their absorption of a particular pump wavelength is exceptionally low, it can only be increased up to their solubility limit. At the other extreme, the concentration of fluorescers could be reduced to as close to zero as one wanted, but lack of reproducibility and non-uniformity eventually become problematic.

5.2 *Fluorescence Spectra*

Figure 13 shows the four fluorescence spectra produced by this sensor in an empty tank. Their relative magnitude is of no significance; the curves were scaled for readability. All spectra extend to about 600 nm, consistent with information supplied by BICRON. The obvious "unfluorescent-like" feature of the three curves associated with the laser lines is the laser line itself. (The laser lines are actually ~ 0.0025 nm wide; the spectrometer used in these measurements artificially broadened them.) The LED

produces a less dramatic "unfluorescent-like" feature of its own: the shoulder extending down from about 480 nm. This shoulder corresponds to the region near the maximum in the LED emission spectrum. The presence of these features, superimposed upon the normal-looking fluorescence curve, suggests the existence of a substantial reflection from somewhere in the system, despite the conclusions reached through the use of the filter. Since the tank was empty when these curves were obtained, an obvious possibility is the reflection of the pump beam off the mirrorized bottom surface, with a residual amount of pump power reaching the fiber bundle. However, regardless of how much water was added to the tank, the laser line did not disappear from the fluorescence spectra. But its intensity did diminish along with the continuum. With a little thought, one realizes that the pump beam, undergoing a purely specular reflection off the bottom of the slab, could not have been guided by the fiber bundle. The numerical aperture of these fibers was 0.55; thus, the maximum angle that the pump could have made with the axis of the slab and still be guided by them was $\sim 20.4^\circ$. This is much less than the 45° occurring in this experiment. To eliminate the possibility of some other reflection in the vicinity of the coupler, it was decided to radically change the input geometry. The input fiber was removed from the collimating lens and positioned such that pump light entered the slab horizontally from the outside of a full tank and about half way down from the top. Yet the laser line was still present in the fluorescence spectrum. We thus conclude that the presence of the laser lines in the fluorescence spectra is not extrinsic, and that their strength is indeed level-dependent. Their prominence may be the result of a power density in the pump beam high enough to cause induced emission.

Another "unfluorescent-like" feature of the curves is the fact that some of the fluorescent light is of shorter wavelength than the pump, an apparent violation of energy conservation. From Figure 13, we see that the wavelength difference extends to ~ 20 nm, which corresponds to an energy difference of ~ 0.08 eV. However, associated with the electronic states of fluorescent dyes is a manifold of vibrational states.⁶ This energy difference could easily have been produced by the thermal population of these states at room temperature, where $kT = 0.026$ eV. Therefore, the energy difference was supplied by the temperature reservoir in which the slab was immersed.

6 SUMMARY

The operation of a fluorescence-based optical liquid level sensor has been demonstrated with water and its response has been shown to be consistent with theory. Details of its construction have also been presented, and its applicability to other liquids has been discussed. Furthermore, its fluorescence spectra have been presented and certain anomalies explained

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FIGURE CAPTIONS

Figure 1: Schematic of the basic fluorescent optical liquid-level sensor.

Figure 2: Absorption coefficient of the impurity-doped methyl styrene slab.

Figure 3: Emission spectrum of the blue LED.

Figure 4: Photograph of the prototype sensor without water. The pump beam is the 488 nm laser line, some of which can be seen in the background leaking out of the assembly that couples the fiber to the argon-ion laser. The light "zig-zagging" down the slab is the fluorescence radiation. Both appear bluer here than in reality.

Figure 5: Photograph of the prototype sensor partially filled with water. The light clearly escapes into it at the top of the liquid column. Because the absorbing black velvet strips are rotated out of the way, some of the scattered pump light can be seen below the liquid level.

Figure 6: Simplified schematic of the liquid-level sensor used in the calculation of its response.

Figure 7: Calculation of the sensor response at 496 nm ($\alpha = .005/\text{cm}$), 488 nm ($\alpha = .014/\text{cm}$), 476 nm ($\alpha = .029/\text{cm}$), and for $\alpha = .075/\text{cm}$. The pump beam is just wide enough to avoid dead zones.

Figure 8: Calculation of the sensor response at 488 nm for a beam half the width in Figure 7.

Figure 9: Normalized signal response vs liquid level using a 476 nm pump beam.

Figure 10: Normalized signal response vs liquid level using a 488 nm pump beam.

Figure 11: Normalized signal response vs liquid level using a 496 nm pump beam.

Figure 12: Normalized signal response vs liquid level using the LED pump beam.

Figure 13: Fluorescence spectra from this sensor produced by the four pump sources used in these experiments. The curves were scaled for optimum readability.

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Fig 12