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Short note

Microfiber loop resonator for formaldehyde liquid sensing

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A R T I C L E I N F O

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A B S T R A C T

This work employed the whispering gallery mode (WGM) of microfiber loop resonator (MLR) for formaldehyde (CH_2O) liquid sensing application. A significant sensing response to different concentrations of formaldehyde liquid from 0% to 5% was observed due to the surface absorption and changeable refractive index resulting in different light attenuation in the silica microfiber. As the concentration increases, the output power of the MLR decreased linearly from −18.9 dB m to −36.2.dBm with sensitivity increased by a factor of 2.5 as compared to straight microfiber (SmF). As for resolution, the MLR improved by a factor of 3.28 as compared to SmF.

1. Introduction

Formaldehyde (CH_2O) also known as methanal is a carcinogenic volatile organic compound (VOC). It is a pungent-smelling gas, colourless and commonly used as a regent for adhesives such as phenol-formaldehyde (PF) resins and urea-formaldehyde (UF) [1]. It has been commonly employed in various industries applications such as in resins, plastics, and paints production factory. It has also been illegally exploited as a preservative in fish, meat, vegetables, and fruits to avoid spoilage and increase value from their fresh appearance [2]. It is soluble in water and could cause irritating through direct contact [3]. It could become serious threatening to human health such as vomiting, abdominal pain, renal injury, coma, coughing, breathing difficulties, nausea and sneezing due to inhaled and absorption of skin if it is over ingest [4]. In the low concentrations at between 1 to 3 ppm levels could cause irritation in the throat, eyes and nose and levels more than 15 ppm would cause a fatality. Furthermore, it could affect the nervous system and has been identified as a substance that could cause cancer in living tissue. Therefore, detection, monitoring and controlling the formaldehyde concentration level is of paramount importance [5]. Thus, a highly sensitive formaldehyde sensor is essential for environmental protection and human health

Microfiber has received great attention for optical sensing due to its unique features such as compact size, evident surface field enhancement, strong evanescent field, configurability, large abnormal waveguide dispersion, strong near-field interaction with its surrounding and good evanescent coupling between itself and other waveguides [6]. Power fraction in the evanescent field varies

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with the changes of surrounding refractive index. It is essential for sensing application where significant interaction with the surrounding medium is a need [7,6]. High fractional evanescent field enabling fast responses and highly sensitive refractive index measurement towards physical sensing [8]. The sensing performance is normally observed based on the loss of light energy or phase change [9]. Thus, extensive sensing applications have been conducted by utilizing the microfiber such as ultra-sensitive surface absorption spectroscopy [10], hydrogen detection [11], humidity [12], temperature [13], rotation [7] and the most rampant refractive index sensor [14]. In order to improve the sensing performance, numerous microfiber structure has been developed such as microfiber knot resonator [15], microfiber loop resonator [16], Fabry-Perot interferometer [17] and fiber coupler [18].

Microfiber loop resonator (MLR) is a miniature version of the fiber loop resonator that consists of a directional coupler and single mode fiber which was developed back in 1982 [19]. The MLR's overlapping area is maintained by the Van der Waals force and static electricity. The coupling efficiency of the MLR can perform better by adiabatically slow variation during the tapering process in the coupling region [19]. MLR exhibit numerous advantages such as high resolution, quick response, anti-interference, stable measurement and small size [20]. In addition, it offers large fractions of evanescent waves, stable chemical properties, simple structure, easy preparation, and low transmission loss. These factors enhance the interaction between guided light and surrounding specimens which is the dominant factor for the optical sensor. Furthermore, the concept of whispering gallery mode (WGM) resonating on the resonator cavity cause MLR to have minimal insertion losses which is suitable for sensing application. The resonation quality is calculated using Q-factor based on resonated wavelength.

Up to the present time, several sensing methods to detect formaldehyde has been employed such as spectroscopy [21], cataluminense [22], chemiresistor [23] and bio-sniffer [24]. While numerous existing optical formaldehyde sensors with coated nanomaterials required highly meticulous attention during the synthesis process and have the possibility to degrade the performance of the microfiber [13,25,26]. These existing methods required high cost, huge equipment, complicated manufacturing process and high-temperature operation [13]. Therefore, we proposed a low cost, simple and workable formaldehyde liquid sensing which employs the microfiber loop resonator that is capable to overcome those drawbacks on the current sensing method develops [1]. In this paper, an application of MLR for formaldehyde liquid sensing is demonstrated for the first time to our knowledge. It has been realized by manually twist the tapered fiber under an optical microscope into a self-touching loop. The proposed sensor could reduce the complexity to access the interaction of the evanescent wave from MLR for formaldehyde liquid sensing. The experiment results prove that the proposed sensors are capable to comply with the key requirements of the optical sensor such as high linearity, high sensitivity, and high resolution. In future, other microfiber geometries structures can be employs for formaldehyde liquid sensing to compare their sensing performances.

2. Experimental details

In the beginning, the microfiber was fabricated from a standard single-mode fiber (SMF-28, Corning) using flame brushing technique [27]. The silica fiber was tapered into uniform waist diameters of 7 μm for around 8 mm tapering length. The MLR was manually looped under an optical microscope into a 300 μm self-touching loop. The output ends aligned in parallel to each other due to the surface attraction by Van Der Waals force and electrostatic which avoid the elastic forces that could straighten out the microfiber [28]. The MLR waist and loop diameter were measured by using the microscope (Medilux-12) with 20X magnification. Fig. 1 shows the example of MLR with a waist diameter of 7 μm and loop diameter of 300 μm.

The experimental setup of the formaldehyde liquid sensing is illustrated in Fig. 2. The MLR was positioned inside the sealed chamber (22 × 12 × 12 cm). An Amplified Spontaneous Emission (ASE) from an erbium doped fiber amplifier (EDFA) with wavelength range of 1530 nm – 1560 nm and maximum total output power of + 20 dBm was launched through one end of the MLR and the other end was connected to an optical spectrum analyzer (OSA) (Anritsu: MS9710C) for measuring the transmissions mode and

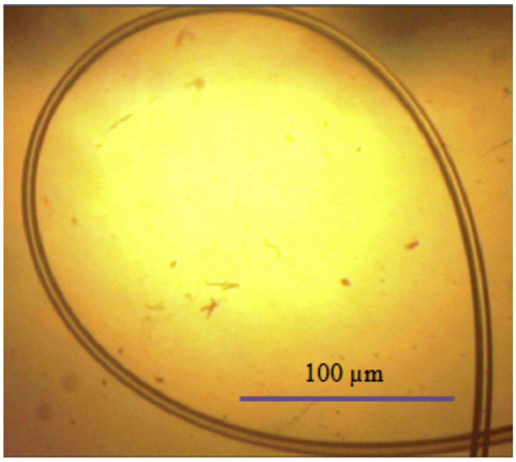


Fig. 1. Microscopic image of the MLR with a waist diameter of 7 μm and loop diameter of 300 μm.

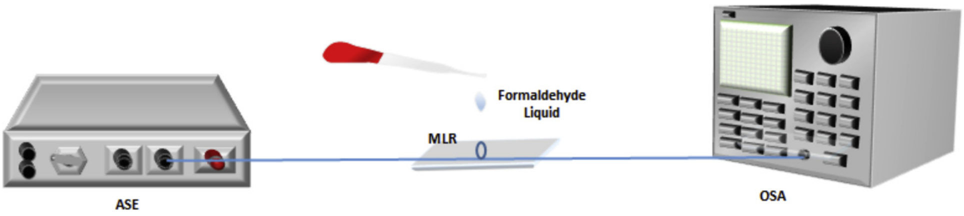


Fig. 2. Experimental setup of formaldehyde liquid sensing.

output power. The output power spectrum from the MLR was measured using the OSA measured in dBm. The formaldehyde liquid was dropped onto the MLR and the change of output power was observed. As a remark, the liquid need to evenly spread out around the MLR. The concentration of the formaldehyde was varied from 0% to 5%. The readings were recorded several times for repeatability and stability of the detection. The sensitivity (S) was obtained through the slope of sensing response of the MLR in unit dBm/%. Eventually, the experiment was then repeated on SmF for performance comparison purpose.

3. Sensing mechanism

The liquid molecules absorbed to the surface of MLR's cladding increased when the formaldehyde liquid concentrations vary from 0% to 5%. Hence, the refractive index of the cladding would increase when the air medium is replaced with other specimens. Refractive index is correlated with evanescent field and play dominant role to the sensor's performances. Evanescent field absorption varies when the surrounding environment change. As the liquid concentrations increases, the absorption on the cladding surface also increase due to the interaction between the evanescent field and the liquids. Therefore, more evanescent field appeared at the sensing region would leads to the changes in the refractive index of the cladding and modulate the output light intensity. This scenario increase the surface absorption of liquid particles that induces additional scattering losses which increase the transmission losses [29,30]. In the case of MLR that exhibit resonation along the wavelength range, additional resonator loss occurs that resulting in the reduction of light propagation inside the MLR when the liquid concentrations increase. This is due to the light oscillation in the MLR magnifies the loss, thus reduced the intensity of guided light inside the MLR. Henceforth, the amount of transmitted light reduced and consequently translated into changes of output power and increased the sensor sensitivity [31,32]. Fig. 3 illustrates the transmitted light of SmF and MLR during the formaldehyde liquid sensing. Based on Fig. 3(a), the light source is launched in non-tapered region 1 (R1). The transmitted light started to decrease in region 2 (R2) due to the reduction of the waist diameter and continue to reduce in region 3 (R3). Refer to Fig. 3(b), the same behaviour takes place in R1 and R2. However, a rapid reduction occurs in R3 due to the magnification of losses by the MLR. As a result, the output power reduced more drastically and improves the sensor sensitivity as compared to the SmF.

4. Result and discussion

Fig. 4 shows the transmission mode of the MLR when dropped by different formaldehyde liquid concentrations. The insertion loss varies from -25 to -41 dBm when the MLR immersed by the solution. The loss may be optimized by reducing the free overlap of MLR's coupling region. The resonating wavelength with different depth varies in different formaldehyde liquid concentrations. Sharp resonance peaks are apparent for the highest formaldehyde liquid concentration which is 5%. The Q-factor was calculated based on formula $\lambda/\Delta\lambda$, where λ is the resonance wavelength and $\Delta\lambda$ is a Full-Width-Half-Maximum linewidth of the resonant wavelength [9]. As shown in Fig. 4, the calculation was taken from the range of wavelength of 1550 nm to 1560 nm. The range is the selected for Q-

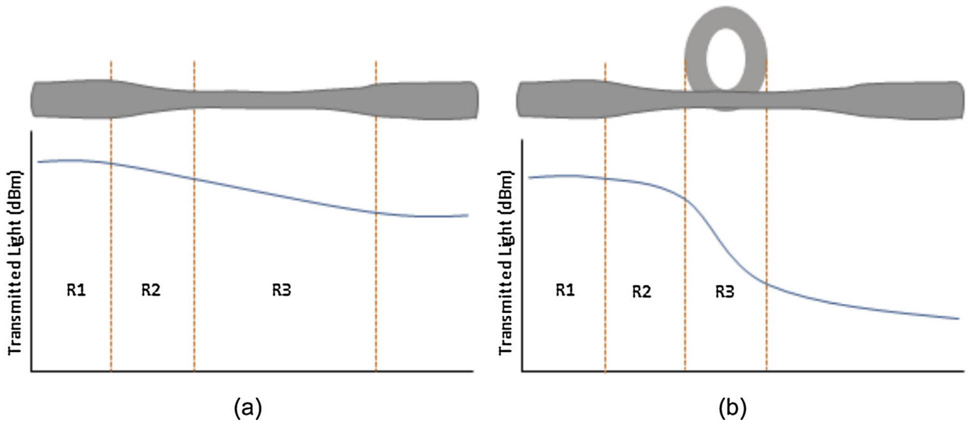


Fig. 3. The transmitted light of (a) SmF and (b) MLR during sensing.

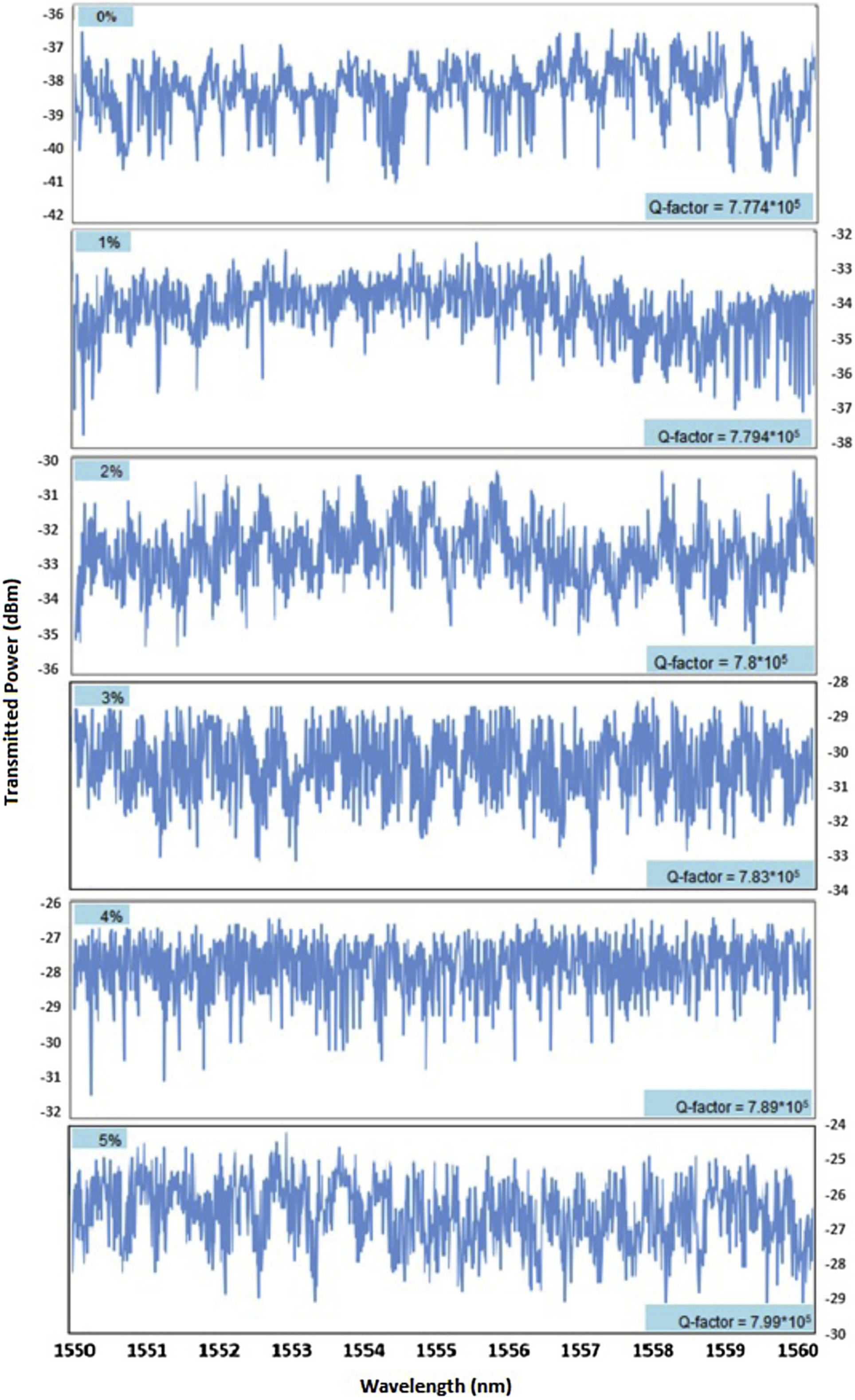


Fig. 4. Whispering Gallery Mode (WGM) transmission modes of MLR.

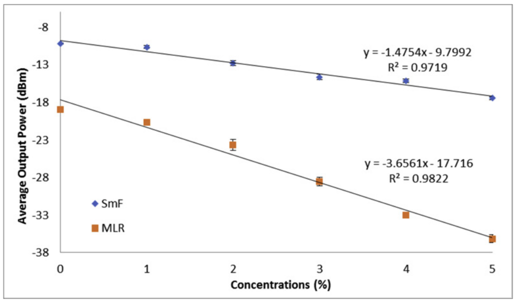


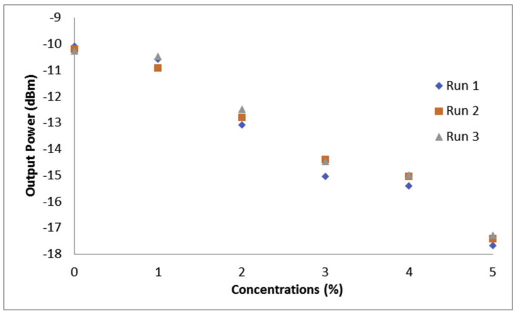
Fig. 5. The response of the MLR and SmF towards formaldehyde sensing.

factor calculations because the resonation is sharp and clear. The Q-factor was calculated to be > 10^5 for all concentrations which represent a high-quality resonator. Any physical changes to the MLR outer environment will change the resonating behaviour and lead to the variation of the output signal which is good for sensing application [20]. The Q-factor increased from 7.774×10^5 to 7.99×10^5 when the concentration increases from 0% to 5%. This is due to the change of refractive index that increases as the formaldehyde liquid concentrations increase [5].

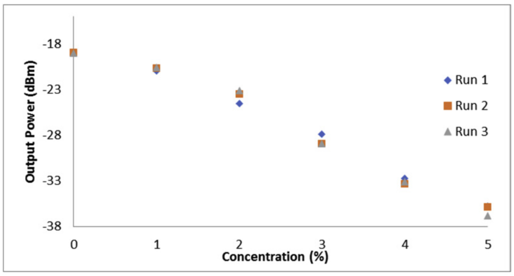
The real-time responses of the MLR and the SmF towards formaldehyde liquid concentrations from 0% to 5% were recorded as shown in Fig. 5. It was found that the output power decreased linearly when the formaldehyde liquid concentrations increase. MLR showed higher linearity and sensitivity as compared to the SmF. It is eminent that the refractive index of the MLR increases with the increment of liquid concentrations due to the surface absorption of water molecules [31]. This lead to the more resonator loss which causes light propagation inside the MLR relatively reduced when the liquid concentrations increase. This is due to the light oscillation in the MLR magnifies the loss, thus increasing the sensor sensitivity. In the case of SmF, the sensor was also able to respond to the change of the concentrations but the loss of light is lesser due to the absence of resonation. Consequently, the intensity of guided light inside the SmF has less affected upon the liquid concentrations changed [32].

Fig. 6 depicted the repeatability of the MLR and SmF towards formaldehyde liquid sensing. Based on Fig. 6(a), SmF produces an irregular trendline especially at 1%, 2% and 3% concentrations which illustrates the inconsistent results for repeatability. For MLR in Fig. 6(b), the trendline graph of all three runs of experiments improved throughout the concentration range. Eventually, the stability of the MLR was observed by acquiring data for every 1 s for a total period of 10 min (600 s) [33]. Fig. 7(a) and (b) depict the graph of the output power against time of the SmF and MLR for formaldehyde sensing from 0% to 5% respectively. The results show that the output power obtained for MLR is more stable throughout the period as compared to the SmF especially at 0%, 1% and 3% liquid concentration.

Table 1 summarizes the sensing performances of the SMF and MLR configurations. It is noteworthy that the overall sensing

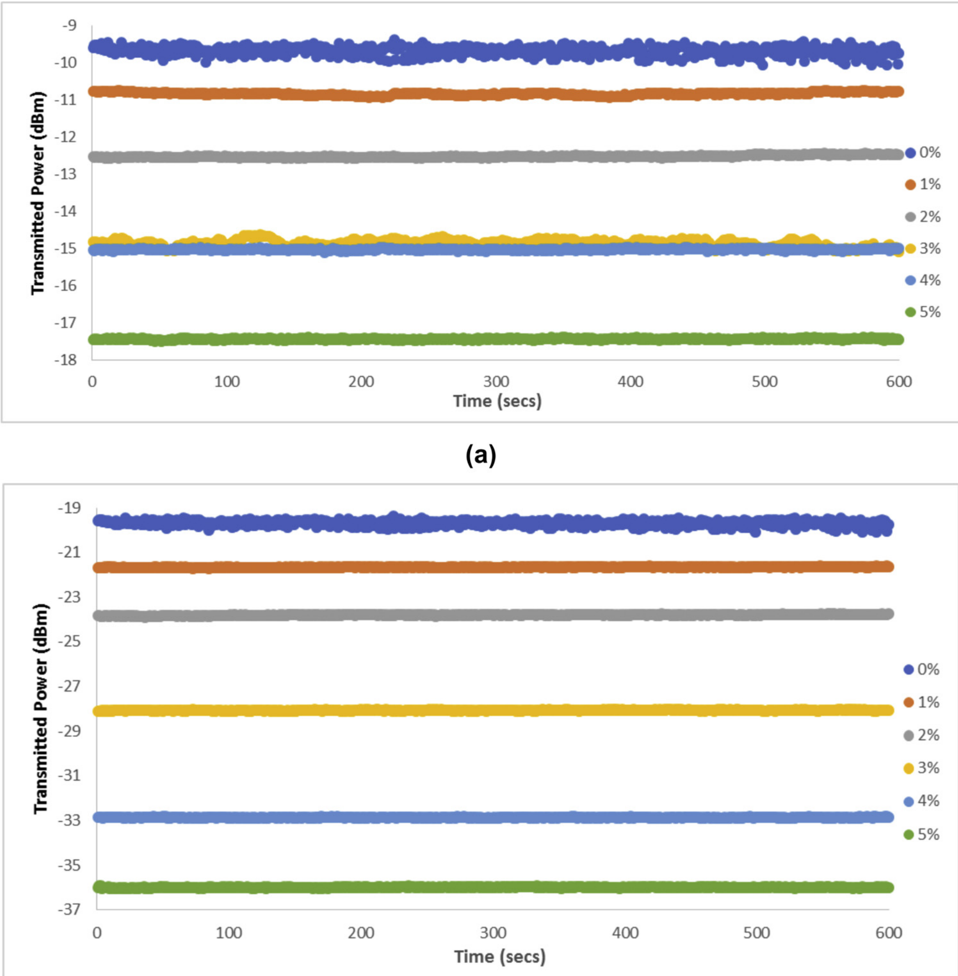


(a)



(b)

Fig. 6. The repeatability of (a) a SmF and (b) a MLR towards formaldehyde liquid sensing.



(a)

(b)

Fig. 7. Stability of the proposed sensor incorporating (a) a SmF and (b) a MLR in formaldehyde liquid sensing.

Table 1
Sensing performance of the formaldehyde liquid sensor.

Parameters	SmF	MLR
Linearity (%)	98.60%	99.10%
Sensitivity (dBm/%)	1.4754	3.6561
Standard Deviation (dBm)	0.1000	0.0757
Resolution (%)	0.0678	0.0207

performance of the MLR towards formaldehyde liquid is superior as compared to SmF. The linearity of the MLR is better with 99.1% as compared to SmF with 98.6%. Furthermore, the sensitivity of the MLR improved impressively by a factor of 2.5 as compared to the SmF. The standard deviation of the MLR is 0.0757 dB m which is better than SmF with 0.1 dB m. Moreover, the MLR produced better sensing resolution as compared to the SmF with a factor of 3.28. As reported aforementioned, Q-factor increased as the formaldehyde liquid concentration is increasing due to changes in the effective refractive index.

5. Conclusion

A formaldehyde liquid sensor was successfully demonstrated by using microfiber loop resonator. The simple and workable sensor reduced the complexity during the fabrication and manufacturing process because there was non-involvement of sensitive material coated on it. Overall, MLR has shown better sensing performance as compared to the SmF. The sensitivity enhanced by a factor of 2.5 as compared to SmF. The resolution also improved by a factor of 3.28 as compared to the SmF. The MLR demonstrated significant improvements in terms of linearity, sensitivity, standard deviation, and resolution towards formaldehyde liquid concentration level detection as compared to SmF. This is due to the power loss due to light leakage during the formaldehyde liquid sensing is magnifies inside the MLR lead to a better sensing performance. This phenomenon does not exist in SmF due to the absence of resonation. The proposed sensor has superiority in term of simplicity, highly sensitive, easy fabrication, low cost and small in size. It is crucially important in the applications such as determining toxic gases and monitoring human health [3]. In future, the formaldehyde liquid sensing could be applied to a more complex optical microfiber resonator to identify the sensing performance.

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