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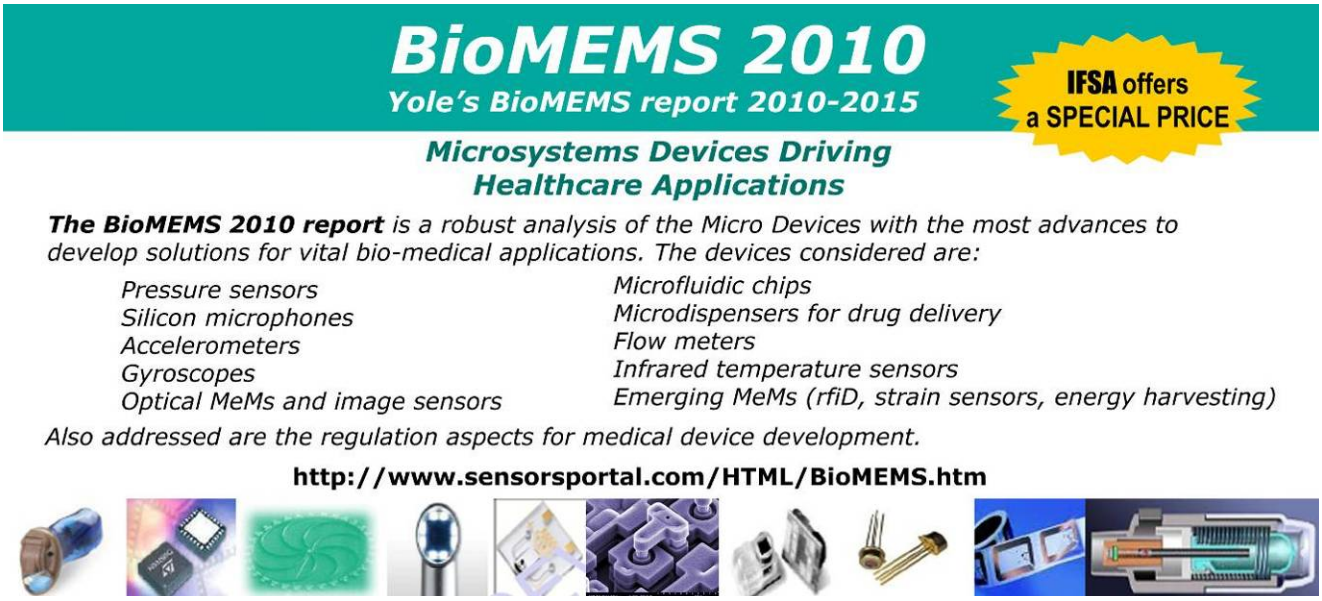

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A Novel Liquid Level Sensor Design Using Laser Optics Technology

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Abstract: New materials and technological developments in electronics and computers have changed all of the industries, as well as the world itself. These technological advancements have evolved automotive industry by redefining the concepts like: performance, efficiency, fuel consumption, driving dynamics, ergonomics etc. to a level far beyond expected. Oil level in an internal combustion engine today is estimated by use of ultrasonic sensor devices. In this paper, the development stages of a novel liquid level sensing device and the development strategy is presented in detail. Several prototypes of the proposed new sensor are developed and tested. Experimental results indicate that by using the laser optics technology, sensitivity ranges of 0.0266 Pa in air pressure and 0.0064 mm water height measurements may be achieved. *Copyright © 2012 IFSA.*

Keywords: Sensor(s), Laser optics, Liquid level sensor, Engine oil, Whispering Gallery Mode (WGM).

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1. Introduction

Oil sensors and analyzers are used in automotive and industrial applications to gather or send valuable information to ensure that the level of the engine oil does not become dangerously low without being noticed. The sensor monitors the oil level continuously during the entire engine operation, which means that the oil level can be prevented from falling below the minimum level during operation, which in turn means the oil film is not interrupted (which would lead to engine damage). Secondary influences such as the slope of the vehicle's lateral and longitudinal accelerations are compensated by the vehicle control unit calculating a mean value [1].

There are many oil level sensors in automotive, but most common approaches are ultrasound and resistance sensors [1, 2]. Sensors using a resistance wire work with the principle of changing resistance and temperature of the wire between under and over the liquid. Sensor sends a current to the wire, and the output voltage differs by changing liquid levels.

The ultrasonic level sensor, however, works on the principle of measuring the time-frame between transmitting and receiving of ultrasound waves. The ultrasound wave travels through material [2]. The sensors emit high frequency (20 to 200 kHz) acoustic waves that are reflected back to and detected by the emitting transducer affected by the changing speed of sound according to moisture, temperature, and pressures. Correction factors can be applied to the measurement level to improve the accuracy of measurement. Ultrasonic sensors have advantages in dynamic measurements; nevertheless they are more complex and more expensive when compared with the resistance wire type level sensors.

A new liquid level sensor design, aiming to place the ultrasonic sensor within the oil level pan to avoid external damage effects is presented in [1]. In this paper, a novel design using laser optic technology based on Whispering Gallery Mode (WGM) theory into liquid level sensing is presented [3, 4].

2. Liquid Level Sensor Development History

An ultrasonic wave propagation method was developed in 2001 by BF Goodrich airplane advanced sensors department [5]. The principle is the same with the study before, sending and collecting ultrasonic waves, and finding the liquid levels according to the wave transfer times.

A totally different method is the usage of fiber optics in liquid level measurement [6]. Fiber optic cables reflect the laser/light signal when in the air. However, when the density difference reduces, it transfers the laser light to the liquid environment and thus the sensor detects the liquid environment.

Fiber optics is used again in another study [6]. The methodology used is as follows. While in air, most of the light rays reflect back, but in water light rays continue their way. The decrease in the level of reflected signals indicates that the optical fiber tip is inside the water. The simplicity of the methodology implies that within the material property boundaries (between -20 ^{0}C and +70 ^{0}C) usage of optical fibers is easy, accurate and inexpensive.

In the case for automotive engine applications however, although all of the above methods have different advantages, a new method is required. The design must have high precision, and needs to be small enough to be located into the engine and must be durable enough for working under flammable liquids or gasses safely.

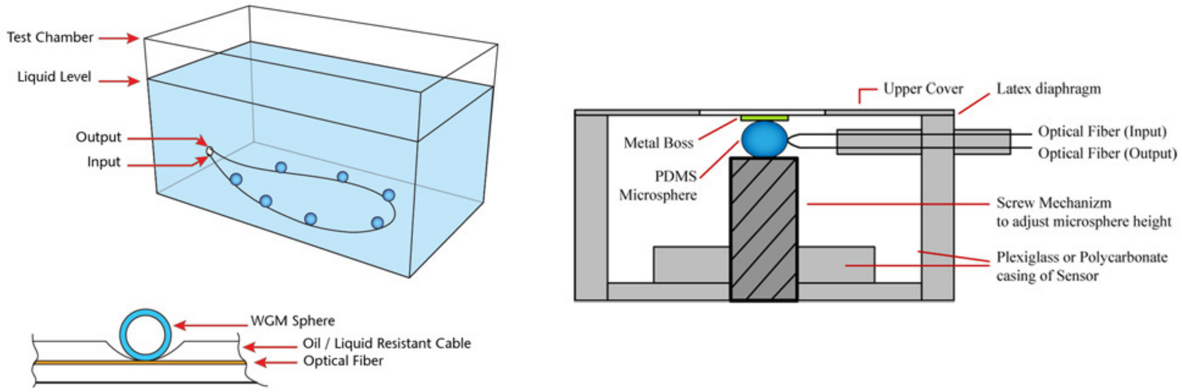
3. Whispering Gallery Mode Phenomenon

3.1. Sensor and Experimental Design

In collaboration with the Southern Methodist University Mechanical Engineering Faculty's Micro Sensors Lab. a totally new type of liquid level sensor is developed.

This new sensor is designed to detect pressure/force by using whispering gallery mode (WGM) phenomenon, and capable of working nearly in everywhere including underwater.

The target is to develop sensor prototypes using the existing WGM theory. The experimental design includes equipment such as; laser as the signal source, micro sphere as the sensing element, fiber optics, and a liquid container as the test medium (Fig. 1).



(a) (b)

Fig. 1. Experimental setup of liquid level sensor using WGM method (a), WGM sensor (b).

WGM sensor should be resistant to fluids therefore a latex type membrane is used in the experiments. Fig. 2 shows detailed proposal of how to encapsulate the WGM sphere to make the sensor resistant to the medium including liquids.

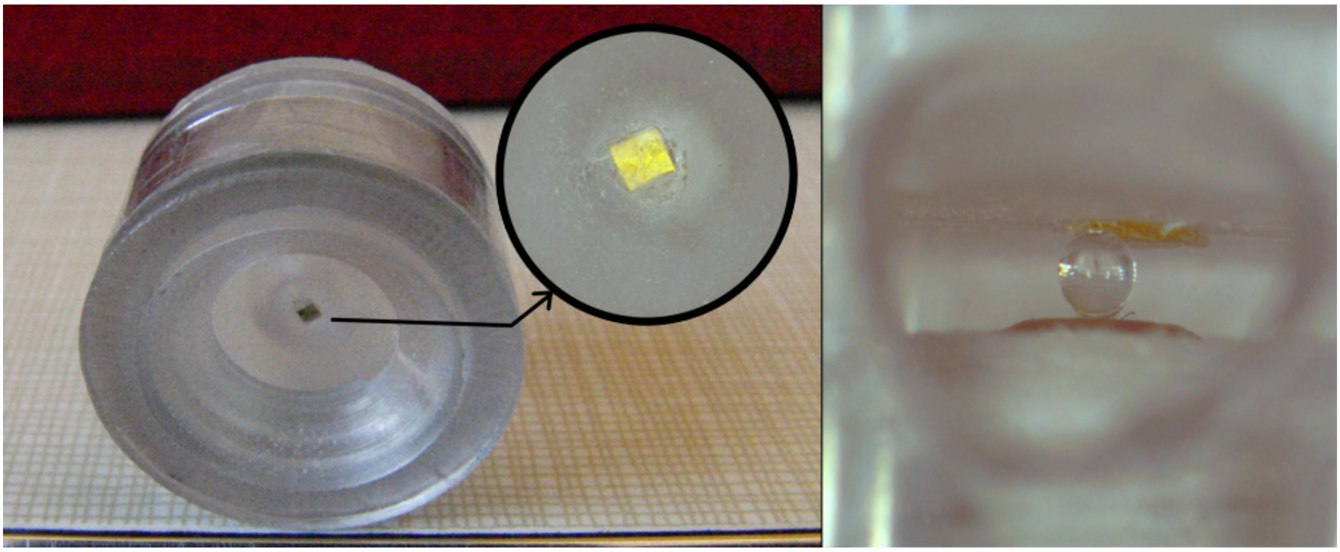
(a) (b)

Fig. 2. Screw mechanism (a); Optical fiber placed in sensor (b).

To obtain traceable WGM shifts, first the fiber is tapered to very small diameters, and then touches the tapered fiber's core to the exact center of a PDMS sphere by using many translational stages. When the correct location of the fibers by is assessed using optical devices, the resonances are observed clearly by using the in house developed software. After observing the WGM resonances, the locations of the fiber ends are kept stable in the sensor by using adhesives. After completing this step, the sensor can be re-placed into its exact measurement location.

When building the sensor, a metal boss of size 1 × 1mm was also added inside the membrane, by having metal surfaces in both ends of the sphere. After adding the metal boss, PDMS sphere is placed between two metal surfaces, where the upper boss surface exerts the pressure to the sphere, while the bottom screw stays stable.

There is a screw mechanism to place and tune the location of the PDMS sphere in its correct position to touch the metal boss above. Metal boss (Fig. 3.) of size 1x1mm is assembled on the diaphragm, and directly applies the pressure on the sphere.



(a) (b)

Fig. 3. Metal boss added to the latex membrane for greater sensitivity (a);
The microsphere touching metal boss (b).

3.2. Theory and Equations

In the whispering gallery mode theory, light undergoes total internal reflection, and because it is trapped inside the sphere, WGMs are observed under certain conditions.

The details of the theory, the changes in WGM spheres applied force is as follows [7]:

$$2\pi n_0 a = l\lambda , \tag{1}$$

where, λ is the vacuum wavelength of laser, n_0 is the refractive index , a is the radius of the sphere, l is the integer indicating the circumferential mode number.

A minute change in the size or the refractive index of the microsphere will lead to a shift in the resonance wavelength as:

$$\frac{d\lambda}{\lambda} = \frac{dn_0}{n_0} + \frac{da}{a}. \tag{2}$$

When a solid dielectric sphere of radius that is compressed by two pads made of high stiffness material, the applied force F will lead to a mechanical stress field inside the microsphere. It will also deform the sphere (strain), leading to a WGM shift. The deformation of the sphere can be obtained by solving the Navier equation [7]:

$$\nabla^2 u + \frac{1}{1 - 2\nu} \nabla \nabla \cdot u = 0, \tag{3}$$

where, u is the displacement of a given point within the sphere and ν is the Poisson ratio.

For a symmetric loading, the expression is:

$$u_r = \sum_n [A_n(n+1)(n-2+4\nu)r^{n+1} + B_n n r^{n-1}]P_n(\cos\vartheta), \tag{4}$$

r radial coordinate, ϑ polar coordinate, u_r radial component of displacement, P_n Legendre polynomial, A_n - B_n constants determined by the boundary condition at the sphere surface.

For an elastic body along with the stress-displacement relationship, the stress distributions within the sphere are obtained as:

$$\sigma_{rr} = 2G \sum [A_n(n+1)(n^2-n-2-2\nu)r^n + B_n n(n-1)r^{n-2}]P_n(\cos\vartheta),$$

$$\sigma_{\varphi\varphi} = 2G \sum \left\{ [A_n(n+1)(n-2-2\nu-4n\nu)r^n + B_n n r^{n-2}]P_n(\cos\vartheta) + [A_n(n+5-4\nu)r^n + B_n r^{n-2}]\cot\vartheta \frac{dP_n(\cos\vartheta)}{d\vartheta} \right\},$$

$$\sigma_{rr} = 2G \sum [A_n(n+1)(n^2-n-2-2\nu)r^n + B_n n(n-1)r^{n-2}]P_n(\cos\vartheta),$$

$$\sigma_{r\vartheta} = 2G \sum [A_n(n^2+2n-1+2\nu)r^n + B_n(n-1)r^{n-2}]\frac{dP_n(\cos\vartheta)}{d\vartheta}. \tag{5}$$

G= shear modulus of the sphere material.

Neglecting the friction at the contact point between the sphere and the plates, the boundary conditions are

$$\sigma_{rr}(a) = \begin{cases} -p(\vartheta), & 0 \le \vartheta \le \vartheta_0 \quad \text{and} \quad \pi - \vartheta_0 \le \vartheta \le \pi \\ 0, & \vartheta_0 \le \vartheta \le \pi - \vartheta_0, \end{cases}$$

$$\sigma_{r\vartheta}(a) = 0 \quad 0 \le \vartheta \le \pi, \tag{6}$$

where angle Vo defines the extent of the contact between the plate and the sphere. The pressure p exerted by plates of infinite stiffness on the sphere is given by

$$p(\vartheta) = \frac{3F}{2\pi a_0^3}\sqrt{a_0^2 - a^2\sin^2(\vartheta)}, \tag{7}$$

a_0 = the radius of contact area, as shown in Fig. 1 (b).

In order to obtain coefficients An and Bn in Eqs. (4) and (5), the boundary condition given in Eq. (6) has to be expanded in terms of the Legendre polynomial in the following form:

$$\sigma_{rr}(a) = \sum_n H_n P_n(\cos\vartheta). \tag{8}$$

Then the coefficient H_n is obtained as

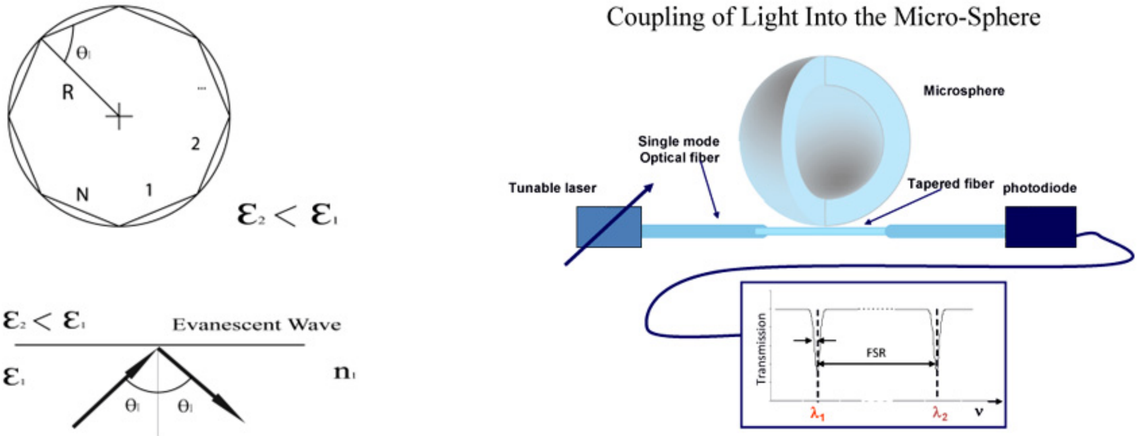
$$H_n = (2n+1) \times \int_0^{\pi/2} P_n(\cos\vartheta)\frac{3F}{2\pi a_0^3}\sqrt{a_0^3 - a^2\sin^2(\vartheta)}\,\sin\vartheta\, d\vartheta \tag{9}$$

By satisfying the boundary condition, Eq. (6), for Eqs. (5) and (8), coefficients A_n and B_n are obtained as follows:

$$A_n = \frac{H_n}{2Ga^n[(n+1)(n^2-n-2-2\nu)-n(n^2+2n-1+2\nu)]}.$$

$$B_n = -\frac{H_n}{2G[(n+1)(n^2-n-2-2\nu)-n(n^2+2n-1+2\nu)]} \times \frac{(n^2+2n-1+2\nu)a^{2-n}}{(n-1)} \tag{10}$$

When we look at Fig. 4, it can be seen that each time the light bounces off the inner surface of the sphere due to total internal reflection, the reflected wave experiences a “phase delay”, ϕ. This phase delay is a function of the light wavelength, λ; and incidence angle; as well as the sphere-to surrounding refraction index ratio, n_1/n_2.



(a) (b)

Fig. 4. Total internal reflections of the sensor (a); WGM Shifts (b).

As it can be seen easily, the laser light comes into the microsphere in its contact point in the tapered film, and the light undergoes total internal reflections in the sphere, which causes the phase shifts or in other words WGM shifts.

As illustrated in Fig. 5, while light starts re-circulating in the sphere a resonance shift occurs in the light when compared with the reference light beam.

Fig. 5 presents the experiment setup in its general form. The light coming from the laser splits into two, leaving a small percentage for reference going directly to the photodiode, while keeping a high percentage (90 % in this scenario) for WGM shift, which goes directly to the microsphere. So after the WGM phase shift occurs, it has been noticed by checking the differences between the reference light and WGM part of it.

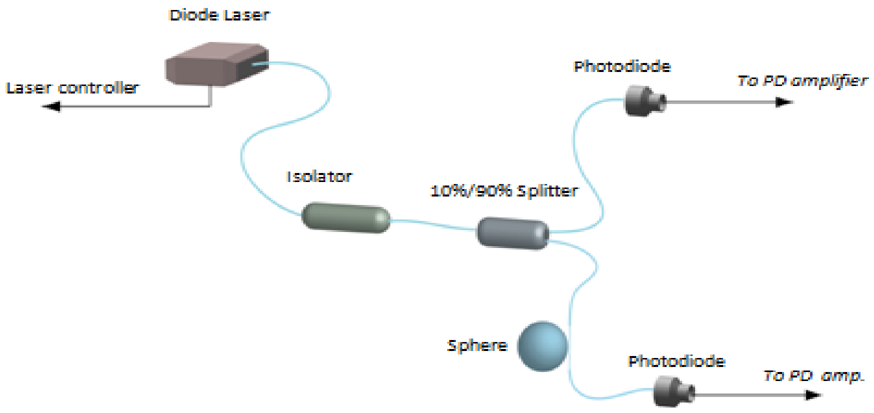
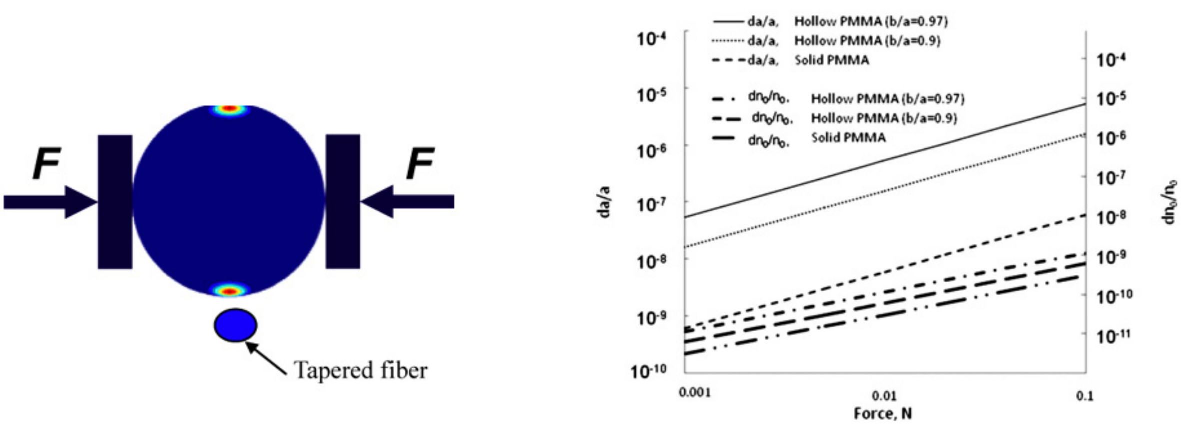


Fig. 5. The experiment setup [3].

The system is driven by a tunable distributed feedback laser (with 1.312 μm central wavelength and 10 mW maximum power). The current is tuned over a range of ~ 0.1 nm. The laser is coupled into a single mode optical fiber, whose output end is connected to a fast photodiode to monitor the transmission spectrum. A section of the fiber is tapered down to a diameter of ~ 10 μm (by heating and stretching the fiber). The microsphere is brought into contact with the tapered fiber section to facilitate light coupling between fiber and resonator. The transmission spectrum through the fiber is normalized by a reference signal taken directly from the laser. The transmission spectrum is digitized using a 16 bit analog to digital converter and the WGM positions are determined using an in-house software. A personal computer controls both the frequency tuning of the laser and the data acquisition [7].

When force is applied to the resonator, a change occurs in both the shape and index of refraction of the resonator (Fig. 6). The formulas below demonstrate that we can measure the force by detecting the changes occurred in the shape and the index of refraction [4].



(a) (b)

Fig. 6. Force is applied to the resonator (a); Force shifts the resonance(b).

Fig. 6 above shows that, the force shifts the resonance, but more importantly according to different materials, resonance shift also differs.

For the solid microsphere, the last term in Eq. (2) can be calculated by evaluating Eq. (4) at r=a and then dividing it by the sphere radius a:

$$\frac{da}{a}=\sum_{n}\frac{H_n}{4G(n^2+2n\nu+n+\nu+1)}\times\left[\frac{2-4n^2+\nu(4n^2-2n-4)}{n-1}\right]P_n(0) \tag{11}$$

Next the effect of stress on refractive index perturbation, dn_0/n_0, in Eq. (2) is determined.

Using the coordinate system illustrated in Fig. 7, Neumann–Maxwell equations provide the relationship between stress and refractive index as follows:

$$\begin{aligned} n_r &= n_{0r}+C_1\sigma_{rr}+C_2(\sigma_{\vartheta\vartheta}+\sigma_{\phi\phi}) \\ n_\vartheta &= n_{0\vartheta}+C_1\sigma_{\vartheta\vartheta}+C_2(\sigma_{rr}+\sigma_{\phi\phi}) \\ n_\phi &= n_{0\phi}+C_1\sigma_{\phi\phi}+C_2(\sigma_{\vartheta\vartheta}+\sigma_{rr}) \end{aligned} \tag{12}$$

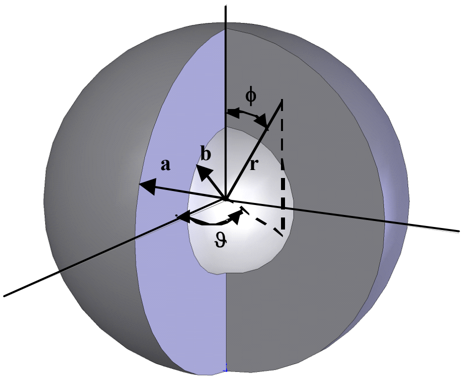


Fig. 7. Coordinate sytem used in the stress and strain formulation of a sphere.

Here n_r, n_ϑ, n_ϕ are the refractive indices in the direction of the three principle stresses and n_{0r}, $n_{0\vartheta}$, $n_{0\phi}$ are those values for the unstressed material. Coefficients C_1 and C_2 are the elasto-optical constants of the material, and for both PMMA and PDMS, $C_1=C_2$. For PMMA $C_1=C_2=C=-10^{-10}$ m^2 /N and for PDMS this value is $C_1=C_2=C= -1.75+10^{-10}$ m^2/N. Thus, for a spherical sensor, the fractional change in the refractive index due to mechanical stress is reduced to

$$\begin{aligned} \frac{dn_0}{n_0} &= \frac{n_r-n_{0r}}{n_{0r}}=\frac{n_\vartheta-n_{0\vartheta}}{n_{0\vartheta}}=\frac{n_r-n_{0\phi}}{n_{0\phi}} \\ &= \frac{C(\sigma_{rr}+\sigma_{\vartheta\vartheta}+\sigma_{\phi\phi})}{n} \end{aligned} \tag{13}$$

In the present WGM optical sensor, light is traveling in a plane that is normal to the applied force. Thus, evaluating the appropriate expressions for stress in Eq. (5) at $\vartheta=\pi/2$ and $r=a$, and introducing them into Eq. (13), the relative change in the refractive index due to force F is obtained as

$$\frac{dn_0}{n_0}=\frac{C}{2n_0}\sum_{n}\left[\frac{H_n(n+1)(n^2+3n+4+4\nu+4\nu n)}{(n^2+2\nu n+n+\nu+1)}\right]P_n(0). \tag{14}$$

Equations (11) and (14) represent the effect of strain and stress, respectively, on the WGM shift of the solid dielectric sphere. Plugging these into Eq. (2), we obtain the total WGM shift as

$$\frac{d\lambda}{\lambda}=\sum_{n}\frac{H_n}{2(n^2+2n\nu+n+\nu+1)}\times\left[\frac{2-4n^2+\nu(4n^2-2n-4)}{(n-1)2G}+\frac{C(n+1)(n^2+3n+4+4\nu+4\nu n)}{n_0}\right]P_n(0). \tag{15}$$

3.3. PDMS Sensor

Polydimethylsiloxane (PDMS) belongs to a group of polymeric organosilicon compounds that are commonly referred to as silicones [7].

PDMS is an elastomer that is a mixture of two components: a base and a curing agent. By changing the ratio between the base and the curing agent, it is possible to obtain elastic materials with Young's modulus ranging between 3 and 1000 kPa (corresponding to a baseto- curing agent volume ratio of 60:1 and 10:1, respectively) [7].

The Young modulus of a PDMS microsphere is substantially smaller than that of PMMA sphere of the same diameter resulting in comparable sphere deformations at much smaller force levels. Thus, determining the sensitivity of the PDMS force sensors is a more challenging task; the load-cell based measurement setup of would not provide sufficient resolution for sensor calibration. Moreover, since the force levels in these calibrations are ($<10^{-6}$ N), even the aerodynamic forces due to air currents (air drafts and natural convection) would have considerable adverse effect. To avoid such problems, the setup shown in Fig. 5 has been built and kept enclosed in a vacuum chamber, as shown in the figure.

In order to account for the sphere deformation, a Hertz-contact analysis was carried out on the spheres for a range of force values. Using this force versus deformation data and modeling the sphere as a linear spring system, the equivalent spring constant k_{sphere} was determined for each sphere size and PDMS mixture ratio used in the experiments. Then, the equivalent spring constant of the beam-sphere system was determined as: [4]

$$\frac{1}{k_e}=\frac{1}{k_{sphere}}+\frac{1}{k_{beam}}, \tag{16}$$

where the spring constant for the beam is

$$k_{beam}=\frac{3E\,\pi D^4}{64L^3}. \tag{17}$$

Here, E is the Young modulus, D is the diameter, and L is the length of the silica beam. The force exerted on the sphere is then calculated as

$$F=k_e\delta,, \tag{18}$$

where δ is the displacement of the translation stage and is determined by the Michaelson interferometer signal as

$$\delta=I\frac{\lambda_m}{2}. \tag{19}$$

Here, l is an integer and λ_m is the wavelength of the He–Ne, laser (632.8 nm).

The WGM shift dependence on the applied force for a solid PDMS microsphere of 910 μm diameter with base-to-curing agent volume ratio of 50:1 (E =10 kPa). The figure indicates a strong agreement between the experiments and Eq. (15).

3.4. Sensor Bandwidth

Sensor bandwidth is an important variable in most force measurements. We take the frequency at the first peak of the frequency response of the sensor as the first natural frequency of the sphere. In this approach, the other moving parts of the sensor are not taken into account and the sphere is considered undamped. It should be noted that the additional mass of the other moving parts will reduce the bandwidth estimate. We calculate the resonant frequency by numerically solving the characteristic equation for the sphere.

$$\frac{1-\nu}{1-2\nu}{}^{2}\left(a\frac{\omega_n}{C^*}\right)J_{1/2}\left(a\frac{\omega_n}{C^*}\right)-2\left(a\frac{\omega_n}{C^*}\right)J_{3/2}\left(a\frac{\omega_n}{C^*}\right)=0, \tag{20}$$

where 1n is the angular frequency, J_n's are the Bessel functions of first kind, and C^* is the compressive wave velocity defined as

$$C^*=\sqrt{\frac{\hat{\lambda}+2\mu}{\rho}}, \tag{21}$$

Where $\hat{\lambda}$ and μ are the Lamé constants and ρ is the microsphere material density.

As shown in Fig. 8, the sensor bandwidth is significantly smaller for sphere sensors with low Young's moduli than those with the higher values. For a given E, the smaller the sensor, the larger the bandwidth due to the effect of sensor mass.

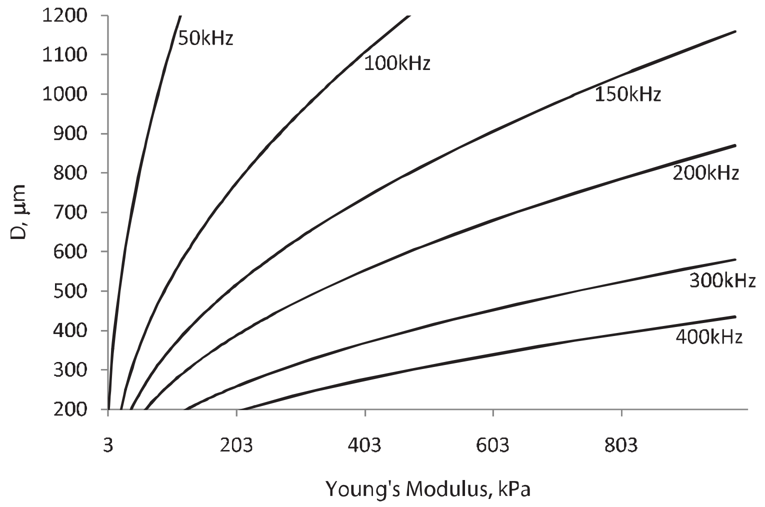


Fig. 8. Estimated sensor bandwidths for solid PDMS spheres.

Analytical studies of polymeric spheres under the effect of uniaxial compressive force have been carried out and the analysis has been validated through experiments. The results show that the force sensitivity for a WGM sensor is a function of the sphere material property and geometry. A wide range of sensitivities can be obtained by choosing different combinations of sphere material and geometry.

While the sensitivity can be improved by choosing a material with lower Young's modulus, there is a tradeoff in performance. For solid polymeric microspheres, the bandwidth of the sensor becomes smaller as the sensitivity increases.

For PDMS microsphere sensors, the analysis indicates that thin walled hollow PDMS sensors have both higher force resolutions and larger bandwidths than their solid counterparts, making them highly attractive in sensor applications. But in our case, a solid sphere is enough to measure the liquid depths, even more sensitive than its current competitors.

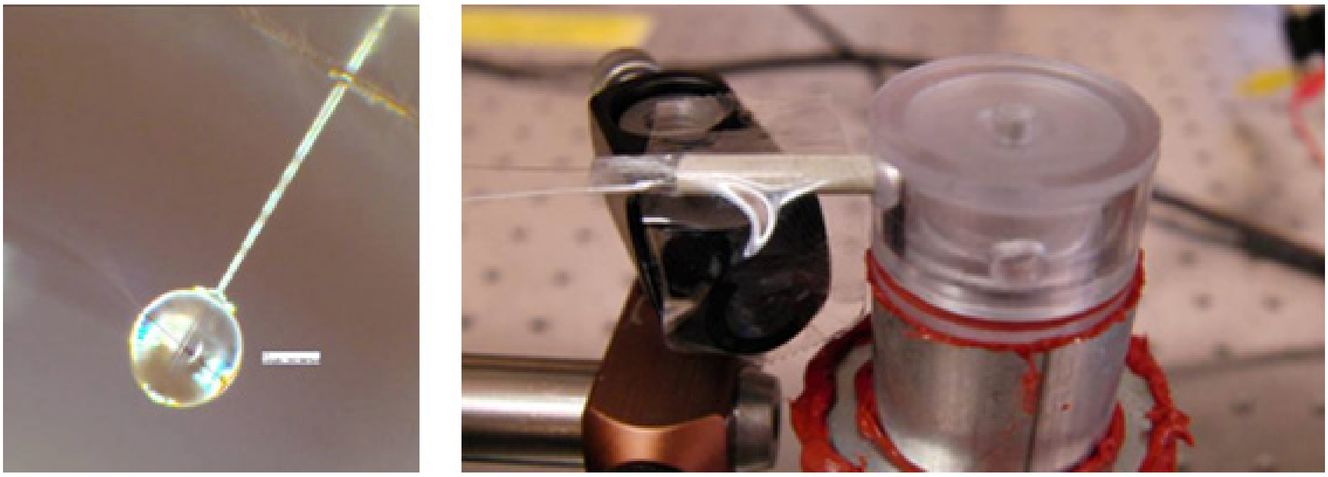
4. Experimental Results

4.1. Experimental Design

Using the above summarized approach; WGM shifts may be calculated according to the pressure changes of the medium, or in other words the external pressure changes.

For this aim, the most suitable experiment set up has been built to measure the pressure changes of the medium, which is related with the height of the liquid.

Sensor is produced in SMU's Micro Sensor Laboratories by the aid of manufacturing facilities. Then glassfiber has been thinned by using fire torch, to make it thinner enough to interact the core of the fiber with the sphere. After the tapering stage, by using different translational stages, fiber core touched to sphere's mid-point to turn the theory into reality (Fig. 9).



(a) (b)

Fig. 9. A typical PDMS sphere (a); sensor (b).

When the fiber core transfers the light to the sphere, light undergoes total internal reflections, and because it is trapped inside the sphere, where the WGM shifts are observed as shown in Fig. 10, which shows the WGM shifts are tracked and recorded by special software.

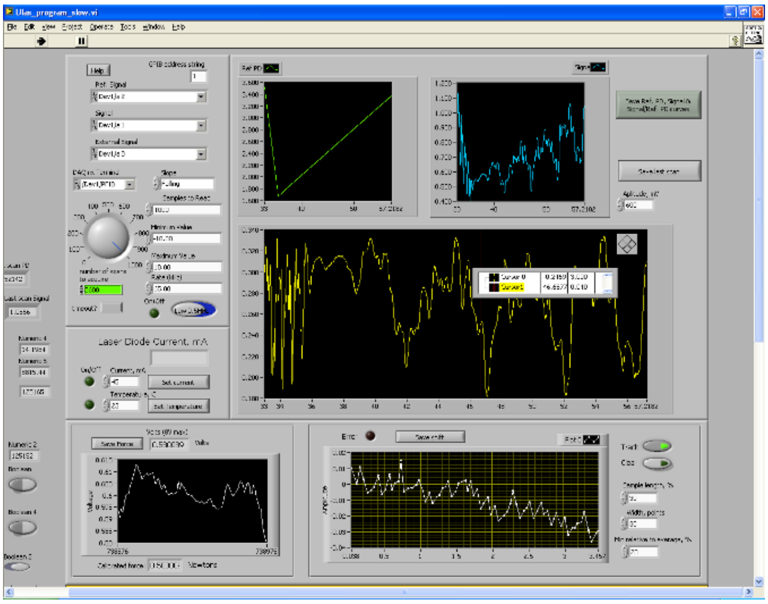


Fig. 10. The snap-shot of the software screen.

The air pressure experiments have been performed by applying pressure to a cylinder assembled on top of the sensor, by using a syringe (Fig. 11). A reference pressure signal is measured by a pipe which is connected to pressure transducer.

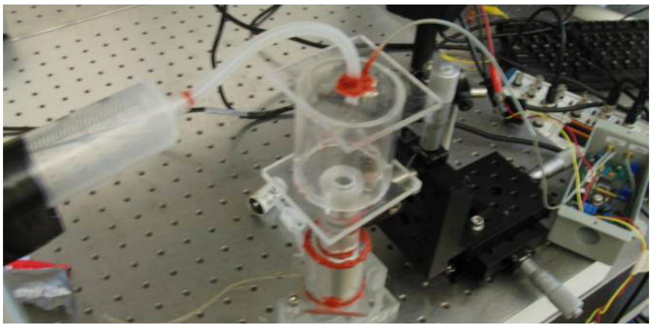


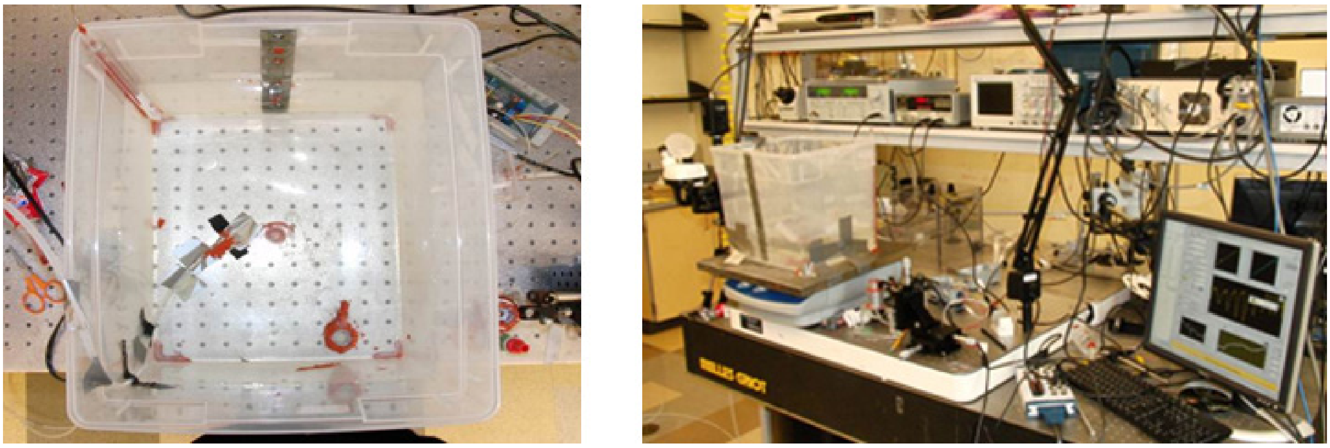
Fig. 11. The air pressure experiment.

Water pressure/depth experiments have been more complex. A u tube, again sealed and connected to the pressure transducer, as well as a mm scale added for calibrating the pressure transducer and changing the pressure values into mm water height.

General experiment setup can be seen in Fig. 12(b). For draining and adding water a pipe added to the container.

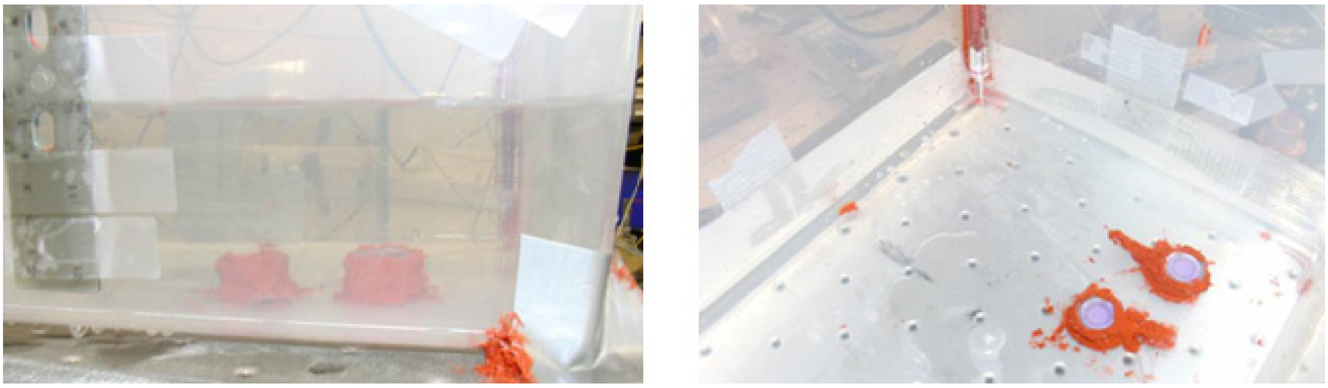
Two sensors were also put together, but the software was not able to track WGM shifts of two sensors at the same time.

For the industrial usage, serial production sensors with better quality products and finishes should be used according to the application requirements.



(a) (b)

Fig. 12. Water pressure/depth experiments(a); General experiment setup (b).



(a) (b)

Fig. 13. Two sensors in container (a); The sensors have covered with high temperature resistant silicon for water sealing (b).

4.1. Experimental Data

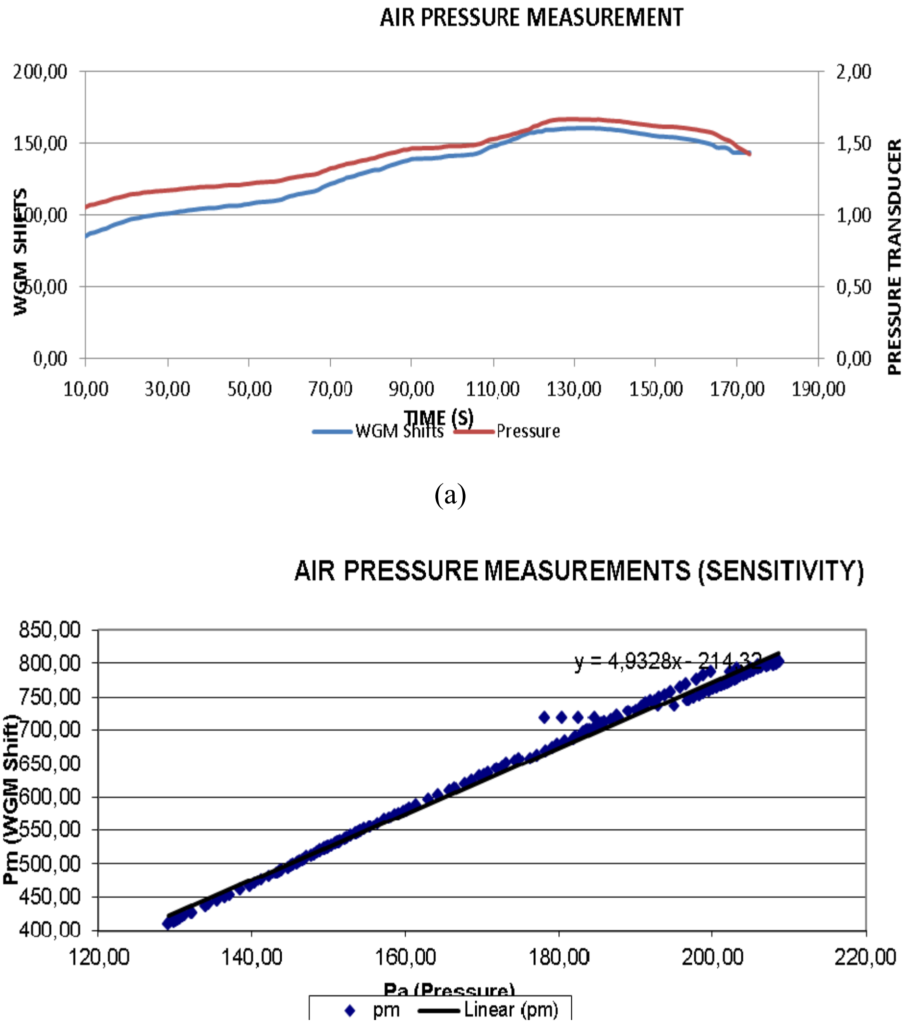
As expressed in the previous section, the initial experiments have been performed by first changing the air pressure, and then changing the liquid depths.

The recovered data is reviewed according to the experimental order.

Fig. 14 (b) shows the sensitivity of the sensor in air pressure measurements. Y axis represents the resonance shifts in Pm, while X axis represents the pressure changes in Pa.

The red line represents the pressure transducer, while the blue line represents the WGM resonance shifts in miliampers.

According to the data above, the sensitivity of the sensor is around 4-5 Pm/Pa.



(a)

(b)

Fig. 14. Air pressure measurements (a); The sensitivity of the sensor in air pressure measurements (b).

When we use the sensitivity formulas:

$$dF = \frac{1}{Q} \cdot \frac{\lambda}{S},$$

where Q is the Quality factor, S is the sensitivity of the sensor, dF is the minimum force difference that can be used, and λ is the laser's wavelength.

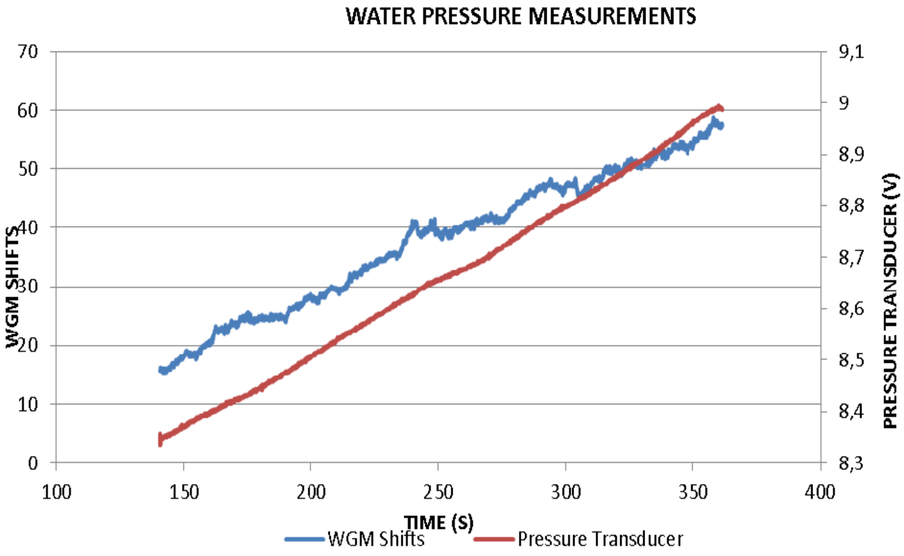
Therefore, in our case, the minimum force/pressure that can be detected is:

$$dF = \frac{1}{10^7} \cdot \frac{1{,}310 \cdot 10^6\, pm}{4{,}9238\, \dfrac{pm}{Pa}} \cong 0{,}0266\, Pa$$

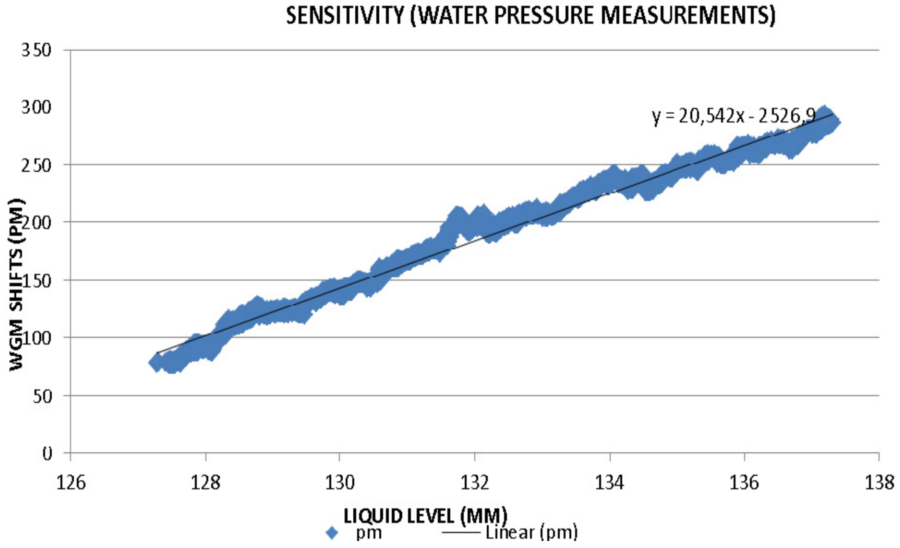
which is a very precise value.

Fig. 15(a) shows the water pressure measurements. The red line represents the pressure transducer, while the blue line represents the WGM resonance shifts in mA.

Fig. 15 (b) shows the sensitivity of the sensor in water pressure measurements during adding water. Y axis represents the resonance shifts in Pm, while X axis represents the pressure changes in Pa.



(a)



(b)

Fig. 15. Water pressure measurements (a); sensitivity of the sensor in water pressure measurements during adding water (b).

For reliability of the results, the pressure transducer was calibrated for each measurement either when filling or draining water.

Fig. 17 (a) shows the water pressure measurements during draining water. The red line represents the pressure transducer, while the blue line represents the WGM resonance shifts in miliampers.

Fig. 17 (b) shows the sensitivity of the sensor under water while draining water. Y axis represents the resonance shifts in Pm, while X axis represents the pressure changes in Pa.

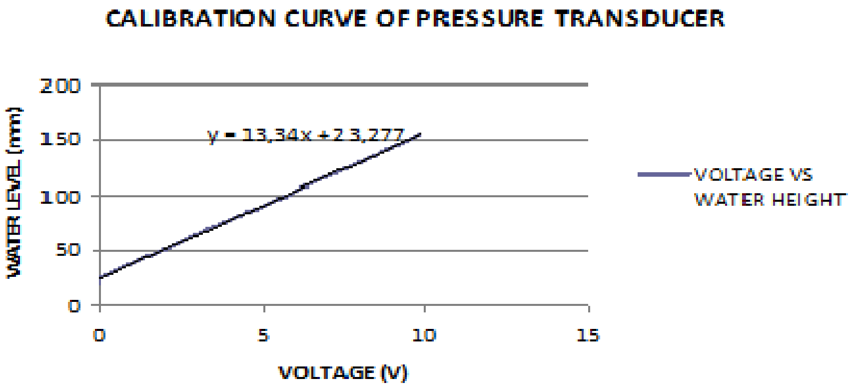
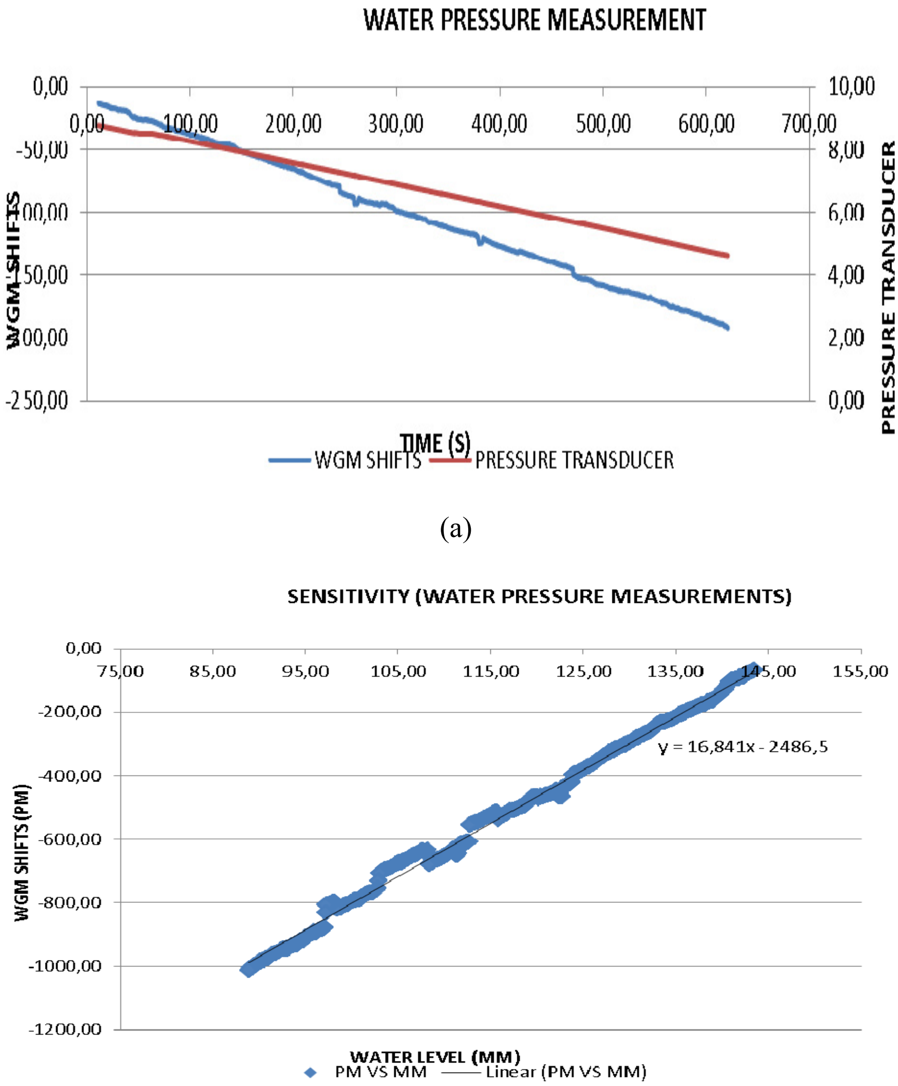


Fig. 16. Calibration of the transducer.



(a)

(b)

Fig. 17. Water pressure measurements during draining water (a); the sensitivity of the sensor under water while draining water (b).

When we use the sensitivity formulas for liquid level measurements:

$$dF = \frac{1}{Q} \cdot \frac{\lambda}{S}$$

So in our case, it can the minimum force/pressure that can be measured is:

$$dF_{Filling} = \frac{1}{10^7} \cdot \frac{1{,}310 \cdot 10^6\, pm}{20{,}542 \frac{pm}{mmH_2O}}$$
$$\cong 0{,}00637 mmH_2O = 0{,}0637 Pa$$
$$dF_{Draining} = \frac{1}{10^7} \cdot \frac{1{,}310 \cdot 10^6\, pm}{16{,}841 \frac{pm}{mmH_2O}}$$
$$= 0{,}0077 mmH_2O = 0{,}077 Pa$$

which is also a very precise value for sensing the liquid levels.

5. Conclusions

According to the results, it can be said that, we have a new WGM pressure sensor which has 4 Pm/Pa sensitivity in air pressure applications, so it is sensitive to measure 0.0266 Pa.

The sensors also have a sensitivity around 20 Pm/mmH_2O in water measurements, which is equal to the sensitivity of 0.0064 mm of water height differences, which is also a lot more sensitive than the current competitor devices capable of measuring ± 2 mm of water height differences. Also because of its optical principle can be worked in any environment without being affected by the availability of flammable liquids and gasses etc. it is a sensor that has a wide range of applications, therefore it is definitely a better sensor to be used in many different areas all around the globe.

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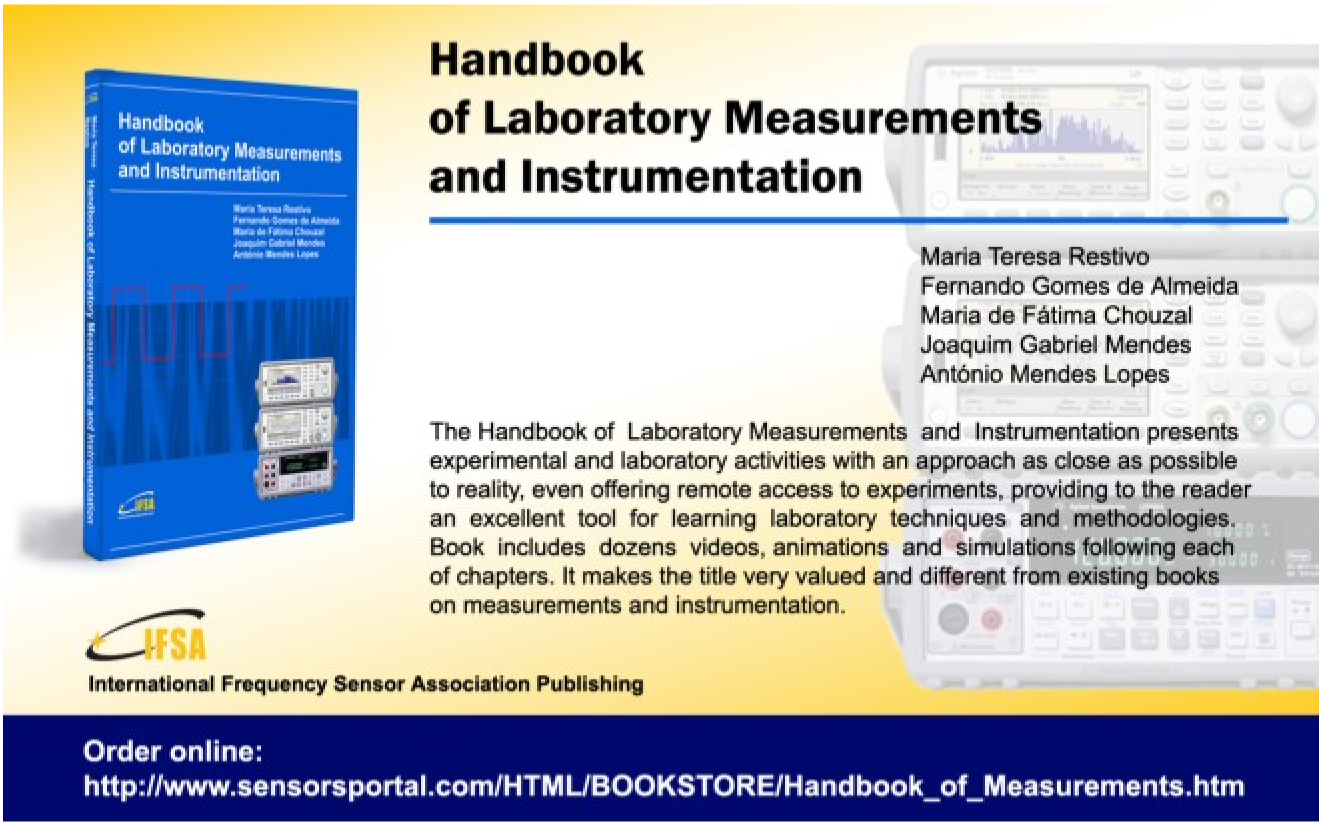

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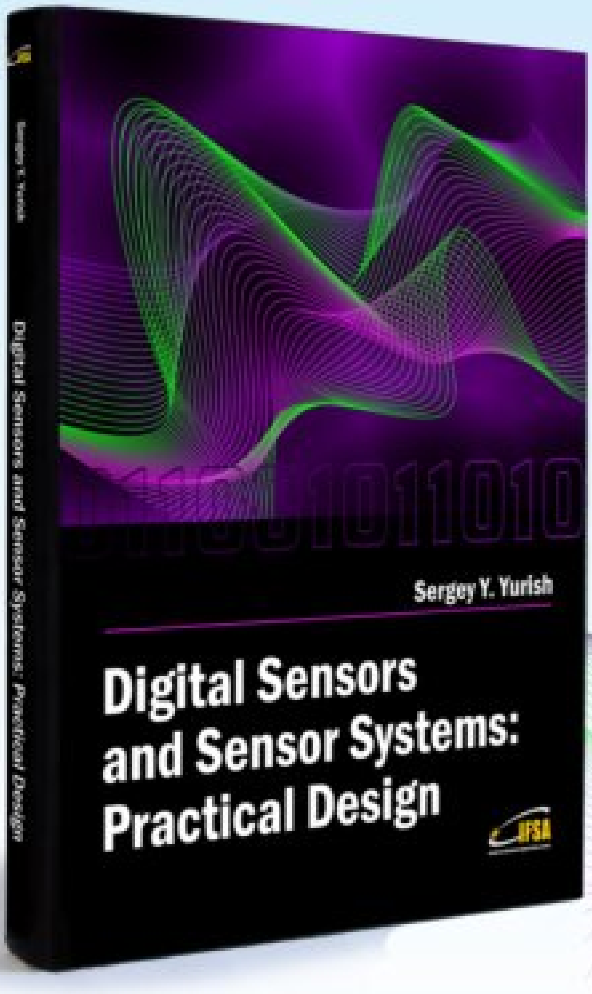
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