An experimental demonstration of all-optical Isopropyl alcohol sensor for biomedical applications

PIYUSH SHRIVASTAVA[1], SUBHASHISH TIWARI[2,†], ANKUR SAHARIA[1,*,†], GHANSHYAM SINGH[3,†], MANISH TIWARI[1,*,†]
[1]Optoelectronics and Photonics Research Lab, Department of ECE, Manipal University Jaipur, Jaipur, India
[2]Department of ECE, GITAM University, Bangalore, India
[3]Department of ECE, MNIT Jaipur, Jaipur, India

In this work, a sensing technique based on multimode graded index optical fiber in combination with 3-D printed sensing channel for the detection of different concentrations of Isopropyl alcohol (IPA) has been studied experimentally. This work demonstrates an optical fiber-based approach for sensing the IPA concentration in distilled water. This method is based on a real-time sensing mechanism and provides a precise detection of isopropyl alcohol. The molar concentration of isopropyl alcohol dissolved in 20 ml of distilled water is varied and the corresponding change in output voltage is noticed. The sensing is carried out by varying input power of the laser source, coupled to the optical fiber. A multimoded optical fiber having sensing region is used to perform sensing experiments. It is found that the experimental and theoretical values of absorbance and power loss due to Isopropyple alcohol are in close agreement with each other.

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1. Introduction

Isopropyl Alcohol (IPA) is a colorless, volatile and flammable liquid [1]. It has found uses in number of applications such as antiseptic, surface disinfectant, astringent to name a few. IPA is a good solvent and completely soluble in water. In the past few years, IPA was widely included as a main chemical in sanitizers to curb Covid-19 infection [2]. The application of sanitizers having 70 percent IPA as a disinfectant is effective to remove the viruses [2]. Due to this widespread use of IPA, the need to sense the concentration of IPA in a particular amount of chemical/ liquid also finds its significance. Since IPA is a volatile liquid if it gets inhaled by a person in a significant amount then it can be hazardous too. Also, as a chemical, IPA presence needs to be ascertained in various solutions for its chemical examination [3] in their work have studied the IPA application for de-contaminating a particular medical equipment viz. stethoscope. The stethoscope diaphragm is cleaned by IPA and found to be showing reduced bacterial growth. A stethoscope is used on different patients in a hospital environment, after being applied to a certain number of patients, the cleaning of it is effectively done with the help of IPA. Also, in the work mentioned above, the authors have studied the effects of ethanol-based cleanser in a similar manner to that of IPA and found both the chemicals to be equally effective [4] in their work have studied and investigated the presence of IPA in the blood of a patient without its direct intake. The presence of IPA in blood was a byproduct of acetone metabolism that happened in the body of the patient. The patient was suffering from high levels of blood sugar when the IPA presence in the blood was ascertained. IPA in the form of gas has been detected and studied by [5]. In the work, authors have used Zinc Oxide (ZnO) coated on a part of PMMA fiber to detect the IPA in gaseous form. It was observed that the light spectrum intensity obtained at the end of the fiber decreased due to the increase in the concentration of the IPA gas. Evanescent wave absorption-based sensing phenomenon is implemented in this experimental setup which is offered by the loss of electromagnetic energy at the interface of core and cladding medium in parallel with the Total Internal Reflection (TIR) event. Fractional Power and Penetration Depth are the two major parameters that were evaluated in applications of evanescent wave absorption sensor [6] [7]. Optical fibers based sensors have found applications in a broad spectrum of usage. They are applied in medical sensing, bridges health monitoring, perimeter sensing at border areas of countries, chemical plants parameters such as temperature and pressure sensing etc. Variety of optical fibers are tailored to cater multiple sensing requirements. Multimode fibers made out of glass or plastic are generally applied in sensing because of their various advantages over other conventional types of fibers [8]. Nowadays specialty optical fibers (SOF) are being used for sensing of specific parameters [9]. SOF are manufactured in such a way that they can be applied to sense a particular parameter efficiently and accurately [10]. Specialty optical fibers for astrophotonics applications have been studied by [11] in their work. The high temperature and radiation associated with a vehicle in space environment can be measured by using SOFs. These SOFs can be manufactured by altering the material and design of the preforms from which the conventional optical fibers are drawn [12]. Distributed optical fiber based sensing of underwater tunnels for any deformations has been studied and demonstrated experimentally by [13] in their work. In distributed sensing, an optical fiber is attached along the length of a structure that is to be monitored and one or both ends of the fiber are connected to an interrogator. With the abnormality occurring in the continuous signal being observed on the interrogator, the location and type of deformation can be established inside the tunnel surface [14] in their work have employed four different types of optical fibers for sensing of temperature, stress, refractive index and humidity. The proposed work in this manuscript has demonstrated an experimental method to sense the isopropyl alcohol with its varying concentrations. It can be employed further for various biomedical applications. The article is organized as follows, section 2 explains the method and material used for the experimental setup of the proposed sensor. It is followed by a discussion over the theoretical and experimental results obtained during the observations. It is further followed by the conclusion and references.

2. Methodology

In the proposed work, an experimental setup was utilized (as illustrated in Fig. 1), featuring a laser source with a central wavelength of 1310 nm (Thorlabs S1FC1310). A 3-dB fiber-type Planar Lightwave Circuit (PLC) splitter, operating over the wavelength range of 1260–1650 nm, is connected to the laser source to evenly split the input power between two optical fibers. At one output port of the splitter, an industrial multimode graded-index fiber (OM-3) is connected, incorporating a 1 cm-long sensing region fabricated via micromachining, as shown in Fig. 2(a). This sensing region is housed within a 3D-printed channel made of Polylactic Acid (PLA), as depicted in Fig. 2(b). The sensing channel, measuring 25 mm × 25 mm, was specifically developed during the experimental phase of this work. Based on available literature and experimental observations, Polylactic Acid (PLA) demonstrated reasonable resistance to both water and isopropyl alcohol (IPA) in terms of solubility [15].

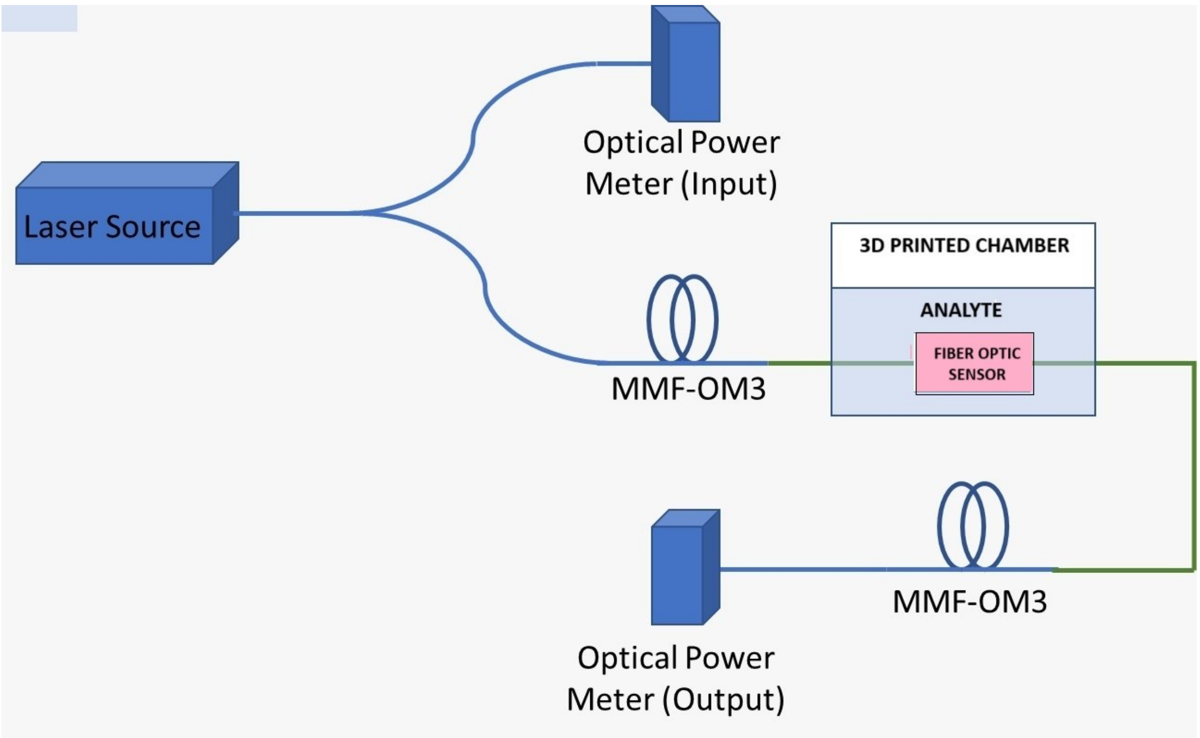
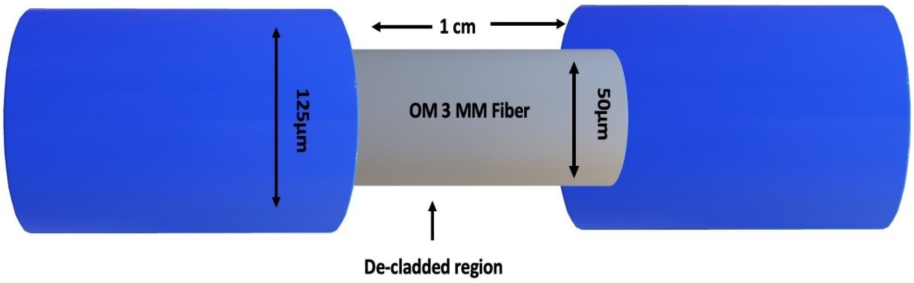
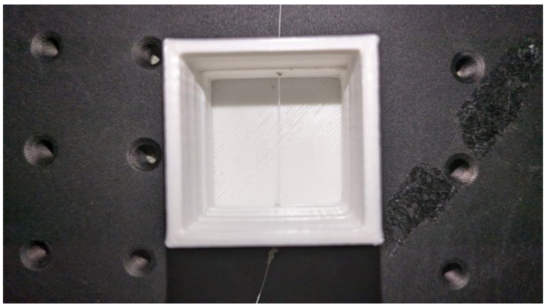


Fig. 1. Block diagram of proposed 3D Printed optical sensor setup (colour online)

The other end of PLC splitter which provides a constant laser output, is connected to an optical power meter to monitor the input to the sensing arm. In the experiment, IPA is taken and converted into solutions of different concentrations by mixing distilled water in the appropriate proportions. For example, if a 20% alcohol solution needs to be created then the pure IPA will be mixed with water in a 20: 80 ratio where 80 is the percent of water. In this experimental work, a total 20 ml sample was used with different proportions of water and isopropyl alcohol. The complete experimental setup is demonstrated in Fig. 3.



(a)



(b)

Fig. 2. (a) Schematic of fiber sensing region. (b) 3D Printed chamber (colour online)

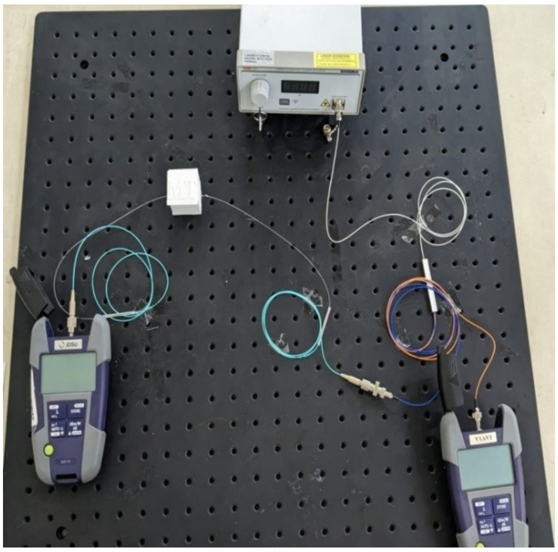


Fig. 3. Experimental setup for IPA sensing (colour online)

3. Sample preparation

Since IPA is a viscous liquid, its volume in ml is not equal to its weight in grams. So first we have to convert the different volumes of IPA, to grams. According to the data available, 1 ml of IPA is equal to 0.785 gram of the same.

$$m = V \cdot D \tag{1}$$

where:

m: mass (in gms),
V: volume (in ml),
D density of IPA.

The molar mass of IPA (C_3H_8O) is 60.1 grams. For example to calculate the number of moles in 10 ml of IPA, the grams of IPA present in 10 ml will be divided by molar mass i.e. (7.85/ 60.1) which is equal to 0.13 moles/ solute. The values of molar concentration, i.e. 'C' have to be found out. The molar concentration of a particular amount of liquid is the number of moles present in that amount divided by the volume (litres) of the second liquid in which it is dissolved to make a solution. For making of 10% IPA solution, the 10 ml of IPA has to be dissolved in 90 ml of distilled water. Thus, the molar concentration of 10% IPA solution is equal to 'moles in 10 ml of IPA / 90 ml of distilled water in litres i.e. 0.13/ 0.09 = 1.44. The values of C for different concentrations of IPA are provided in the Table 1.

Table 1. Molar concentration (C) values for IPA and water

S.N	IPA Solution (%)	C(IPA) (Moles/Litres)	C(Water) (Moles/Litres)
1	10	1.44	500
2	20	3.25	222
3	30	5.57	129.33
4	40	8.67	83.25
5	50	13	55.4
6	60	19.5	37
7	70	30.33	323.85
8	80	52	13.87
9	**90**	**118**	6.11

Moles present in specific volumes of IPA:

$$M = \frac{W_{IPA}}{m_{IPA}} \quad (2)$$

where:

- M: number of moles,
- W_{IPA}: weight of IPA (in gms),
- m_{IPA}: molar mass of IPA.

The mole fraction is calculated by dividing the moles of a particular substance (liquid here) by total moles present in the solution.

$$x = \frac{n_y}{n_{total}} \quad (3)$$

- x: mole fraction of X in Y ml of solution, n_y : number of moles of Y ml of solution,
- n_{total} Total moles of the solution containing substance x.

For example, mole fraction of 10 ml of IPA in 10% solution of IPA = 0.13/ (0.13+ 5) = 0.025. Here 0.13 is the moles value of IPA in its 10 ml volume and 5 is the moles value of water in its 90 ml volume. The refractive index of pure IPA at 1310 nm is 1.3685 [16] and the refractive index of pure water at 1310 nm is 1.3223. Using mole fraction values and refractive index values of individual components, the refractive indices of various IPA concentration can be found. Calculation to find the mole fractions and refractive indices of IPA solution at different concentrations was done using Eqs. 4 & 5 respectively and values are shown in Table 2. The molar concentration (M_c) is calculated using the formula:

$$M_c = \frac{M_{IPA}}{V_W} \quad (4)$$

- M_c is the molar concentration,
- M_{IPA} is the moles of pure IPA in the solution,
- V_W is the volume of water in the IPA solution (in liters).

4. Refractive Index and absorbance

To calculate the refractive index of IPA solutions at 1310 nm, the following relation is used:

$$(RI)_{IPA} = (M_{IPA} \cdot RI_{IPA}) + (M_W \cdot RI_W) \quad (5)$$

- $(RI)_{IPA}$: RI of IPA Solution
- M_{IPA} : Mole fraction of pure IPA
- RI_{IPA}: Refractive Index of Pure IPA
- M_W : Mole fraction of Pure water
- RI_W; Refractive Index of Pure water

The refractive indices in the above relation are taken at 1310 nm, which is the operating wavelength of the laser used in our experimental work. The multimode optical fiber used in this experimental setup is an industrial multimode OM3 fiber, which provides negligible loss in a small distance, hence all the loss calculation is done keeping the fiber losses negligible.

$$A = \frac{P_{Clad}}{P}\left(\frac{\alpha.C.L}{2.303}\right) \quad (6)$$

where,

$$\frac{P_{Clad}}{P} = \frac{4\sqrt{2}}{3}\left(\frac{\lambda}{2\pi r\sqrt{n_{core}^2 - n_{cladding}^2}}\right) \quad (7)$$

where,

- P_{Clad} = Power in the cladding
- P = Total power in the optical fiber
- λ = Wavelength of light
- r = Radius of the core of fiber
- n_{core}= Refractive index of the core
- $n_{cladding}$= Refractive index of the cladding
- α = Absorption coefficient
- C = Concentration
- L = Path length

Table 2. Calculation of absorbance of IPA solution

Serial Number	IPA Solution (%)	Overall Absorbance of IPA Solution (%)	Refractive Index
0	0	A	–
1	10	1.37473 × 10−5	**1.324**
2	20	6.50833 × 10−6	**1.325**
3	30	4.00238 × 10−6	**1.32**
4	40	2.69426 × 10−6	**1.32**
5	50	1.86096 × 10−6	**1.33**
6	60	1.29443 × 10−6	**1.33**
7	70	8.67326 × 10−7	**1.34**
8	80	5.43005 × 10−7	**1.35**
9	**90**	**3.2589 × 10−7**	**1.35**

5. Results and discussion

In the experiment, the variation of output optical power with respect to input power in the sensing region has been observed. This data is further used to determine the performance parameters of the proposed optical sensing circuit such as absorbance and sensitivity. The values of absorbance are calculated theoretically with the help of Eq. 6. The absorbance is also calculated by measuring the output optical power corresponding to different input power are observed for different IPA concentrations for different solutions containing different proportions of IPA as shown in Table 2. The absorbance for different values of input power for each concentration of IPA is plotted together with the theoretically calculated absorbance in Fig. 4. It is observed that experimental values are in confirmation with the theoretical values of absorbance, decrease with the increase in concentration of IPA applied to the sensing region of the optical fiber. The sensitivity of a sensor refers to change in output power with change in IPA concentration. The sensitivity of the sensor is calculated using Eq. 8.

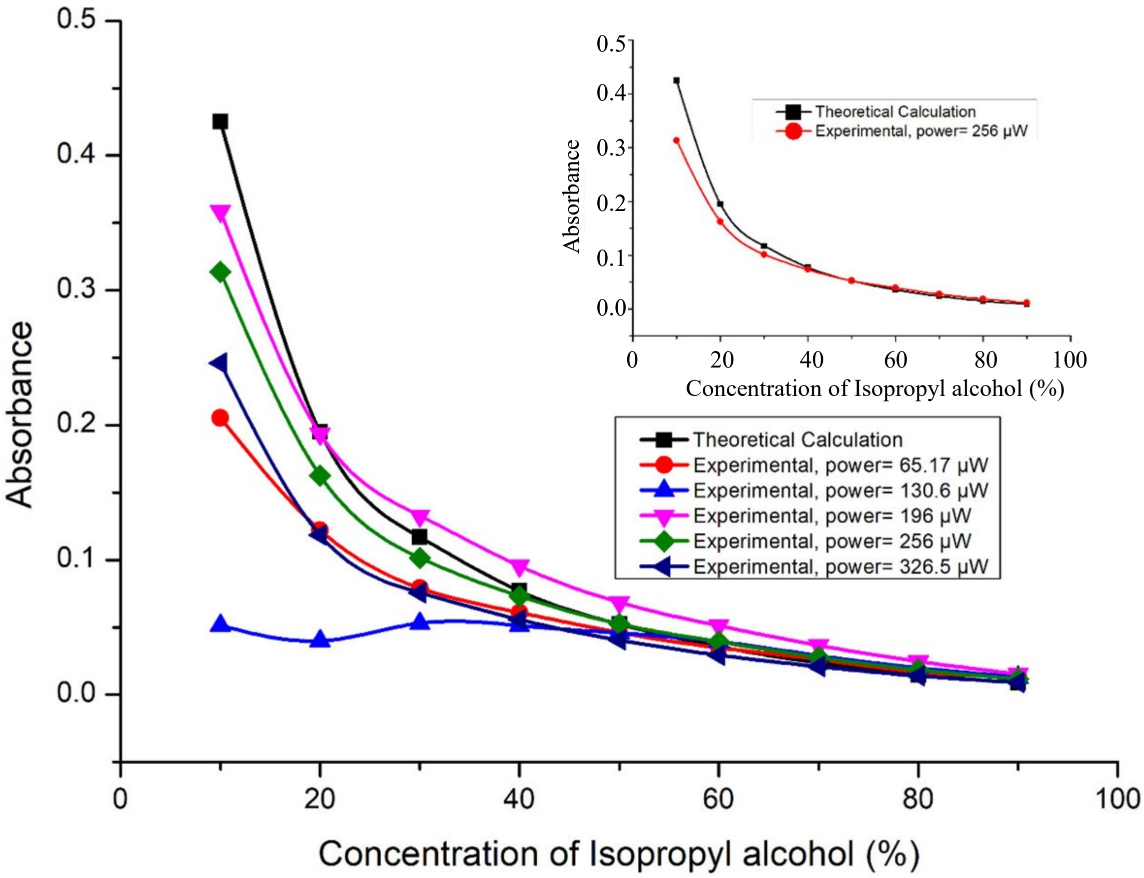


Fig. 4. Variation in absorbance with IPA concentration for different input optical power (colour online)

$$S = \frac{\Delta P_{out}}{\Delta P_{in}} \quad (8)$$

where:

- ΔP_{out}: Change in output power
- ΔP_{in}: Change in input power

Fig. 5 shows the graphical representation of sensitivity calculations for different IPA concentrations for various input powers. The power lost at the IPA application site on the optical fiber for various concentrations of IPA are calculated as the difference of the input power and the output power.

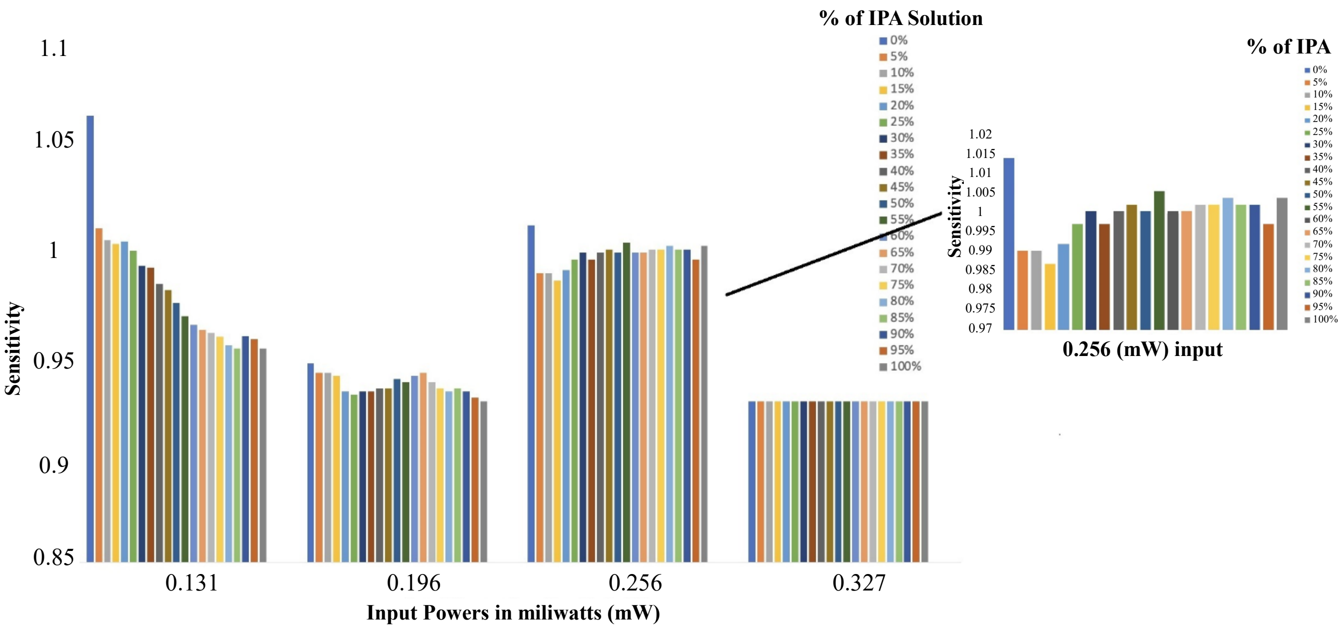


Fig. 5. Variation in sensitivity with variation in input power for different IPA concentrations (colour online)

6. Conclusion

The absorbance values for various concentration (0-100%) of IPA, applied at the sensing region of an optical fiber, calculated theoretically are closely matching with the experimental values of losses in the optical power for the optical fiber part used for sensing of IPA. Hence, an Isopropyl Alcohol detection and concentration sensor based on optical fiber is successfully demonstrated. As the concentration of the IPA increases, the absorbance also increases or the output optical power decreases. Since optical fiber based sensing method is fast and efficient in nature, this sensor can be used to sense IPA in actual environment to detect its presence and quantity. Also, this sensor has no recurring cost and once the setup is created, it can be used for sensing any number of times.

Declarations

• Funding: There was no funding for this research project
• Conflict of Interest: The authors have declared no conflict of interest.
• Availability of data and materials: Not Applicable
• Code Availability: Not Applicable.
• Consent to Participate: All authors are agreed and gave their consent to participate in this research work.
•†These authors contributed equally to this work.

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*Corresponding author: mt.jaipur@gmail.com; ankursaharia07@gmail.com