Simple fiber optic sensor based on tapered fiber for aliphatic alcohol detection

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A simple fiber optic sensor based on a tapered fiber is demonstrated to detect aliphatic alcohols such as methanol, ethanol, 1-propanol and 2-propanol. The change of the refractive index in the evanescent field in the tapering region of the fiber due to an aliphatic alcohol varies the output power. The optimum radius of tapered fiber core is theoretically found to be approximately 282 µm. It is observed that increasing of alkyl substituent of primary aliphatic alcohol from C = 1 to C = 3 significantly decreases the output intensity of light that is transmitted through the tapered fiber. The output intensity increases slowly as the concentration increases from 10% to 50%. However, the intensity increases drastically as the concentration is increased from 50% to 100% especially for the methanol, which has a lower alkyl substituent (C = 1). The sensitivities of the tapered plastic fiber for 2-propanol, ethanol and methanol detections are obtained at 0.911, 1.046 and 5.234, respectively.

(Received April 27, 2011; accepted June 9, 2011)

Keywords: Tapered fiber; plastic optical fiber; refractive sensor; aliphatic alcohol

1. Introduction

Aliphatic alcohols such as methanol, ethanol, 1-propanol, 2-propanol have been used as fuels in direct liquid fluid feed fuel cells (DLFCs) and also plays a significant role as a solvent in broad range of applications in medical, biological and chemical industries [1,2]. Due to the manifold applications of these aliphatic alcohols, to date, many techniques have been proposed to monitor the concentration of these alcohol solutions [3-4]. On the other hand, plastic optical fiber has received much attention in Fiber-To-The-Home (FTTH) communication networks because of its improvements in transparency and bandwidth. This fiber is made of polymethylmethacrylate (PMMA) and perfluorinated PMMA and suitable for use in short distance communication system. They are also becoming prevalent in the sensor applications due to its evanescent wave, good flexibility, electro-magnetic interference immunity, low weight, easily handling, cheaper installation cost and poor heat tolerance [5-6]. The plastic optical fiber also shows high numerical aperture and high mechanical flexibility [5].

In general, many techniques have been adopted to implement refractive index sensor such as fiber-optic displacement sensor, using the deformed fibers cores like U-bends, tapers, and D-fibers [7-10]. Among these techniques, fiber tapering is the most simplest for the sensor application. This technique is based on the fact that light wave guided in a fiber has a power fraction in the cladding in the form of evanescent wave [9]. A tapered fiber can enhance the power fraction of evanescent wave in the cladding so that it is sensitive to environmental changes. Though single mode fiber tapers have larger power portion in the cladding, they are fragile and difficult to manufacture. Multimode plastic fiber tapers are easier to fabricate and use.

One of the techniques to fabricate a tapered fiber is by stripping off the cladding. The removal of the cladding usually requires an etching process with careful control since the materials of the core and cladding are similar. Chemical tapering of plastic optical fibers has been reported previously by Bayle et al. [11] and Merchant et al [12] using a solution of acetone in water to remove the cladding of polymer optical fiber chemically. In this paper, a refractive index sensor for detection of aliphatic alcohols such as methanol, ethanol, 1-propanol and 2-propanol is demonstrated using a tapered multimode plastic fiber, which is also obtained using the chemical tapering. Compared to the previous work [11-12], the tapering method is improved in this work by using an acetone, a distilled water, a 2-propanol and a sand paper. The proposed sensor is used to evaluate the aliphatic alcohols covering a concentration range from 10% vol to 100% vol.

2. Theory

The fiber tapering by removing the cladding encounters the problem of waveguide parameter (V number) mismatch between the clad portion and the sensing element of the fiber. The V number is defined as

$$V = \frac{2\pi r_o}{\lambda}\sqrt{{n_{co}}^2 - {n_{cl}}^2} \qquad (1)$$

where λ is the wavelength of transmitting light, r_o is the radius of fiber core, n_{co} and n_{cl} are the refractive index of fiber core and cladding, respectively. In condition of V mismatch, a fraction of light is transformed into higher order propagation modes in the sensing area and finally leak out from the core. The number of modes inside the fiber is equals to $V^2/2$ for step-index multimode optical fibers. The parameters of plastic optical fiber and laser source used in this paper are r_o = 500 μm, n_{co} = 1.492 and n_{cl} = 1.402, λ = 594 nm. Thus, the V number for cladding fiber is calculated to be 1377.5 based on Eq. (1). Among the aliphatic alcohol used in this study, methanol posses the lowest refractive index (RI) of 1.3284 which will give the highest transmission loss compared to other alcohols such as ethanol (RI = 1.3617), 1-propanol (RI = 1.3856) and 2-propanol (RI = 1.3772). By replacing the cladding portion with methanol, V number of the fiber in the sensing region becomes 3593, which can be calculated by replacing the refractive index of the cladding n_{cl} with the refractive index of methanol. During the light transmitting from the sensing region to the clad fiber, approximately 33.1% of light power of the propagation modes is lost in the sensing region.

To avoid the V number mismatch, a V number matching radius for tapered fiber without cladding should be;

$$r_t = r_o \sqrt{\frac{{n_{co}}^2 - {n_{cl}}^2}{{n_{co}}^2 - {n_s}^2}} \tag{2}$$

where n_s is the refractive index of surrounding medium. According to Eq. (2) and the parameters given above, the optimum radius of tapered fiber core r_t is theoretically found to be approximately 282 μm. Therefore, a radius of a tapered fiber used in this study is chosen to be 240μm to prevent the propagation modes loss.

In sensing applications, the transmitting light should be perturbed by the medium that surrounded the fiber. Removing of cladding is a better way to expose the evanescent field of light and fiber tapering is the method to get the optimum coupling light modes. The penetration depth is used to describe the distance of evanescent field extends beyond the core-surrounding mediums interface in the tapered fiber without cladding. The electric field of transmitting light in the fiber core is decayed exponentially in the medium with lower refractive index as

$$E(x) = E_0 \exp(\frac{-x}{d_p}) \tag{3}$$

where x is the distance from the interface and d_p is the penetration depth given by [13],

$$d_p = \frac{\lambda}{2\pi\sqrt{{n_{co}}^2 \sin^2\theta - {n_s}^2}} \tag{4}$$

where θ is the incidence ray angle with the normal to the fiber core and surrounding medium interface.

3. Experiment

Fig. 1 shows the schematic diagram of the experimental set-up of the proposed sensor. The sensor is based on attenuated total reflection (ATR) spectroscopy method in which the cladding of the optical wave guide is removed and the exposed core is surrounded by a sensing medium [8]. The sensor system consists of a He-Ne light source, an external chopper, photo-detector and lock in amplifier. The light source operates at wavelength of 594nm with an average output power of 3.0 mW, beam diameter of 0.75mm and divergence of 0.92 mRads. The light source is modulated at frequency of 100Hz before it is launched into the tapered plastic fiber, which is placed in petri dish for detection of alcohol. A photodetector is located at end of the fiber to convert the received power into voltage. A mechanical copper is used in conjunction with a lock-in amplifier for data-acquisition. It functions to match the phase between the transmitting light and receiving light, and removes the noise generated by laser source, photo-detector and amplifier [14]. The laser light, petri dish and detector are aligned in one straight line to minimize the bending loss in the plastic fiber and thus increase the accuracy of the measurement.

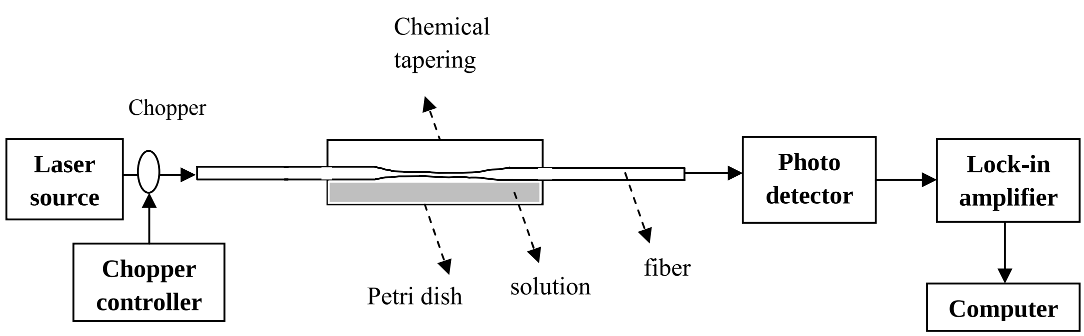

Fig. 1: Experimental setup to detect alcohol solutions

The fiber used has an outer diameter of 1000 µm with 30cm long and the core and cladding of this fiber is made from PMMA and fluorine polymer (CF_2=$CFOCF_2CF_2CF$=CF_2), respectively. The fiber is chemically tapered using an acetone, distilled water, 2-propanol and a piece of sand paper. Acetone solution is applied to an optical fiber by using a cotton bud. Then the fiber is neutralized with the distilled water. After that, the milky white surface is removed by using a sand paper. The process is repeated until a tapered fiber with different length and diameter is obtained. Finally, the tapered optical fiber is cleaned by using the 2-propanol. The tapered optical fiber used in this study has a stripped region length of 5.0 cm and diameter of 480 µm. The tapered optical fiber obtained is then used as a refractive index sensor to detect different types of aliphatic alcohols; methanol, ethanol, 1-propanol and 2-propanol at various concentrations ranging from 10% vol to 100% vol.

3. Results and discussion

Figs. 2 and 3 show the output power intensity variation against time for methanol and ethanol solutions, respectively at various concentrations ranging from 10 to 100% vol. In this experiment, the methanol and ethanol used have refractive indices of 1.3284 and 1.3617, respectively at room temperature of 20^{o}C. It is seen in both figures that the output intensity increases slowly as the concentration increases from 10% to 50% for both methanol and ethanol. However, the intensity increases drastically as the concentration is increased from 50% to 100% especially for the methanol, which has a lower alkyl substituent (C = 1) as shown in Fig. 2.

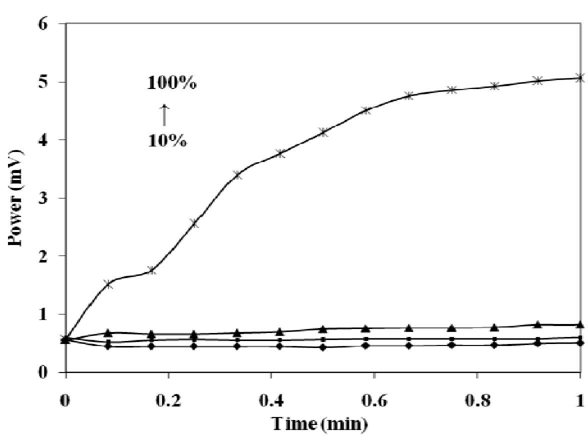

Fig. 2. Power intensity against time for different concentrations (10% - 100%) of methanol solution.

For aliphatic alcohol with higher alkyl substituent (C = 2, ethanol), the increase of intensity is so much lower as the concentration is increased from 50% to 100% as shown in Fig. 3. The similar experiments are also conducted for other aliphatic alcohols with higher alkyl substituent such as 1-propanol (primary alcohol) and 2-propanol (secondary alcohol), which have 3 alkyl substituent (C = 3). 1-propanol and 2-propanol have refractive indices of 1.3856 and 1.3772, respectively. Both results show a similar trend with ethanol and therefore they are not presented here. As also shown in Figs 2 and 3, the pure methanol and ethanol (100% vol) have response times of 0.0833s and 0.25s respectively until a stable value is achieved for the intensity. The maximal power intensity of 5.2 mV is achieved by the pure methanol.

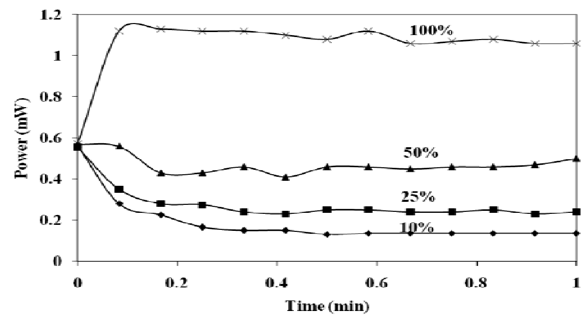

Fig. 3. Power intensity against time for different concentrations (10% - 100%) of methanol solution.

Fig. 4 shows the output intensity against time for different aliphatic alcohols at concentration of 25 % vol, which was obtained within 1 minute. It is observed that increasing of alkyl substituent of primary aliphatic alcohol from C = 1 to C = 3 significantly decrease the power intensity. However, 2-propanol (secondary alcohol) gives higher output intensity compare with 1-propanol (primary alcohol) that having the same number of alkyl substituent (C = 3). If the incidence angle of the light ray is above critical angle of the fiber, the light intensity will be lost due to the intensity leakage from core to cladding area. The output intensity from the tapered fiber is a linear function of the refractive index of surrounding medium. The bigger the refractive index of the medium (alcohol), the bigger the critical angle of the fiber, which in turn increases the transmission loss. As shown in Fig. 4, the power intensity of methanol is 3 times of 1-propanol, which is in agreement with the theoretical analysis that the maxima penetration depth is achieved by 1-propanol while the minima penetration depth is achieved by methanol. Thereby, the higher penetration depth reduces the output intensity from the tapered fiber and is achieved with the higher refractive index of medium (alcohol). This is attributed to the reduction of Fresnel reflection from the interface of fiber core and surrounding medium, which contributes to the reduction in output intensity [15]. From Fig. 4, 1-propanol and ethanol show the response time of about 0.42s while 2-propanol and methanol show the response time of 0.18s.

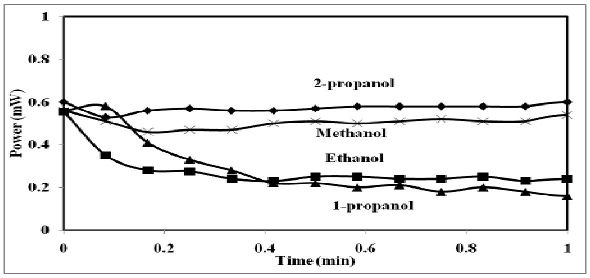

Fig. 4. Output power curve against time for various aliphatic alcohols when the alcohol solution concentration is fixed at 25% vol.

Fig. 5 shows the output intensity characteristic as a function of material concentration for various aliphatic alcohols. It is observed that the curves are in linear form at lower concentration (≤ 50% vol) and become non-linear at higher concentration (≥ 50% vol). Aliphatic alcohols with higher carbon contents (C ≥ 2) such as ethanol and 2-propanol show a more linear and consistent curves covering a range from 10-100% vol. On the other hand, aliphatic alcohol with lower carbon content (C = 1, methanol) shows extremely high output intensity especially for higher concentration (100% vol). In general, polymers especially PMMA is significantly affected by solvent exposure even in the absence of applied stress [16]. As shown in Fig. 5, 1-propanol and 2-propanol shows almost similar trend due to the same number of alkyl substituent in which C = 3. Thus, the physical property for both alcohols is almost similar. Based on the linear curve that obtained in Fig. 5, the sensitivities of the tapered plastic optical fiber in detection of 2-propanol, ethanol and methanol are calculated to be 0.911, 1.046 and 5.234, respectively. As conclusion, plastic optical fiber sensor with chemical tapering shows a fast and clear response within 1 minute in different aliphatic alcohols covering a concentration range from 10-100% vol.

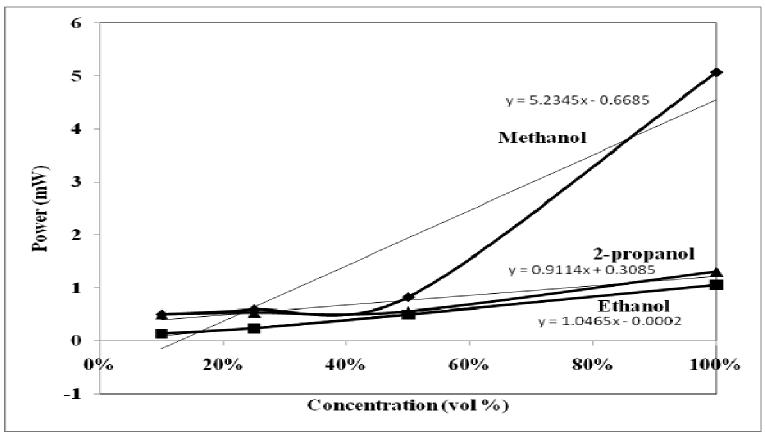

Fig. 5. Output power against the concentration for various aliphatic alcohols solutions.

4. Conclusion

A simple fiber optic sensor with fast response time is demonstrated using a tapered fiber to detect various concentrations of aliphatic alcohols such as methanol, ethanol, 1-propanol and 2-propanol. The evanescent field in the tapering region of the fiber changes with refractive index of the surrounding medium and therefore different aliphatic alcohols shows different output intensity. The optimum radius of tapered fiber core is theoretically calculated to be approximately 282 μm. It is found that increasing of alkyl substituent of primary aliphatic alcohol from C = 1 to C = 3 significantly decreases the output intensity of light that is transmitted through the tapered fiber. The output intensity increases as the solution concentrations of the alcohol increases. The drastic increase of the intensity is also observed as the concentration is increased from 50% to 100% especially for the methanol, which has a lower alkyl substituent (C = 1). The sensitivities of 0.911, 1.046 and 5.234 are obtained for 2-propanol, ethanol and methanol detections, respectively.

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