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High repeatability adiabatic microfiber sensor in ethanol detection

L. H. KAMARUDIN[1,2], M. N. H. JAMALUDDIN[1,2], S. N. F. AZHAN[1,2], S. A. SAMSUDIN[3], M. S. BAHARI[4], M. Z. ZULKIFLI[1,2,*],
[1]*Advanced Photonics Devices Research Laboratory, Department of Physics, Kulliyyah of Science, International Islamic University of Malaysia, Bandar Indera Mahkota, 25200 Kuantan, Pahang, Malaysia*
[2]*Biophotonics Research Unit, Department of Physics, Kulliyyah of Science, International Islamic University of Malaysia, Bandar Indera Mahkota, 25200 Kuantan, Pahang, Malaysia*
[3]*School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia*
[4]*Faculty of Mechanical Engineering Technology, Pauh Putra Campus, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia*

Optical microfibers are being widely used in a vast numbers of sensing applications especially for liquid concentration. Although the flame brushing technique is the most common method used in fabricating an optical microfiber, this experiment proposed an easy and low cost designed taper machine with only single stretch linear stage. This technique has proven to be able to design a specific liquid ethanol concentration sensor from an adiabatic microfiber with low loss, high sensitivity and great repeatability sensor. The experiment results demonstrated the adiabatic microfiber structure with approximate 20μm waist diameter with transmission loss less than 3 dBm and achieved to obtain high sensitivity, 0.1932 dBm/% ranging from 70% to 0% of ethanol concentration in distilled water. Despite the vast number of reported research studies in microfiber size and sensitivity, repeatability tests are rarely reported. The study of repeatability in our paper demonstrated a high repeatability result with 0.401 dBm per number of tests. The robustness criteria show by the sensor granting a high advantage in commercializing for various liquid concentration sensor and refractive index measurement.

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Keywords: Microfiber, Tapered fiber, Adiabatic, Ethanol

1. Introduction

Ethanol belongs to the alcohol class of organic compound, having a molecular structure consisting of two single bond carbon atoms and five hydrogen atoms. It appears in a clear, colourless and volatile liquid, that can be manufactured by the process of fermentation of carbohydrates or the hydration of ethylene [1]. Ethanol is utilized in a wide range of industries that are closely related to human lives. These include fuel, medical treatment, food industry and also scientific experiments [2-4]. Therefore, in order to justify the toxicological effect of ethanol, appropriate rationale and reliable detection of its concentration are required. The most common method used for determining ethanol is based on gas chromatography [5, 6], colorimetric analysis and other electrical based sensor [7]. However, these techniques came with drawbacks as they required expensive instrumentation and low stability due to the electromagnetic interference.

The development of fiber optic has provided the world with the most effective and efficient application for sensing technologies such as temperature, stress and strain, vibration, humidity and others [8-10]. When compared to other technologies, optical fiber has been the most popular approach as a result of its superlative advantages over the conventional sensors such as immunity to electromagnetic interference, capability of measuring multiple measurands, long-distance sensing, ability for high temperature measurement, high resolution, high accuracy and small span (~μm) [11]. Fiber optic ethanol concentration sensors are surprisingly more inclined to show their full potential under those specific conditions mentioned above. For instances, an optical planar waveguide used for measuring water content in alcohol solution [12] and plastic optical fiber as ethanol real-time sensing in biofuel production [13, 14]. There are also some research in using D-shaped optical fiber for temperature and humidity sensing on ethanol [15] and material coated fiber ethanol sensor based on Lossy Mode Resonance technique [16]. These sensing systems, even with them having achieved outstanding accomplishments, have begun to deteriorate from some drawbacks. Some of them can be attributed to the delicate coating material, precision and complexity of special fibers to remain efficient.

Recently, continuous analysis and study has been done to modify the physical structure of the fiber in order to create a highly sensitive and selective sensor to be applied in the industry. The advancement in research development of nanotechnology and optical fiber has provided an opportunity for novel exploration in manufacturing fiber in nano and micro scale [17]. Rapid development of tapered/micro/nano fiber suit to become an incredible candidate due its cost effectiveness, miniature size yet flexible structure and high sensitivity [17, 18] Optical microfiber also has the ability to exhibit a unique optical and mechanical properties which are essential for numerous sensing applications [19]. Evanescent field is one of the optical properties arise due to the tapering or etching a conventional fiber. The fundamental concept of evanescent field is the propagation of a portion of light outside the physical boundary of the fiber due to the process of stretching and heating the fiber segment [20]. Large propagation of evanescent field present outside of the fibers physical boundary is an important property to design sensors due to the strong interaction overlap between the evanescent field and the surrounding environment [21]. In terms of manufacture, the most famous technique used in microfiber fabrication is the flame brushing technique [22].

In this work, we explore the potential of adiabatic microfiber for liquid ethanol detection sensor. The adiabatic microfiber was fabricated using the designed microfiber fabrication machine using the flame brushing technique with further modification using controllable stretched by a single translation stage. For the purpose of characterization, we analysed the structure and measured the optical transmission power before and after fabrication process. In term of sensitivity and repeatability, a measurement based on the fabricated microfiber transmission power was presented, for analysing the ethanol concentration in the range of 0% to 70%. The proposed work shows a high repeatability and sensitivity with simple and low-cost experimental setup for ethanol sensor application.

2. Experimental set-up

2.1. Microfiber fabrication machine

The method of fabrication of optical microfiber adopted the flame-brushing technique. The experimental setup for the fabrication process is shown in Fig. 1. The set-up consists of two linear stages with difference in length, controlled by two stepper motor connected to power supplies. Each stepper motor is connected via coupler to minimized the vibration produce when the motor rotates. The speed of the stepper motors is controlled by two Arduino Uno microcontrollers that embedded with a motor driver each. Fiber optics holders are used to clamp the fiber horizontally whereas the flame torch is used to heat the fiber.

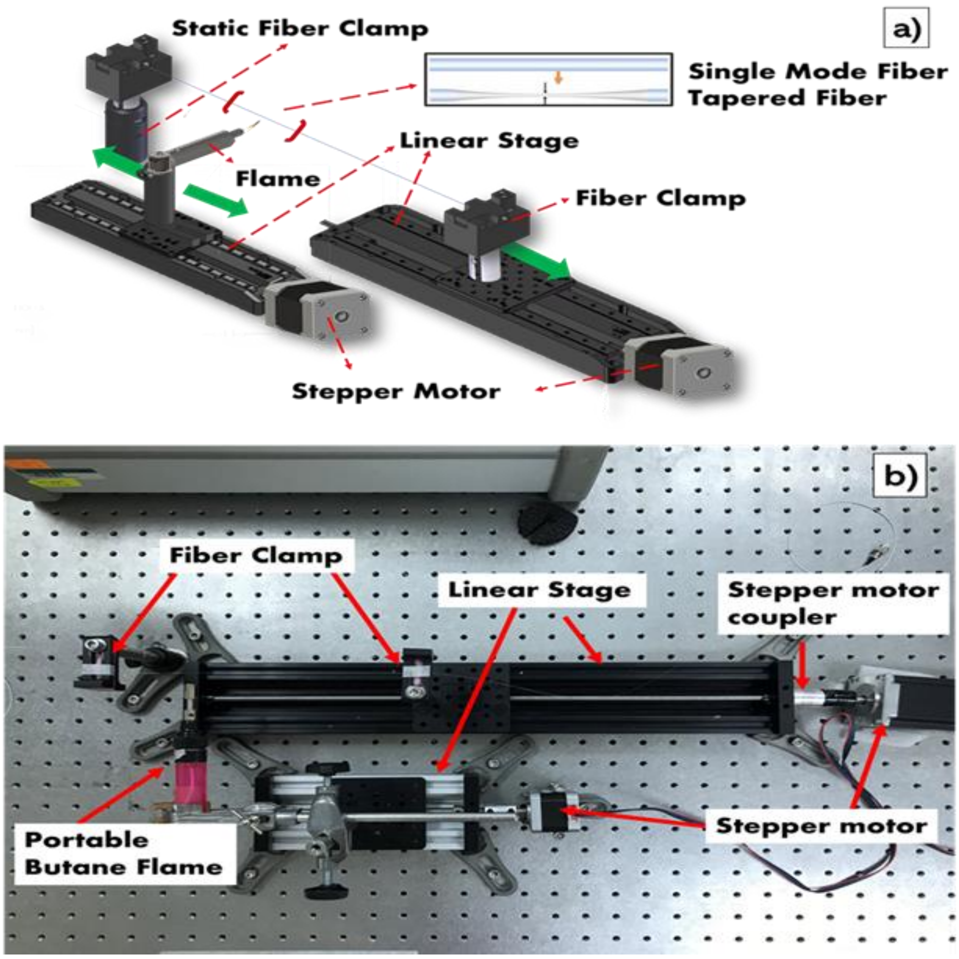
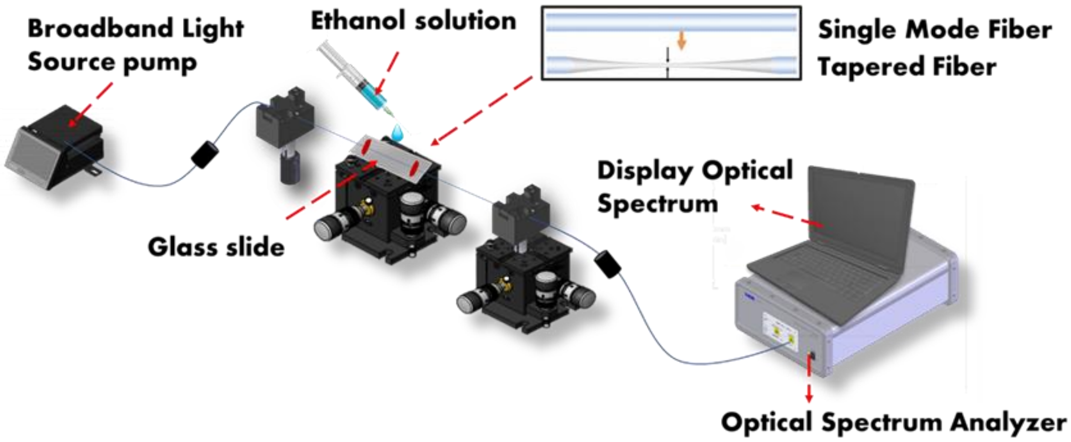


Fig. 1. (a) Schematic of the microfiber fabrication machine setup; (b) Microfiber fabrication machine. Not seen in the picture: power supplies, Arduino Unos, motor drivers and portable microscope (color online)

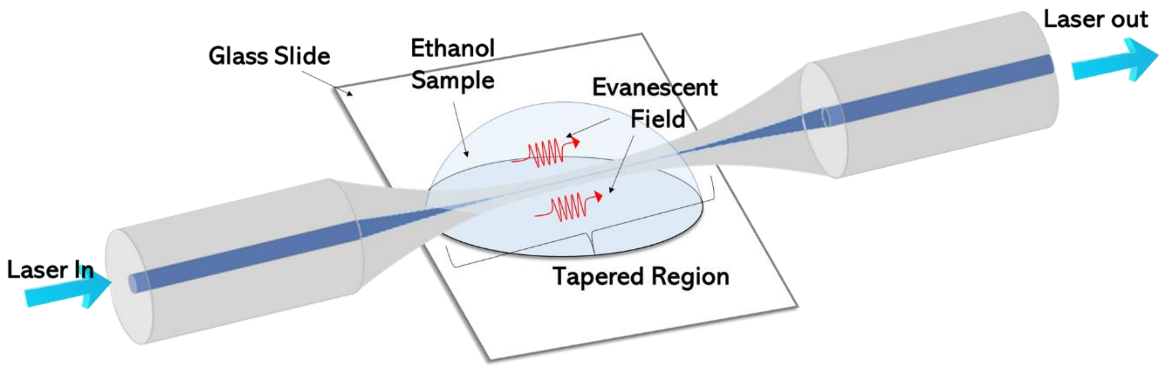
The single mode fiber is placed horizontally with one end is clamped at the fiber clamp located on the linear stage and one end clamped at the static fiber clamp. The static fiber clamp would hold the fiber while the fiber clamp on the movable linear stage pulled the fiber during the tapering process to elongate and stretch the fiber axially. This linear stage that pulled the fiber is set at low rate of speed to reduce any mechanical vibration and ensuring smooth microfiber fabrication process. The linear stage that held the flame torch is positioned opposite to the longer linear stage. The flame is put exactly at the uncoated segment of the fiber. The flame is moved back and forth with specific optimization, portraying a brushing manner. This is to melt the fiber glass before it starts to elongate and stretch. The linear stage holding the fiber that acted as the pulling mechanism executed specific revolution per minute. The difference between the power before and after the tapering process is recorded to observe the insertion loss. After the process of fabrication is completed, a portable microscope is placed at the waist region to observe the structure of the microfiber.

2.2. Adiabatic microfiber for ethanol detection sensor

The experimental setup for ethanol concentration sensor is shown in Fig. 2. To monitor the sensitivity of adiabatic microfiber, correspond to the ethanol concentration, the setup consists of amplified spontaneous emission (ASE) source generated from erbium-doped fiber (EDF) which generates a C-band ASE spectrum. The source provided a broadband spectrum from 1530nm to 1560nm. A schematic diagram of adiabatic microfiber ethanol concentration sensor placed on top of a glass slide which clamped on a multi-axis stage in shown in Fig. 2 (b). First, this experiment is done by placing five drops of ethanol solution on the glass slide using syringe. Then, the glass slide containing the ethanol sample was slowly raised toward the microfiber sensor. The tapered region must be fully immersed in the ethanol sample before proceed with the data collection process. As a precautionary step, any significant movement must be avoided to prevent the ethanol sample on the glass slide to overflow thus affecting the deformation of microfiber structure.



(a)



(b)

Fig. 2 (a) Configuration setup for the sensitivity analysis of the adiabatic microfibers; (b) Schematic diagram of the experiment. The fabricated microfiber sensor is fully immersed when tested with the ethanol of different concentration sample (color online)

The optical spectrum of the adiabatic microfiber sensor is analysed by using Thorlabs OSA202 optical spectrum analyser (OSA) with a resolution of 0.06 nm. This experiment is repeated by decreasing the concentration of ethanol solution using dilution method, 70%, 50%, 35%, 20% of ethanol concentration, and 0% indicating pure distilled water. The tested ethanol solution is removed using a syringe and left to dry within a few minutes before continuing with the following concentrations. This is to make sure the ethanol is fully vapourised before being tested with the next solution. To increase the efficiency output of the experiment result, this experiment is done in a closed compound with a controlled air circulation.

3. Results and discussion

Fig. 3 shows the structure of adiabatic microfiber transition region and waist under portable microscope. In Fig. 3, a) indicated the transition change of size from a conventional single mode fiber to microfiber. It can be observed that the transition region of the fabricated microfiber reduces gradually following the adiabatic criterion. In Fig. 3, b) the red arrow shows the observed waist of the fabricated microfiber approximately at 20µm. Fig. 3, c) shows the other end of the microfiber transition region. However, due to the designed microfiber machine, the length of transition region is long.

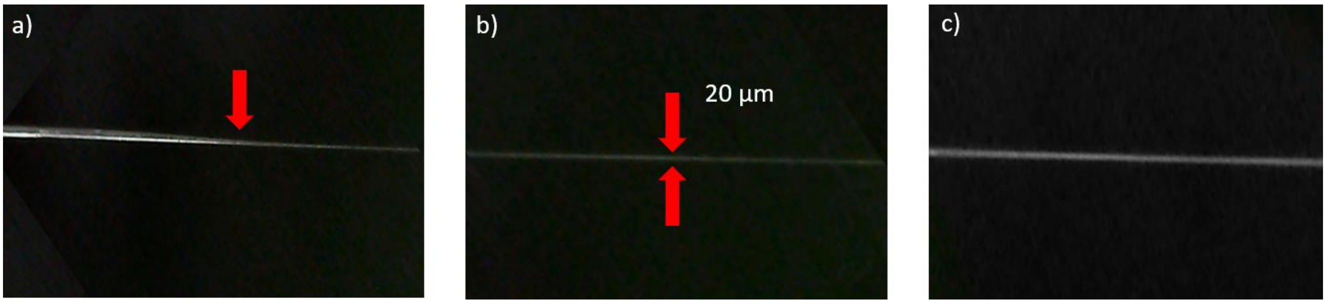


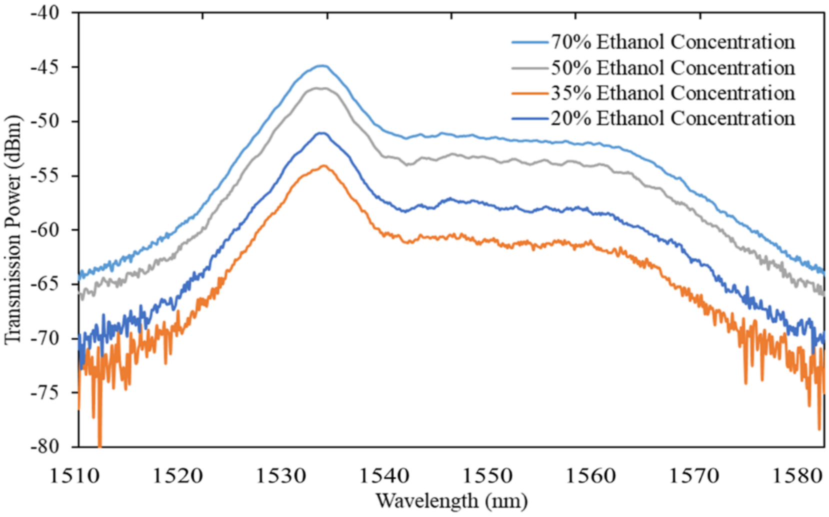
Fig. 3. Adiabatic microfiber structure: (a) Right transition region, (b) Waist diameter and (c) Left transition region (color online)

Table 1 show adiabatic structure microfiber transmission power and insertion loss. The transmission power of conventional fiber is -31.875 dBm before the tapered process, and slightly dropped to -33.214 dBm after fabricate. From this transmission power measurement, the transmission loss of the microfiber is 1.339 dBm. The adiabaticity of microfiber is obtained by using the proposed method of fabrication and shows that the adiabatic structures have low transmission power loss.

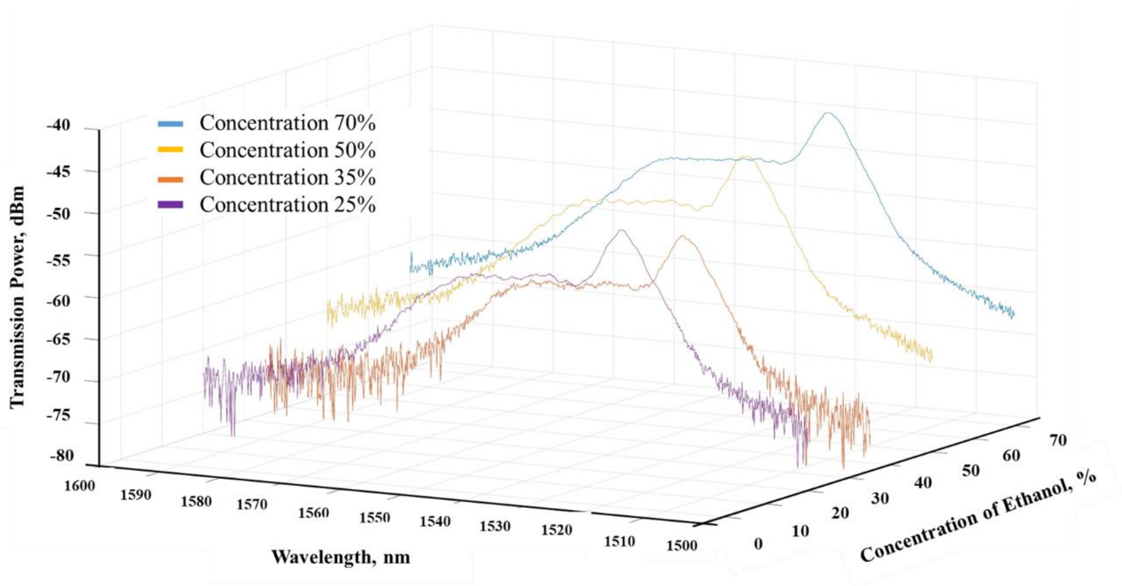
Table 1. Transmission power and insertion loss of adiabatic microfiber

Power (dBm)		Insertion loss (dBm)
Before Tapered	After Tapered	
-31.875	-33.214	1.339

The transmission spectra (dBm) of the adiabatic microfiber at different concentration of ethanol is shown in Fig. 4. The transmission spectra of the microfiber displayed the same pattern for 20% until 70% of ethanol concentration with the difference only in the output power level. Based on the pattern formed, with the exception of distilled water, the fabricated microfiber retains its adiabaticity characteristic for all value of ethanol concentration tested. Fig. 5 illustrates the peak of transmission power (dBm) of the adiabatic microfiber at different concentration of ethanol. From Fig. 5, the total difference between transmission power ranging from 0% to 70% of ethanol concentration in distilled water is 14.26 dBm. A linear correlation coefficient can also be established between transmission power of an adiabatic microfiber sensor and the increasing ethanol concentration with an optical power rate change of about 0.1932 dBm/%. This number demonstrates the sensitivity of the microfiber sensor when subjected to varying concentrations of ethanol.



(a)



(b)

Fig. 4. (a) The transmission spectra of adiabatic microfiber sensor with different ethanol concentration ranging from 70% until 0% and (b) The 3D Model representation of Optical Transmission Power against different Concentration (color online)

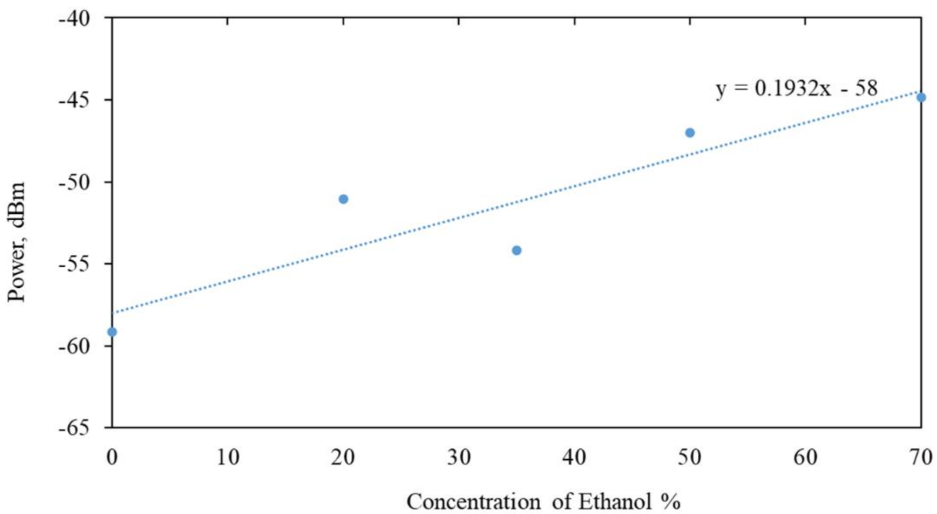
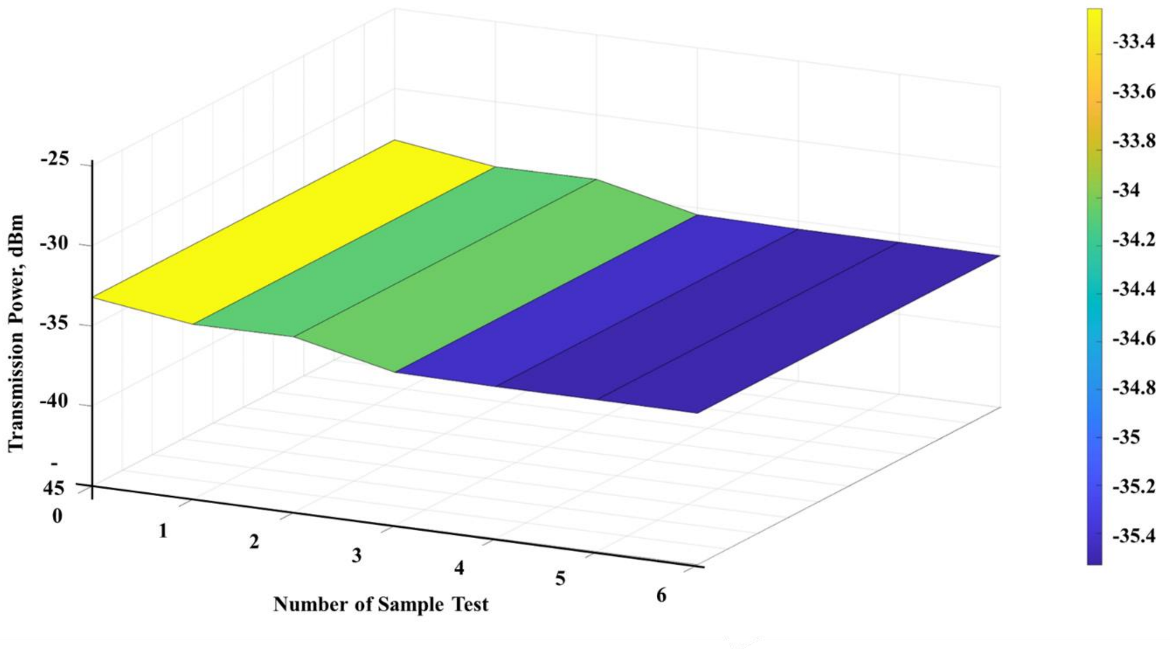
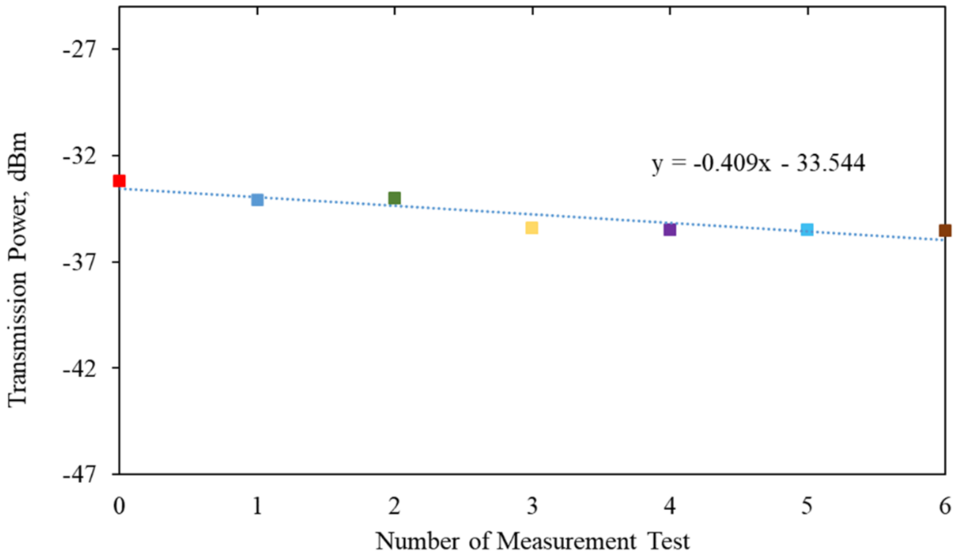


Fig. 5. The peak of transmission power of adiabatic microfiber sensor at different ethanol concentration (color online)



(a)



(b)

Fig. 6 (a). The power characteristic without any ethanol after number of test and (b) 3D graph of power characteristic without any ethanol after number of tests (color online)

In Fig. 6 (a) and (b), the power characteristic without any ethanol after number of tests. The graph shown that the power characteristic remains almost the same after performing the 6-sample test. This data shown the repeatability of the proposed microfiber sensor and prove that the sensor can be use many times using a single sensor. In general, the fabricated microfiber sensor experiences only a small change of power as a function of the number of tests showing a fluctuate power is about 0.409 dBm per number of tests. Besides that, a slight mechanical strength induced by water's surface tension also may result in this condition. Overall, it is worth mentioning that the optical microfiber sensor in this work is remarkably easier to fabricate with a modification of controllable single translation stage. This innovation of the low cost and simple experimental project have achieved to fabricated a huge potential of robust ethanol sensor supported with a promise data of high repeatability and stability test. In preparation for future research, the produced sensor can be packaged in a suitable casing to improve the device's mechanical stability and its reliability.

4. Conclusion

A low cost and simple method of fabrication of adiabatic microfiber sensor is proposed and demonstrated. The result, based on the designed microfiber machine, confirmed its ability to fabricate a small diameter of microfiber waist about 20 μm with low value of transmission loss, 1.339 dBm. The fabricated adiabatic microfiber sensor shows a linear relationship between the transmission power and ethanol concentration ranging from 0% to 70%. The fabricated sensor shows a sensitivity of and great repeatability in measurement with only 0.401 dBm per number of tests. The proposed sensor possesses significant application in ethanol detection due to its high sensitivity and robust structure.

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*Corresponding author: mzz@iium.edu.my