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Demonstration of a Polymer-Based Single Step Waveguide by 3D Printing Digital Light Processing Technology for Isopropanol Alcohol-Concentration Sensor

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Abstract: A polymer based horizontal single step waveguide for the sensing of alcohol is developed and analyzed. The waveguide is fabricated by 3-dimensional (3D) printing digital light processing (DLP) technology using monocure 3D rapid ultraviolet (UV) clear resin with a refractive index of $n = 1.50$. The fabricated waveguide is a one-piece tower shaped ridge structure. It is designed to achieve the maximum light confinement at the core by reducing the effective refractive index around the cladding region. With the surface roughness generated from the 3D printing DLP technology, various waveguides with different gap sizes are printed. Comparison is done for the different gap waveguides to achieve the minimum feature gap size utilizing the light re-coupling principle and polymer swelling effect. This effect occurs due to the polymer-alcohol interaction that results in the diffusion of alcohol molecules inside the core of the waveguide, thus changing the waveguide from the leaky type (without alcohol) to the guided type (with alcohol). Using this principle, the analysis of alcohol concentration performing as a larger increase in the transmitted light intensity can be measured. In this work, the sensitivity of the system is also compared and analyzed for different waveguide gap sizes with different concentrations of isopropanol alcohol (IPA). A waveguide gap size of 300 μm gives the highest increase in the transmitted optical power of 65% when tested with 10 μL (500 ppm) concentration of IPA. Compared with all other gaps, it also displays faster response time ($t = 5$ seconds) for the optical power to change right after depositing IPA in the chamber. The measured limit of detection (LOD) achieved for 300 μm is 0.366 μL. In addition, the fabricated waveguide gap of 300 μm successfully demonstrates the sensing limit of IPA concentration below 400 ppm which is considered as an exposure limit by "National Institute for Occupational Safety and Health". All the mechanical mount and the alignments are done by 3D printing fused deposition method (FDM).

Keywords: Polymer; 3D printing; digital light processing (DLP); isopropanol alcohol (IPA); swelling effect; fused deposition method (FDM)

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1. Introduction

Modern optical sensors detect rapid changes in the environment with very high sensitivity, such as temperature, pressure, humidity, and volatile organic compounds (VOC's). The use of light with different

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properties (e.g., wavelength shift due to changes in the surroundings) makes optical sensing platforms of great interest for different applications including metrology, quality and process control, health, and security [1–3]. Polymer based sensors have been widely used in various fields, such as optics, electromagnetics, and biomedicine [4]. For the applications of optical sensors and devices, polymer materials have been commonly used in the fabrication of optical waveguides, fibers, and micro-optics devices due to their optical properties, plasticity, and outstanding mechanical stability [5]. One such application of polymer materials is for optical waveguide sensors in detection of alcohol solutions based on its swelling characteristics [6]. Table 1 shows some similar types of sensing mechanism.

Table 1 Alcohol sensing mechanism using different polymers.

Polymer	Refractive index	Method	Application	Dimension	Response time	Sensitivity	Complexity
Poly-ethylen-vinyl-alcohol (PEVA) [6]	1.495	Refractive index change by vapor-phase alcohol and alcohol solutions	Channel type waveguide sensor	50 μm×40 μm	Less than 1 minute	1% menthol detection	Low
Novolac resin [6]	1.610	Refractive index change by alcohol solutions	Plastic optical fiber sensor	0.25 mm core diameter	Less than 1 minute	Concentration of methanol (2% to 11%)	Low
Nonbornene polymer ARTON [12]	1.510	Refractive index change by alcohol concentration of liquors	Plastic optical fiber sensor	0.255 mm core diameter	Less than 1 minute	Beer (5 v/v%) to whisky (40 v/v%)	Low

Alcohol has a very strong toxicity and its vapor is rapidly absorbed by human lungs. The exposure of alcohol can be life threatening if no measures are taken properly. Alcohol such as isopropyl alcohol (isopropanol) is a clear, colorless, and flammable organic solvents [7]. There has been a report that isopropyl alcohol (IPA) exposure mainly affects the nervous system, but it may also lead to reproductive development problems [8]. Considering its major health impacts and to prevent accidents and explosions, such sensor for the detection of alcohol must be developed to be fast, reliable, and possibly low-cost. In this work, a single step polymer-based waveguide is fabricated by using the digital light processing (DLP) technology and implemented as the alcohol sensor which meets the aforementioned attributes. Here, a photopolymer resin named monocure rapid 3-dimensional (3D) clear resin is used with a refractive index of n = 1.50. This polymer has drawn a strong interest in modern research as it has a property to be cured with specific wavelengths [9, 10]. The advantage of photopolymer offers a liquid suspension form which is suitable for the resin-based 3D printing method like stereolithography (SL) and the DLP technology.

3D printing employs rapid prototyping. It is also referred to as an additive manufacturing process where successive layers of materials are printed to obtain a 3D object. Any structure can be digitally designed in a computer-aided design (CAD) platform and a desired standard tessellation language (STL) file is generated. It is then uploaded in a 3D printer to obtain the final product [11]. In this work, an Autodesk 123D CAD platform is used to design the waveguide structure and later it is transferred in a Wanhao Duplicator D7 Box DLP 3D printer which uses photopolymer resin to obtain the final desired structure. This 3D printer based on the DLP employs an ultraviolet (UV) light to print the structure as resin cures in the 400 nm – 410 nm waveband. It has a resolution of 50 microns where any structure can be printed above the desired range.

One of the interesting properties of polymers is that it exhibits the swelling effect when in contact with different alcohols [6]. These swelling characteristics of the polymer also depend on the concentration of the alcohols used. It has been reported and is shown in Table 1 that poly-ethylen-vinyl-alcohol and novolac resin swell when exposed to vapor-phase alcohol or alcohol solutions. This makes the structure changes from leaky-type to guided-one which helps in detecting alcohol by measuring the output intensity of the signal [12, 13].

Utilizing this swelling mechanism, a type of polymer-based waveguide is fabricated in this work by using the DLP technology. This waveguide is a one-piece ridge structure designed to obtain the maximum light confinement at the core by lifting the ridge section upwards, standing on a tower like structure, thus reducing the effective refractive index of the substrate region [14]. With this configuration, multiple waveguides are printed with different gaps. The interest of a gap is to achieve a strong increase in transmitted light intensity by following the light re-coupling principle in the presence of alcohol. The sensitivity of the fabricated structure is studied and compared by using different waveguide gaps with different concentrations of IPA, i.e., 2.5 μL, 5 μL, and 10 μL. The system sensitivity is also compared with the IPA exposure limit which is 400 ppm as stated by “National Institute for Occupational Safety and Health”. A sensor chamber is fabricated by using the 3D printer fused deposition method (FDM) with an overall chamber volume of 20 cm^3 where all the experimental analyses in this work are performed.

The paper is divided into four sections. Firstly, the design and the fabrication of the sensor structure with its optimized parameters along with the characterization and the design of the sensor chamber is described in Section 2.1. Section 2.2 explains the operating principle and its alcohol detection method of the fabricated sensor. With its detection technique, the details of the experimental setup for the analysis are described in Section 3. The practical responses that are achieved from the fabricated structure by means of alcohol-polymer interaction method are presented, compared and discussed in Section 4.

2. Sensor structure and its operating principle

2.1 Fabrication of the sensor

The fabrication of a single step waveguide-type alcohol sensor is the extended modified version of a tower shape (elevated) waveguide [14] where it is separated by a gap of specific microns in order to obtain a higher increase in the transmitted light intensity, as well as higher sensitivity. In this work, the sensor structure is designed as a one-piece structure where both the base and the tower regions are of the same material. By introducing a gap between the waveguide structures, the re-coupling of light concept is utilized and monitored simultaneously for reduction of the power loss that occurs due to the size of the gap. It is then examined simultaneously for higher transmitted light intensity. Figure 1 shows the schematic of the waveguide overall structure with its front view and side view where the dimensions are marked and used throughout this work by only varying the gap size.

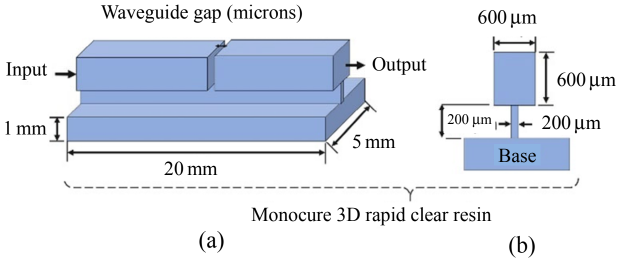
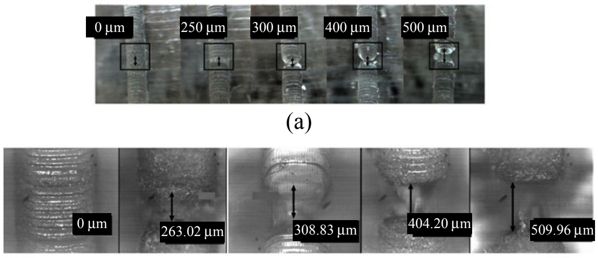


Fig. 1 Schematic structure of the single step waveguide-type alcohol sensor: (a) side view and (b) front view.

The fabrication steps for the sensor structure are similar to a previously conducted work [14], where the parameters for designing the structure (i.e., (tower height, tower width, ridge height, and ridge width) are kept identical. The only change implemented in the design is the introduction of a gap between them which is varied incrementally from 250 µm to 500 µm for the selection of the minimum feature size which can be realized by using the 3D DLP printer.

For parameters' optimization, the first fabrication step implemented is by designing the whole model by using Autodesk 123D software (CAD software) and saved in .stl file format. Later, it is converted to .cws file format by using the Creation Workshop software that is specifically made for the Wanhao Duplicator D7 Box 3D DLP printer. This DLP printer works on a bottom-up approach which is also known as an additive manufacturing (AM) process [15]. It starts by projecting the image file (waveguide structure in this work) by using stationary UV light onto the surface of the resin vat for polymerization process which hardens the desired part of the waveguide model. In the initial stage of the printing, the Z-stage of the 3D printer lowers the building plate into the resin vat keeping a 1 mm gap at the bottom and later the build plate is displaced upwards along the *Z*-axis (50 µm steps) [14]. This process is repeated until the structure is printed completely. After its completion, the structure is then detached from the build platform and it is cleaned by dipping (swinging back and forth for 3 seconds) in a container of isopropanol 5 times to remove the residue part that is attached to the structure from the printing process. It is then followed by washing it with deionized water (DI). The structure is then cleaned with a microfiber cloth and left to dry at room temperature (22 ℃ in this work) for 10 minutes. At the final stage, the structure is placed in a UV light chamber (360 nm – 420 nm) to post-cure for 10 minutes to complete the polymerization process. This also helps to strengthen the printed structure and remove the toxicity of the photopolymer resin.

This fabrication process is applied similarly for all the different waveguide gaps. The printed structures are shown in Fig. 2(a) captured with a USB (universal serial bus) PC (personal computer) camera and acquired in Fig. 2(b) by using optical microscope (OLYMPUS BX60, model BX60F at 5× magnification) at NECTEC (National Electronics and Computer Technology Center), Thailand to measure the actual gap fabrication.



(a)

(b)

Fig. 2 Microscopic images: (a) USB PC camera images and (b) optical microscope images at 5× magnification.

Table 2 shows the comparison of different designed and actual measured fabricated waveguide gap sizes.

Table 2 Comparison of the waveguide gap sizes.

Samples	Designed gap size (µm)	Actual measured fabricated gap size (µm)
Sample 1	0	0
Sample 2	250	263.02
Sample 3	300	308.83
Sample 4	400	404.20
Sample 5	500	509.96

The next step is to place the printed structure in a sensor chamber for the experimental analysis. A sensor chamber is designed in order to detect isopropanol alcohol concentration below 400 ppm as the "National Institute for Occupational Safety and Health" requirement for safe exposure limit to isopropanol alcohol [16]. The dimensions for the sensor chamber are set as 4 cm × 2.5 cm × 2 cm resulting in a volume is 20 cm^3 or 0.020 L. The structure design is shown in Fig. 3.

The sensor chamber is designed by using Autodesk 123D software and then printed by using 3D printer Geetech Prusa i3 Pro W DIY. This 3D printer works on the FDM technology where the structure is printed in a layer-by-layer fashion by using thermoplastic filament. This chamber provides a strong mechanical alignment stability for the sensing analysis of the waveguide structure. Since the sensor chamber volume is 20 cm^3, Table 3 provides the conversion of isopropanol from μL to ppm which is compared in the analysis of alcohol sensing in this work according to the health standards. Therefore, ppm in numbers refers to as quantity of isopropanol in μL/0.020 L.

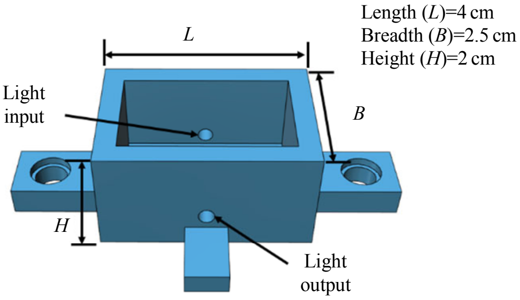


Fig. 3 Sensor chamber design using Autodesk 123D software with 20 cm^3 volume.

Table 3 Conversion of isopropanol from μL to ppm.

Concentration of isopropanol (in μL)		Amount of isopropanol (in ppm)
2.5		125
5	Conversion	250
10		500

2.2 Operating principle of the fabricated waveguide-type alcohol sensor

The interaction of the polymer-alcohol in the fabricated waveguide-type sensor is studied by depositing different amounts of isopropanol alcohol inside the sensor chamber at the specific designated placement.

The detection method of the designed structure is utilized based on the scattering generated due to the rough surface from the 3D printing and polymer swelling characteristics. This was explained and quantified in a previous work [14], where the structure was implemented as a reliable sensor. In this work, the sensing mechanism is enhanced by introducing a gap in the waveguide utilizing the light re-coupling principle along with the scattering and polymer swelling effect. The change of the transmitted light intensity increases when interacting with alcohol and modifies the sensor from a leaky type structure to a guided type structure. The concept behind utilizing this principle is depicted in Fig. 4.

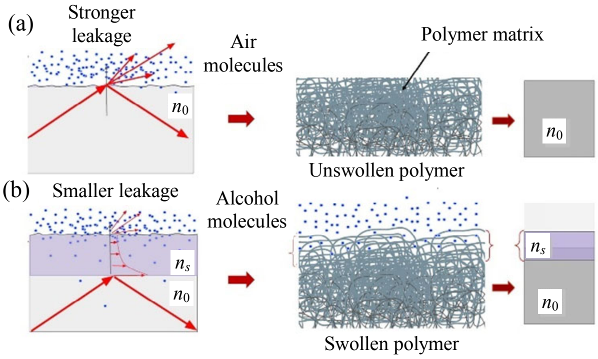


Fig. 4 Scattering and swelling mechanism: (a) structure showing polymer-air molecules interface and (b) structure showing polymer-alcohol molecules interface.

When the structure is not exposed to alcohol, it results in a large amount of scattering (forward and backward) due to rough surface leading to higher leakage of transmitted light. But when it is exposed to alcohol, two mechanisms play an important role. (1) Upon exposure, the alcohol molecules are absorbed and diffused inside the polymer (n_0, refractive index of polymer) resulting in swelling inside the photopolymer matrix which leads to the creation of a cladding layer (n_s, refractive index of new cladding) in the upper part of the waveguide structure. This cladding layer generated now has a lower refractive index than the core region of the waveguide structure. (2) The leakage of the light (forward scattering) now reduces due to the new cladding layer formation having certain thickness from polymer swelling. This reduces the strength of the light intensity reaching the rough surface, thus guiding the light more towards the core region.

These principles are utilized in this work. In Fig. 5, it is shown that due to the introduction of a gap, the light converges to the immediate face of the waveguide (light re-coupling) by decreasing the surrounding cladding region and the region near the tower (net effective index).

Due to this, the sensor becomes a guided type structure resulting in higher transmitted light intensity with smaller leakage. By using this mechanism, the detection of the alcohol is studied in this work by varying different concentrations.

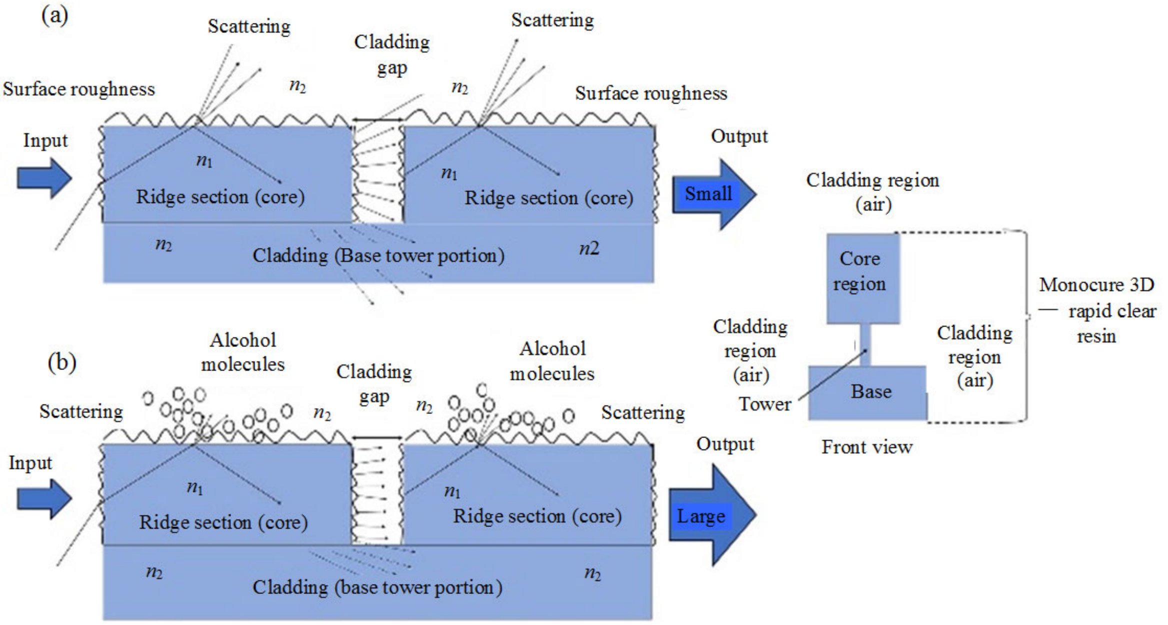


Fig. 5 Designed sensor structure operating principle: (a) leaky-type structure and (b) guided-type structure.

3. Experimental setup

The schematic diagram of the experimental setup along with the actual photograph taken for the measurement analysis is shown in Fig. 6.

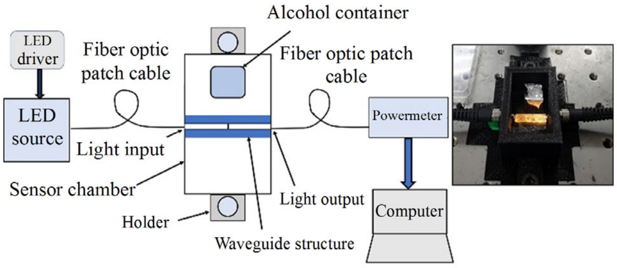


Fig. 6 Schematic diagram of the experimental setup along with the actual photograph of the sensor chamber.

The waveguide structure is placed inside the chamber and it is connected with a fiber optic patch cable on its input and output portion. In this work, a 3 000 K warm white light-emitting diode (LED) light is excited by an LED driver (LED1BB, Thorlabs, Newton, NJ, USA) at moderate intensity (current at 0.7 A) and is guided at the input side through fiber optic patch cable at the ridge section of the waveguide structure. The fiber optic patch cable has a core diameter of 200 µm. At the output end, the transmitted light intensity from the ridge section is collected with another fiber optic patch cable by using a powermeter (PM100USB, Thorlabs, Newton, NJ, USA) and the transmitted data is analyzed by using a computer. For the sensing samples, three volumes, i.e., 2.5 µL, 5 µL, and 10 µL of isopropanol alcohol are deposited on the small alcohol container inside the chamber for the analysis. These volumes correspond to 125 ppm, 250 ppm, and 500 ppm which are mentioned in Section 4. Each of the fabricated waveguide gap structures (250 µm to 500 µm) and the waveguide structures without gap are tested and compared with these three different volumes. Structures with a gap of 100 µm and 200 µm fail to be printed due to the resolution of the Wanhao Duplicator D7 Box 3D DLP printer (50 microns) and poor image projection mechanics during printing. Gaps above the 200 µm are studied in this work and the minimum gap feature size is selected after various experiments.

The light is launched in the sensor chamber at the ridge region of the waveguide structure and the transmitted optical power is recorded for 200 seconds – 300 seconds before dropping the different concentrations of isopropanol.

After dropping isopropanol with a pipette, the sensor chamber is covered with the 3D printed designed lid and the transmitted light intensity is collected by using a powermeter until the power reaches a stable point. Later, the lid is removed and a decrease in power can be observed, which slowly returns back to its initial value (optical power with air). After the optical power settles down, isopropanol is again deposited inside the chamber. This process is repeated three times to check the repeatability response of each of the waveguide structure for all the different concentrations of isopropanol for system sensitivity analysis.

4. Experimental results and discussion

First, the test is carried out with 5 μL (250 ppm) amount of isopropanol to observe the response of the structure and its potential for being able to detect below the safe exposure limit of 400 ppm. The input light launched in the chamber is kept constant for all the different waveguide gap structures and the given amount of isopropanol alcohol is deposited in the desired area. The results are shown in Fig. 7.

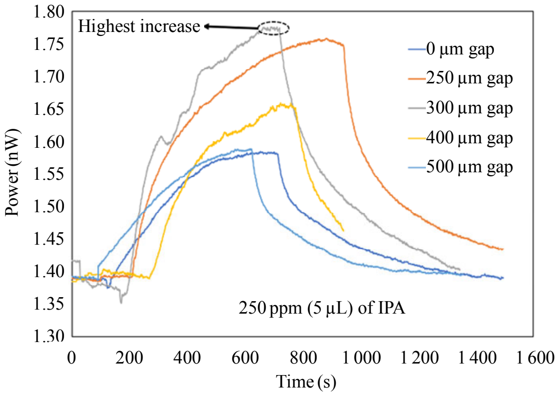


Fig. 7 Time dynamics response of the different waveguide gaps with 5 μL (250 ppm) concentration of isopropanol.

It is observable that there is a different rise in the transmitted optical power for all the different waveguide gap structures. Figure 7 shows the time dynamics of an increase in the optical power for the different waveguide gaps that are recorded over time. It can be seen that an increase in the transmitted optical power is the maximal for 300 μm gap waveguide when compared with the other waveguide gaps for 5 μL (250 ppm) amount of isopropanol. The behavioral response of different waveguide gaps is similar, which is every time the isopropanol is dropped inside the sensor chamber, and the optical power rises until it reaches stabilization. When the sensor chamber lid is removed, the optical power decreases gradually and it returns back to its original power which exhibits a reversible process. This shows the sensing response of the waveguide gap structures due to the swelling of the photopolymer resin along with the optical scattering effect and light re-coupling.

Since the swelling process is reversible, the photopolymer matrix can return back to its original structure due to evaporation of alcohol molecules in the air. However, the increase time and the decrease time for the optical power differ due to the gap for a given amount of isopropanol.

Since from Fig. 7 it is clear that the given structures respond below the 400 ppm limit of isopropanol exposure, it may be possible that the structure can respond to lower amount of isopropanol, i.e., below 250 ppm. For that, further experiments are performed with different amounts of isopropanol for different waveguide gaps.

The experiment is repeated three times for all the different gap waveguides (including the waveguide fabrication) to check its repeatability and its average percentage increases in the transmitted optical power is shown in the Table 4.

The percentage increase power of different waveguide gaps for different amounts of isopropanol is calculated by using the following formula:

$$Power(\%) = \frac{P_{\text{increase}} - P_{\text{initial}}}{P_{\text{initial}}} \times 100 \tag{1}$$

where P_{increase} is the highest rise in the transmitted power after depositing IPA in the container of the sensor chamber, and P_{initial} is the initial transmitted power (in air) recorded over certain time before depositing the isopropanol for different waveguide gaps. Here, the value of P_{initial} ranges from 1.36 nW to 1.42 nW.

Table 4 Comparison of percentage increase power of different waveguide gaps with respect to different amounts of isopropanol.

Amount (μL or ppm)	Increase power (%) (250 μm gap)	Increase power (%) (300 μm gap)	Increase power (%) (400 μm gap)	Increase power (%) (500 μm gap)	Increase power (%) (no gap)
2.5 or 125	20.95	26.66	16.11	11.17	15.17
5 or 250	29.75	30.61	18.76	17.70	21.60
10 or 500	44.99	64.14	22.25	28.59	27.40

Based on these results, it shows that the waveguide structure with the different gaps indeed gives a variation in transmitted optical power and operates as an acceptable isopropanol-concentration sensor. But, to have a sensor with an accurate gap size, faster response time (immediate change of power when depositing isopropanol in the sensor chamber), and sensitivity, further analysis needs to be performed. The range of the gaps is selected in order to sustain sufficient power coupling from the input waveguide (the 1st waveguide to the 2nd waveguide). We assume that the transmitted light/power coming out from the waveguide 1 (600 μm) has an intensity ($I_{\text{intensity}}$) over a distance and the light is diverging in a cone shaped. So, the power at the cone shape (P_{cone}) is defined by

$$P_{\text{cone}} = I_{\text{intensity}} \times A_{\text{cone}}$$

$$P_{\text{cone}} = I_{\text{intensity}} \times \pi R^2 \tag{2}$$

where A_{cone} corresponds to the area of the cone, and R is the radius of the cone. When the second waveguide is placed within the area of the cone (emitted light), the power guided (P_{guide}) inside the waveguide from the emitted light (the 1st waveguide) is calculated as

$$P_{\text{guide}} = I_{\text{intensity}} \times A_{\text{wg}} \tag{3}$$

where A_{wg} corresponds to the area of the second waveguide. Now, the coupling efficiency (η) that is associated due to the specific gap (distance) is calculated from the light emitted from the first waveguide to the light coupled at the second waveguide. And this equation is given by

$$\eta = \frac{P_{\text{guide}}}{P_{\text{cone}}} = \frac{A_{\text{wg}}}{\pi R^2} \tag{4}$$

where $R = d_{\max} \tan\theta$, and θ is the numerical aperture acceptance angle.

It can be calculated that at this distance the light emitted is perfectly coupled to the 2nd waveguide with the associated numerical aperture acceptance angle θ.

Equation (4) becomes

$$\eta = \frac{P_{\text{guide}}}{P_{\text{cone}}} = \mathrm{e}^{-1} = \frac{A_{\text{wg}}}{\pi(d_{\max} \tan\theta)^2}$$

so

$$d_{\max} = \frac{A_{\text{wg}}}{\tan\theta\sqrt{\pi \mathrm{e}^{-1}}}\,. \tag{5}$$

where "$\theta = 61.344\,\text{degree}$" is the numerical aperture experimentally measured using white light excitation. Here, $d_{\max}$ is the maximum distance over which the coupling power drops by 1/e or e^{-1} from the first waveguide.

Based on the waveguide dimensions and numerical aperture, the maximum waveguide dimension is found to be 300 μm. Hence, the following gap dimension is tested.

Since the 300 μm gap waveguide also shows the highest percentage increase in the transmitted optical power as shown in Table 4, this waveguide gap is selected and proceeded with further analysis for the validation as sensor.

The 300 μm gap waveguide is measured against various amounts of isopropanol and simultaneously, temperature and humidity are monitored. A DHT 11 sensor is connected by using arduino board inside the 3D printed chamber. The setup of these measurements is shown in Fig. 8.

The recorded readings of both humidity and temperature are shown in Fig. 9. It can be observed that measurement with the air (for 200 seconds – 300 seconds) gives an optical power of around 1.40 nW which remains stable after every measurement of different amounts of isopropanol. With an increase in the isopropanol amount, the change in the transmitted optical power can be clearly seen along with the temperature and humidity. This shows that with increasing amount of isopropanol alcohol, the optical power, temperature, and humidity inside the sensor chamber have an effect on the measurements. However, the experiment is performed at ambient room temperature (22 ℃).

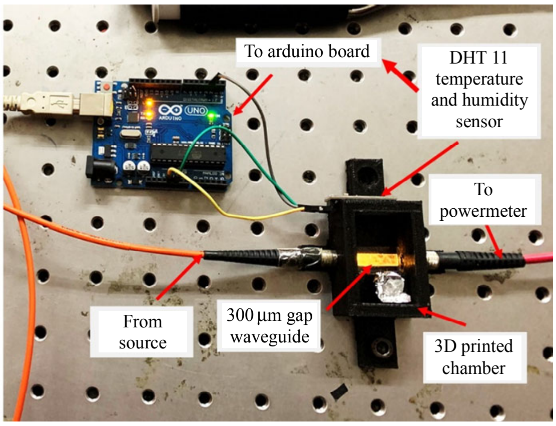
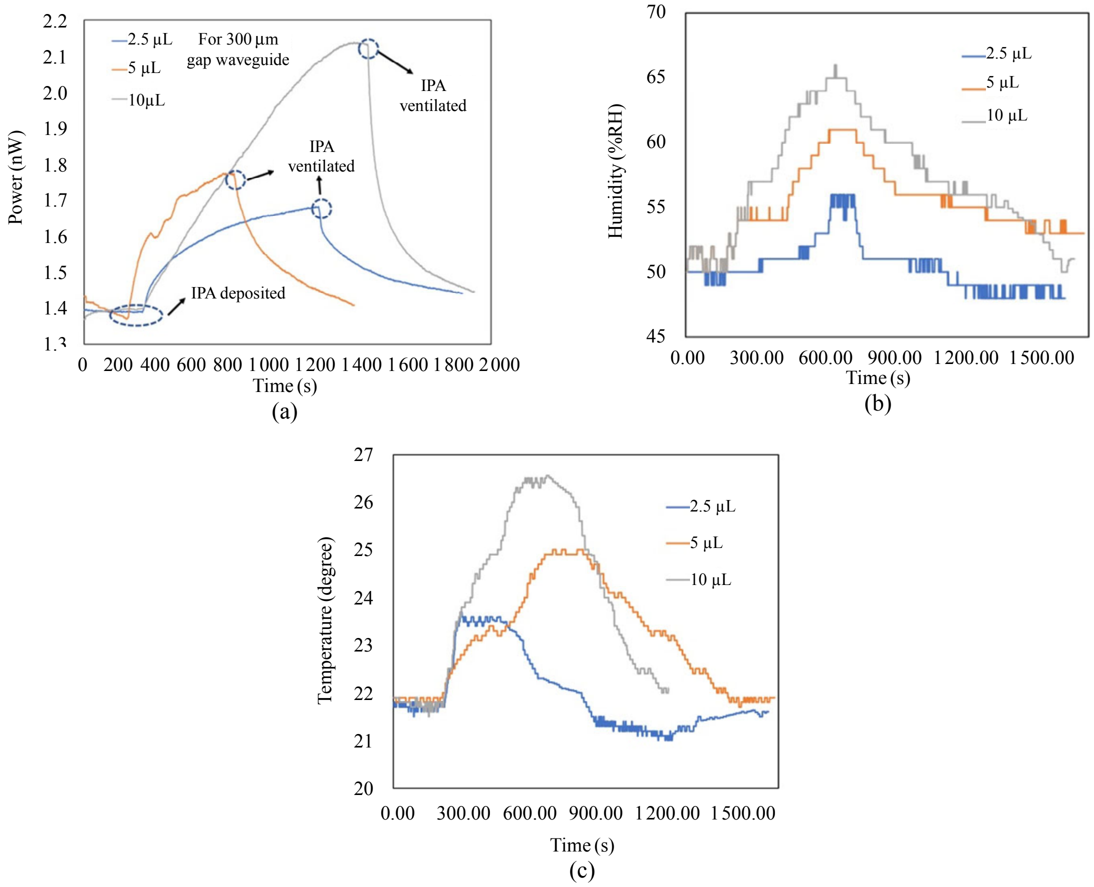


Fig. 8 Experimental setup for optical power, temperature, and humidity analysis.



(a) (b)

(c)

Fig. 9 Time dynamics response of 300 µm gap waveguide: (a) optical power measurement, (b) humidity measurement, and (c) temperature measurement.

The highest increase in the optical power is observed with 500 ppm amount of isopropanol. Figure 9 shows that it is possible to measure isopropanol at a concentration of 125 ppm. At this amount, an increase in the optical power is the highest as compared with other gaps.

This structure satisfies the measurement and sensing capability at lower than the 400 ppm amount of isopropanol defined as health standards mentioned in Section 2.1. In addition, a complete comparison for an increase in the transmitted optical power for all the different waveguide structures is shown in Fig. 10.

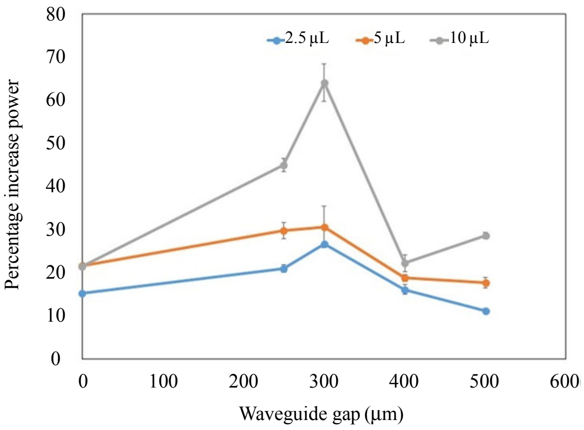


Fig. 10 Percentage increase power vs. waveguide gap comparison with the concentration of isopropanol.

From Table 4 and Fig. 10, it can be observed that the maximum optical power is obtained with the waveguide structure of 300 μm gap as compared with the other gaps. This is due to the diffusion of different concentrations of isopropanol molecules inside the structure. The scattering of light is reduced and stronger light re-coupling from the gap is achieved. In addition, with the 10 μL (500 ppm) of isopropanol, there is nearly a 65% increase in the optical power which is shown to be the highest. Also, with a lower amount of isopropanol, 2.5 μL (125 ppm), there is nearly a 27% increase in the optical power which is also shown to be the highest among the other gaps.

A statistical analysis is performed to obtain the limit of detection (LOD) and the sensitivity for each of the waveguide gaps and the results are show in Fig. 11.

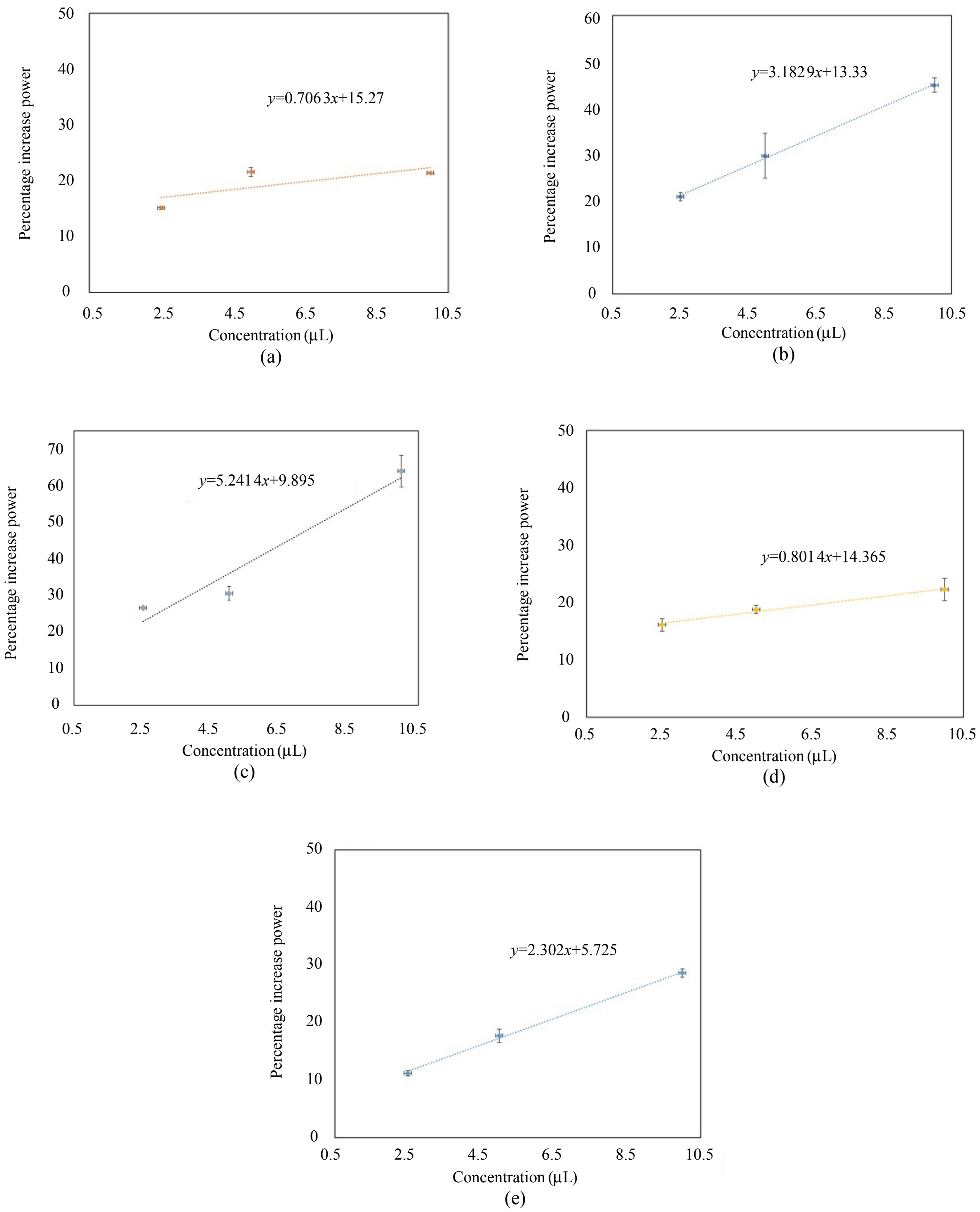
The *LOD* is calculated from measurements (repeated 3 times) of all the waveguides (3 fabricated) with and without gap. The formula for calculation of *LOD* is given by

$$LOD = \frac{Std_{\mathrm{wg}}}{S_{\mathrm{lcc}}} \tag{6}$$

where Std_{wg} corresponds to the standard deviation of each of the waveguide gap measured, and S_{lcc} corresponds to the slope of the linear calibration curve of each waveguide gap. This is done to investigate how much the given waveguide gaps can exhibit a change in the transmitted optical power with a different amount of isopropanol inside the sensor chamber. Table 5 shows the obtained LODs of different waveguide structures.

From the acquired results, the waveguide structure with a gap of 300 μm gives the best result with a LOD of 0.366 μL. This gap can display a shift in the transmitted optical power at a minimum given amount of 0.366 μL. This leads to an agreement as the most suitable one for identifying a change at the output end that corresponds to the system sensitivity. The fast response in the increase transmitted optical power right after depositing IPA is observed due to the change in the surroundings. The 300 μm gap waveguide shows 5 seconds faster response time than other waveguide structures with and without the gap.

From these results, the operating principle of the photopolymer-based waveguide is found to be effective. The analysis performed is validated experimentally. The 300 μm gap waveguide structure above all the fabricated ones, operated as reliable alcohol-concentration sensor by meeting all the conditions (limit of detection, strong light confinement, highest increase in the transmitted optical power, and faster measurement response below 400 ppm IPA exposure limit). Therefore, this designed sensor demonstrates its usefulness as a waveguide-type alcohol sensor.



(a) (b) (c) (d) (e)

Fig. 11 Calculation of LOD for different gaps: (a) 0 μm, (b) 250 μm, (c) 300 μm, (d) 400 μm, and (e) 500 μm.

Table 5 LOD for the different waveguide gaps.

Waveguide gap (μm)	LOD (μL)
0	1.142
250	1.515
300	0.366
400	2.450
500	0.508

5. Conclusions

A polymer based horizontal single step waveguide for the detection of alcohol within the air is studied and performed successfully. With a simple design and fabrication procedure, we are able to achieve a waveguide-type alcohol sensor that gives a satisfactory sensitivity and faster response time to detect the isopropanol alcohol concentrations. With the swelling characteristics of the photopolymer resin, the results are experimentally studied and compared amongst different gap sizes. A fabricated waveguide with 300 μm gap holds a LOD of 0.366 μL and gives a faster response time of 5 seconds as compared with the other gap size and larger transmitted optical power to different amounts of isopropanol used. From this configuration, we are also able to detect the alcohol below the given standards by "National Institute for Occupational Safety and Health" which is stated as 400 ppm to be safe exposure limit. In this work, we successfully demonstrate a waveguide-type isopropanol alcohol concentration sensor by using the 3D printing DLP technology where the dimensions are in hundreds of microns. The fabricated structure holds as a viable alternative fabrication scheme without using a vacuum system.

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