

Optoelectronic Signal Demodulation in Fiber-Optic Sensors for Precise Vehicle Fuel Level Quantification

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Abstract - Analog or digital displays are used in vehicles like two wheelers and four wheelers in recent days. Analog fuel gauges have demonstrated glaring errors that give a misleading impression of the fuel level. On the other hand, analog fuel meters use a needle pointer to represent the three fuel level states: empty, half, and full. In digital meters the amount of fuel indicated by bar levels, that levels are not a numeric values just indication only and also it is integrated to the speedometer. This study, which used embedded technology to provide a digital display of the precise amount of fuel in the vehicles fuel tank, aids in double-checking the amount of fuel added at the fuel station. The proposed fiber optics-based smart fuel meter displays the fuel level in liters, and the mileage can be determined using an Arduino and sensors based on the available fuel. It also calculates and displays the distance that can be traveled with the available fuel. This system measures and displays the amount of fuel added to the tank in liters each time the fuel tank is refilled.

Key Words: *Light diffusing fibers, Arduino, Laser Diode, Photo Detector.*

1. INTRODUCTION

The vehicles are manufactured with in build analog displays and that displays are showing the level of fuel in tank but the owner of vehicle will never get exact idea about how much fuel is available in tank. In Petrol pumps stations there are several complaints registered against the petrol pump owners for refilling errors in fuel tanks. On the other hand, the theft of the petrol from the tank of the vehicle often happens and not registered as a serious crime as its market values is small. The digital system will be effective to display amount of fuel present in tank with use of sensors for precision in readings.

Vehicles that store substantial volumes of Fuel, such two wheelers and four wheelers usually need to measure the fuel levels in their containers. Fuel depots, residential water sources, public water supply, and treatment facilities all

need to monitor liquids. Breweries and bottling firms also depend on liquid level monitoring to maintain standards and minimize financial loss. These liquids could be extremely flammable, inert, conductive, or nonconductive. Manual measurements are difficult in vehicles fuel tank and mechanical measures can be inaccurate for a number of reasons, including human emotions, fatigue, inattention, inaccurate equipment, and so forth. Therefore, research and development efforts have been directed toward creating autonomous liquid level detection technologies (Ehiagwina). The sending unit and the gauge are the two primary components of the analog fuel gauge. In this case, resistance values decrease and current value increases while the gasoline tank is full, and resistance values increase and current value lowers when the tank is empty [2].

In addressing these challenges, we have developed a cost-effective and innovative method and system for providing real-time mileage readings. This system accurately calculates the amount of fuel consumed, the available fuel level, and the distance traveled by the vehicle, while also estimating the remaining mileage in kilometers based on the available fuel.

2. LITERATURE SURVEY

The authors explores the implementation of a new transit time measurement algorithm is reported in this study. By analyzing the identified signal, it has been used to develop an intelligent ultrasonic sensor for fluid level measurement on tank. Additionally, a description is given of an online operational device prototype that was put together to show how well the algorithm works. They have investigated the algorithm performance using simulation experiments and present their results. Furthermore, the outcomes acquired from the field testing and implementation of the created sensor are shared [4].

The study by Anirudha Mule et.al [5] introduces a digital fuel meter that not only displays the fuel level but also has the ability to detect theft. It provides a higher level of accuracy than an analog meter. Even the most inexpensive liquid of days complies with conventional measurements, yet the priciest fuel which is most necessary for day to day life. An instrument used to show the amount of fuel in a tank is called a fuel gauge. These are widely utilized in the majority of cars, but they may be applied to any type of tank, including subterranean storage tanks. The gauge is used in vehicles and is composed of two parts: The indication and the sensing unit.

In a modern car, the sensing unit normally uses a printed ink design potentiometer that is coupled to a float. The float lowers as the tank empties, causing a movable contact to move along the resistor and increase resistance. In addition, certain vehicles will activate a "low fuel" indicator when the resistance reaches a particular point. The quantity of electric current passing through the sending unit is being measured and shown by the indicator unit. The needle indicates a full tank when it points to "F," which is the result of a high tank level and maximum current flowing. The needle indicates an empty tank when it points to "E," which is also the position at which the least amount of current is flowing [5].

Abdusalam Abdullahi Bayo et.al [6] proposes the Creation of a Digital Gauge to Measure Vehicle Fuel Consumption by using Arduino microcontrollers. Responsive buttons were employed to create a dynamic program design and make the application more user-friendly. In order to get the desired result at the lowest feasible cost without sacrificing the project's quality, performance, or functionality, the project circuit was also built utilizing the fewest electronics components that were readily available.

This work by Adebisi O.I. and Adejumbi AI proposes an underground liquid tank fuel level metering device that is straightforward, reliable, and reasonably priced. The most important tasks in the petrol sales industry is measuring fuel levels. It is simple to gather information from this operation about leaks, prompt refilling, fuel delivery, and fuel storage, among other things [7].

There are several methods for monitoring fluid levels, according to the literature [8],[9],[10],[11]. These include, but are not restricted to, inductive, mechanical, capacitive, ultrasonic, acoustic, and optical methods. Based on their

distinct qualities, each of these approaches has been used for a variety of applications. Capacitive and optical techniques have been widely employed for fluid level monitoring, while mechanical and ultrasonic techniques have been used extensively for solid materials in the form of dust (Suleiman et al., 2015 and Montero et al., 2012). In this work, a straightforward and effective fuel level monitoring system for subterranean liquid tanks was developed using an ultrasonic sensor and a microcontroller. The fundamental qualities of the ultrasonic sensor, such as its capacity to be utilized for Being a non-contact device, it has the advantages of continuous and point-level sensing, cheap cost, high precision, and the possibility to be deployed for remote or wireless operations. It operates throughout a broad operating range of 0.02 to 4 m and requires very little power. The system measures fluid level using a signal that travels at 343 m/s, which is easy for the inexpensive microcontroller to process. The microcontroller served as the system's brains, making the produced system more reliable, small, and digital in its output.

Vehicles need to accurately calculate fuel capacity for both safety and financial reasons. To provide information about the fuel level, a variety of fuel gauging systems and sensors have been used. These systems typically require electrical wires, sensors, probes, and other electronic components to extend into the fuel tank. This can pose an explosion risk if the electrical circuits are damaged. As a result, some researchers have proposed using optical sensors as an alternative. A summary of the performance of various continuous optical level sensors is provided in Table 1.

The table 1 provides an overview of various optical sensing mechanisms, which can be linked to light diffusion fiber technology in the context of fuel gauging systems. Light diffusion fiber technology involves the use of optical fibers to detect changes in the environment, such as fuel levels in a tank, through the interaction of light signals. The sensors listed in the table 1 such as macro-bend fiber couplers, etched D-shaped fibers, and Fabry-Perot interferometers are examples of optical sensing technologies that rely on the principles of light propagation and interference. These sensors can be integrated into fuel tanks to precisely measure fuel levels without introducing the risk of electrical sparks or explosions, which is a critical advantage in hazardous environments.

TABLE I: Key Features of Continuous Level Sensing Devices

Authors	Sensing Mechanism Overview	Range[m]	Resolution[mm]
Y. Zhang et al.[21]	Macro-bend fiber coupler	0.6	0.008
S. M. Chandani and N. A. F. Jaeger [22]	Etched D-shaped fiber	0.02	1
G. Betta, A. Pietrosanto, and A. Scaglione [23]	Removed cladding Fiber	1	25
M. Lomer, A. Quintela, M. Lopez-Amo, J. Zubia, J. M. Lopez-Higuera [24]	Side Polished fiber	0.04	2.2
B. Preložnik, D. Gleich, and D. Donlagic [25]	Fabry-Perot Inteferometer	1	3
C. Li et al., [26]	MZ Interferometer	0.0751	15
C. Li et al., [27]	Multimodal Interference	0.045	0.046
B. Yun, N. Chen, and Y. Cui [28]	Etched FBG	0.02	2

The performance characteristics, such as range and resolution, vary significantly across these technologies, with some offering high-resolution measurements at smaller ranges (e.g., the macro-bend fiber coupler with a resolution of 0.008 mm and range of 0.6 meters), while others like the removed cladding fiber provide a larger range but at lower resolution (e.g., 1 meter range and 25 mm resolution). These differences highlight the flexibility of light diffusion fiber technology, which can be tailored to suit specific requirements in fuel monitoring applications, depending on whether high precision or longer range is prioritized.

Overall, light diffusion fiber technology offers a promising alternative to traditional electrical sensing systems, providing a safer and more reliable method for monitoring fuel levels in vehicles while minimizing the risk of explosive hazards. By integrating this optical sensing technology into an intelligent fuel management system using an Arduino setup, it becomes possible to create an efficient, cost-effective, and automated solution for real-time fuel monitoring, optimizing fuel usage, and improving vehicle performance while ensuring safety and accuracy.

3. PROPOSED SYSTEM METHODOLOGY

This paper introduces a novel sensor design for continuous fuel level measurement, utilizing coupled light diffusing fibers (LDFs). In glass-based LDFs, submicron-sized light-scattering centers are embedded within the fiber core [13]. These scattering centers facilitate uniform light scattering along the fiber's sides as it propagates. By choosing a wavelength that is strongly absorbed by the fuel, the length of the fiber coupling is determined by the portion of the fiber immersed in the fuel. The coupling behavior has been analytically modeled using coupled power equations, with co-propagation configuration being examined. In the co-propagation setup, changes in output power exhibit a linear relationship with the fuel level. The scattering-based coupling mechanism enables the optical fibers to couple, even when positioned at relatively large distances, in terms of wavelength. This method simplifies sensor fabrication and improves its overall reliability. Experimental results are in strong agreement with the theoretical model, validating the sensor's performance. The sensor consists of two parallel LDFs that are coupled. The first fiber is connected to a laser diode, which diffuses light into the fuel. A portion of the light is then coupled into the second fiber and directed to a photo detector.

4. PRINCIPLE OF SENSING BASED ON LIGHT COUPLING

The light-diffusing fibers are positioned side by side at a distance d , which is greater than the operating wavelength λ . The illuminating fiber is connected to a light source, while the detection fiber is linked to the detection system. The coupling mechanism used is based on scattering from random imperfections within the light-diffusing optical fiber, which results in power transfer between the two fibers. Consequently, the light scattered by the illuminating fiber is coupled to the detection fiber via scattering. The coupling between the fibers is influenced by the properties of the diffusing fiber, the distance d , and the optical characteristics of the medium between the fibers. When the fuel strongly absorbs scattered power, the coupling amount depends on the length of the fiber portion immersed in the fuel. Therefore, the optical power detected by the detection fiber is directly related to the fuel level being measured [19].

The coupling occurs along the region $C = \{x: 0 < x < L_{max} - L\}$, where L is the fuel level and L_{max} is the sensor's range. In contrast, in the filled region $F = \{x: L_{max} - L < x < L_{max}\}$, no coupling is assumed between the fibers, as the fuel is highly absorbent at the operating wavelength λ .

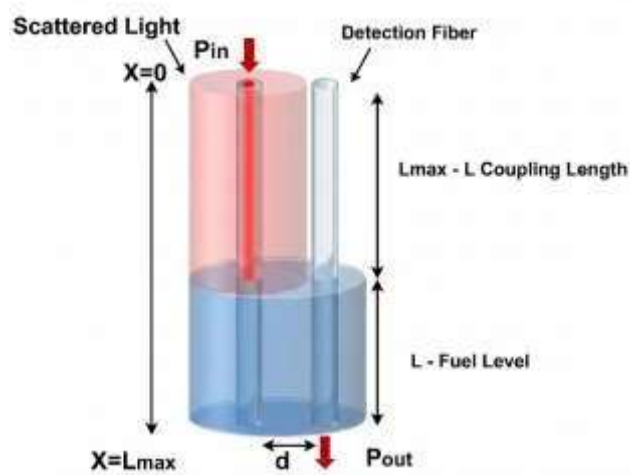


Fig. 1 Co-propagation configuration sensor layout

Within the described framework, co-propagating configurations are considered, as shown in Fig. 1. A detailed quantitative description of the light-coupling mechanism used by the sensor is provided in the analytical model presented in the next section.

5. THEORETICAL ANALYSIS AND MODELING PROCESS

Several authors have analytically derived these coupled power equations using perturbation theory and statistical methods. It is important to note that the existing solutions are typically based on specific assumptions. Therefore, we (re)derive the solution to the coupled power equations in a more general form that is suitable for our application. Coupled power equations are commonly used to describe the effect of mode coupling in single optical fibers or between multiple fibers, caused by imperfections in the fiber structure [15]–[19].

A. Co-Propagation Coupling Approach

The power coupling between two co-propagating waves can be mathematically expressed as a first-order system of ordinary differential equations [16]–[19], given by:

$$\begin{aligned} \frac{dP_0}{dx} &= -(\alpha + \beta)P_0 + \beta P_1 \\ \frac{dP_1}{dx} &= \beta P_0 - (\alpha + \beta)P_1 \end{aligned} \quad (1)$$

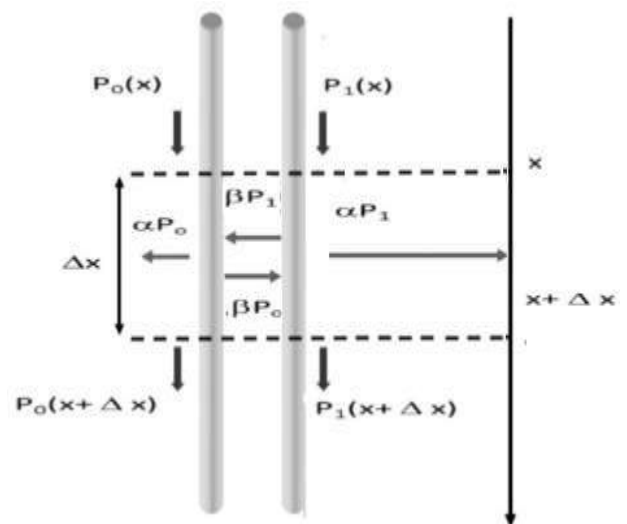


Fig. 2 Co-Propagation Coupling model

In this model, $P_0(x)$ and $P_1(x)$ represent the average power in the illuminating and detection fibers, respectively, while x is the distance along the fiber. The coupling coefficient is denoted by β and α refers to the attenuation coefficient (in terms of power) of the fibers. For simplicity,

it is assumed that the attenuation in both the illuminating and detection fibers is equal.

The system of equations (1) offers a straightforward interpretation. A power balance across an elementary cell of length Δx , which is equivalent to equation (1), is depicted in Fig. 2. Due to fuel absorption, the coupling coefficient $\beta(x)$ can be expressed as:

$$= \begin{cases} \beta_0 & \text{for } 0 < x < L_{max} - L \\ 0 & \text{for } L_{max} - L < x < L_{max} \end{cases} \quad (2)$$

System (1) applies only within the coupling region $C = \{x: 0 < x < L_{max} - L\}$, where L is the fuel level, and L_{max} is the sensor's range.

In the co-propagation configuration, the input power P_{in} is injected into the illuminating fiber at $x = 0$, and the output power P_{out} is measured at $x = L_{max}$ in the detection fiber (see Fig. 1). By applying the boundary conditions $P_0(0) = P_{in}$ and $P_1(0) = 0$, the solution to system (1) can be written in closed form as

$$\begin{aligned} P_0(x) &= \frac{P_{in}}{2} e^{-\alpha x} (1 + e^{-2\beta x}) \\ P_1(x) &= \frac{P_{in}}{2} e^{-\alpha x} (1 - e^{-2\beta x}) \end{aligned} \quad (3)$$

using equation (3), the average power in the detection fiber at the end of the coupling length ($x = L_{max} - L$) can be written as:

$$P_1(L_{max} - L) = \frac{P_{in}}{2} e^{-\alpha(L_{max}-L)} (1 - e^{-2\beta(L_{max}-L)})$$

6. EXPERIMENTAL SETUP

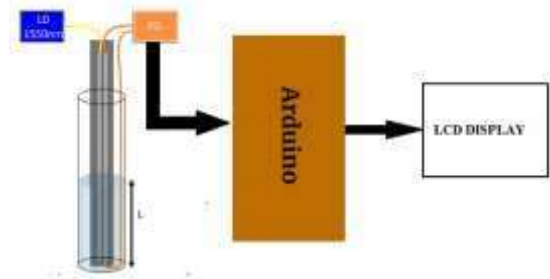


Fig 3. Experimental Setup

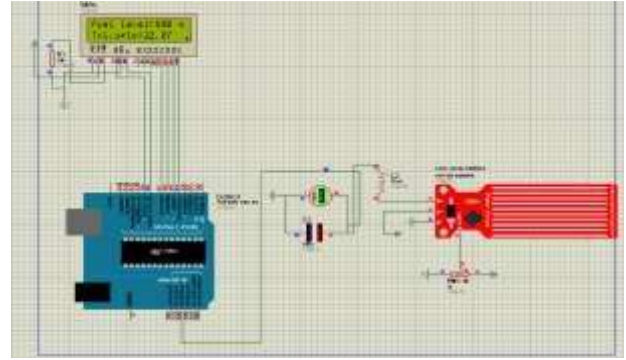


Fig 4. Simulation Setup

Thus, the output power measured at the end of the detection fiber ($x = L$) is:

$$\begin{aligned} P_{out} &= P_1(L_{max} - L) e^{-\alpha L} \\ &= \frac{P_{in}}{2} e^{-\alpha L_{max}} (1 - e^{-2\beta(L_{max}-L)}) \end{aligned} \quad (4)$$

It is important to note that in the region $F = \{x: L_{max} - L < x < L_{max}\}$, the system (1) applies with $\beta = 0$ (for a strongly absorbent fuel), which justifies the factor $e^{-\alpha L}$ appearing in equation (4)

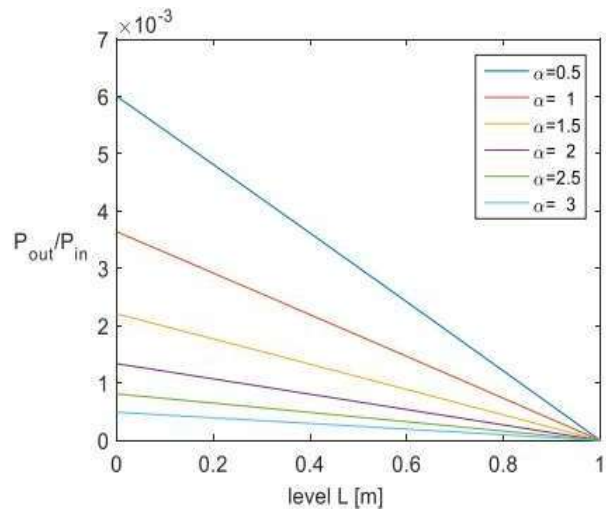


Fig: 5 Normalized output power P_{out}/P_{in} as a function of fuel level L , $\beta = 0.01 \text{ m}^{-1}$ and $\alpha = 0.5 - 3 \text{ m}^{-1}$.

A high-sensitivity photodetector (PD) (Thorlabs PDF10C, $NEP = 7.5 \text{ fW}/\sqrt{\text{Hz}}$, bandwidth of 25 Hz) is connected to a Arduino Board to measure the output power of the detection fiber at different fuel levels. The choice of a 25 Hz bandwidth is based on the fact that the sensor is designed for vehicle, where quick response times are essential. Fuel, with an attenuation coefficient of

$\alpha=1210 \text{ m}^{-1}$ at 1550 nm [29], is used as the test fuel. All experiments are conducted with the sensor shielded from ambient light using a black curtain. The fiber attenuation at 1550 nm is evaluated using the cut-back technique.

The experimental setup and an image of the assembled fuel level sensor are depicted in Fig. 4. The sensor is mounted inside a graduated cylindrical testing container, with the fuel level continuously varying from 0 mm to 950 mm using a peristaltic pump. A 1550 nm fiber-coupled laser diode (LD) with an output power of 30 mW is used as the light source, and the attenuation coefficient α is estimated to be approximately 1 m^{-1} . The key specifications of the fiber used are summarized in Table II.

TABLE II

Parameter	Value
NA (Numerical Aperture)	0.5
Diffusion Length	1.0[m]
Core diameter	$170 \pm 3 [\mu\text{m}]$
Cladding diameter	$230 \pm 10 [\mu\text{m}]$
Jacket diameter	900[μm]

7. CONCLUSION

A fiber optic sensor designed to continuously measure the fuel level within a fuel tank has been proposed. The sensor utilizes two parallel side-diffusing optical fibers coupled together. By selecting a wavelength that is strongly absorbed by the fuel, the power transferred between the fibers varies with the fuel level. The coupling between the co-propagating waves has been both theoretically modeled and experimentally tested. The measurement results align well with the theoretical model, demonstrating that both configurations are suitable for fuel level sensing. In the co-propagation configuration, the resolution ranges from $\pm 5 \text{ ml}$ at low fuel levels to $\pm 10 \text{ ml}$ at higher fuel levels, over a wide measurement range of approximately 20 cm. These results are comparable to the performance of interferometry sensors listed in Table I.

8. REFERENCES

[1]. Johnny J, Amos S, Prabhu R. Optical Fibre-Based Sensors for Oil and Gas Applications. *Sensors*. 2021 Sep 9;21(18):6047.
[2]. RefJaimon Chacko Varghese, Binesh Ellupurayil Balachandran "Low Cost Intelligent Real Time Fuel Mileage Indicator for Motorbikes" (IJITEE), Volume-2, Issue-5, April 2013

ences:
[3]. Chi X, Wang X, Ke X. Optical Fiber-Based Continuous Liquid Level Sensor Based on Rayleigh Backscattering. *Micromachines*. 2022 Apr 17;13(4):633–3.
[4]. G. Bucci, "Numerical method for transit time measurement in ultrasonic sensor applications," *IEEE Trans on Instrumentation and Measurement*, vol. 46, no. 6, pp. 1241- 1246, 1997.
[5]. Anirudha Mule et al. Study Of Digital Fuel Meter And Fuel Theft Detection, *International conference on Emerging Trends in Engineering and Management Research* 2016 March 23, 1531-38.
[6]. David Sánchez Montero et al. Development of a Digital Gauge for Fuel Consumption in Vehicles, *International Journal of Research Publication and Reviews*, Vol 3, no 2, pp 102-108, February 2022.
[7]. Adebisi O. I., et al. Development Of A Fuel Level Measuring System For Underground Liquid Tanks, *FULafia Journal of Science & Technology* Vol. 4 Special Edition, September 2018.
[8]. K. A. Mohd Annuar et al. Design and Construction of Liquid Level Measurement System, *Journal of Advanced Research in Applied Mechanics*, Vol. 12, No. 1. Pages 8-15, 2015
[9]. Suleiman M, Saidu GI, Ilyasu MI, Adeboye OA, Hamza M. Ultrasonic Fluid Level Measuring Device. *International Journal of Research in Science*. 2015 Jun 15;1(1):27.
[10]. Vivek Tiwari and Anshul Jain, Implementation of Capacitive Fluid Level Sensor. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering* Vol. 3, Issue 1, January 2014.
[11]. Montero DS, Lallana PC, Vázquez C. A Polymer Optical Fiber Fuel Level Sensor: Application to Paramotoring and Powered Paragliding. *Sensors*. 2012 May 10;12(5):6186–97.
[12]. Design And Fabrication Of An Automated Irrigation System For Agriculture Fields. *International Research Journal of Modernization in Engineering Technology and Science*. 2023 Apr 27;
[13]. S. Logunov, E. Fewkes, F. Shustack, and F. Wagner, "Light diffusing optical fiber for illumination," in *Proc. Renewable Energy Environ.; OSA Tech. Dig. (Online), Opt. Soc. Amer., Washington, DC, USA, 2013, Paper DT3E.4*.
[14]. D. Marcuse, "Derivation of coupled power equations," *Bell Syst. Tech. J.*, vol. 51, pp. 229–237, 1972. [15] H. E. Rowe, "Propagation in one-dimensional random media," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-19, no. 1, pp. 73–80, Jan. 1971
[17] D. Marcuse, "Coupled power equations for backward waves," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-20, no. 8, pp. 541–546, Aug. 1972.
[18] M. Koshihara, K. Saitoh, K. Takenaga, and S. Matsuo, "Multi-core fiber design and analysis: Coupled-mode

theory and coupled-power theory,” *Opt. Express*, vol. 19, pp. B102–B111, 2011.

[19] Imperatore P, Persichetti G, Testa G, Bernini R. Continuous Liquid Level Sensor Based on Coupled Light Diffusing Fibers. *IEEE Journal of Selected Topics in Quantum Electronics*. 2020 Apr 22;26(4):1–8.

[20] S. Kedenburg, M. Vieweg, T. Gissibl, and H. Giessen, “Linear refractive index and absorption measurements of nonlinear optical liquids in the visible and near-infrared spectral region,” *Opt. Mater. Express*, vol. 2, pp. 1588–1611, 2012.

[21] Y. Zhang et al., “Enhancement of a continuous liquid level sensor based on a macro-bend polymer optical fiber coupler,” *IEEE Photon. J.*, vol. 10, no. 1, Feb. 2018, Art. no. 6800806.

[22] S. M. Chandani and N. A. F. Jaeger, “Optical fiber-based liquid level sensor,” *Opt. Eng.*, vol. 11, 2000, Art. no. 114401.

[23] G. Betta, A. Pietrosanto, and A. Scaglione, “A digital liquid level transducer based on optical fiber,” *IEEE Trans. Instrum. Meas.*, vol. 45, no. 2, pp. 551–555, Apr. 1996.

[24] M. Lomer, A. Quintela, M. Lopez-Amo, J. Zubia, J. M. Lopez-Higuera, “A quasi-distributed level sensor based on a bent side-polished plastic optical fibre cable,” *Meas. Sci. Technol.*, vol. 18, pp. 2261–2267, 2007.

[25] B. Preložnik, D. Gleich, and D. Donlagic, “All-fiber, thermo-optic liquid level sensor,” *Opt. Express*, vol. 26, pp. 23518–23533, 2018.

[26] C. Li et al., “Liquid level and temperature sensor based on an asymmetrical fiber Mach–Zehnder interferometer combined with a fiber Bragg grating,” *Opt. Commun.*, vol. 372, pp. 196–200, 2016.

[27] C. Li et al., “Liquid level measurement based on a no-core fiber with temperature compensation using a fiber Bragg grating,” *Sensors Actuators A: Physical*, vol. 245, pp. 49–53, 2016.

[28] B. Yun, N. Chen, and Y. Cui, “Highly sensitive liquid-level sensor based on etched fiber Bragg grating,” *IEEE Photon. Technol. Lett.*, vol. 19, pp. 1747–1749, 2007.

[29] S. Kedenburg, M. Vieweg, T. Gissibl, and H. Giessen, “Linear refractive index and absorption measurements of nonlinear optical liquids in the visible and near-infrared spectral region,” *Opt. Mater. Express*, vol. 2, pp. 1588–1611, 2012.