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Optimization of sensing performance factor (γ) based on microfiber-coupled ZnO nanorods humidity scheme

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ABSTRACT

An optimization method of the proposed humidity sensing scheme comprises of silica microfiber laid on a glass surface coated with Zinc Oxide (ZnO) nanorods is reported. The silica microfibers were tapered into several waist diameters of 6 µm, 8 µm, 10 µm and 12 µm using flame brushing technique, while the glass surface was coated with ZnO nanorods using hydrothermal method for 6 h, 9 h, 12 h, 15 h and 18 h of growth time. The samples were exposed to the different humidity level ranging from 35%RH to 85%RH to observe several performance parameters such as scattering coefficient (α), sensing performance factor γ, output light intensity and ultimately the sensitivity. 12-h growth sample exhibited the optimum results in term of α, γ, output light intensity and sensitivity towards the %RH level. The sensitivity improved by a factor of 1.3 as compared to the closest best sample. Besides that, it was found that 6 µm waist diameter microfiber sample produced optimum result in term α, γ and sensitivity towards the %RH level. The sensitivity improved by a factor of 1.1 as compared to the closest best sample. The work provided the best optimization method for microfiber and ZnO nanorods samples for the proposed humidity sensing scheme. It utilized the distinctive features of the scattering and surface absorption capability of the microfiber and ZnO nanomaterials coated glass surface to couple with the surrounding water molecules for humidity sensing.

1. Introduction

Relative humidity (%RH) is the ratio of partial pressure of water to the saturated vapor pressure at a certain temperature. It has been widely applied in agriculture, meteorology, sterilizers, incubators, textile production, air conditioning, and chemical gas purification. Even though the cost of the optical fiber humidity sensor is higher than conventional electronics sensors, it has advantages of their small size, the possibility of multiplexing information from several sensors and insensitive to electronic magnetic fields [1]. The existing %RH sensor in the market such as wet and dry bulb psychrometer was not viable due to its low sensitivity and long response time, whereas electronic based %RH sensor has the detrimental effect of electromagnetic interference [2].

Silica optical fiber appears to be less responsive to the outside environment as the cladding is much thicker than the core. However, when the single-mode fiber is tapered, the core/cladding is redefined as multimode fiber that sustains several modes. This eases the interaction of the evanescent field with the outer medium which changes the transmitted optical power. The guided light produced large fraction outside the microfiber which also known as evanescent wave resulted in enhanced sensitivity to the refractive index change to the surrounding medium [3]. Hence the first two modes in the waist have been considered as the main cause of the transmission oscillations when the external refractive index changed [1]. When there is the existence of specimens or even temperature change around the microfiber, it will cause refractive index change which would change the guided light inside the microfiber in term of optical phase and intensity [3]. Tapered optical fiber known as microfiber provides low manufacturing cost and has the capability to produce transmitted optical power variations through tapered region when the external refractive index changes [1]. It draws attention due to the distinctive behaviour such as tight optical confinement [4], large evanescent field [5], field enhancement [6], manageable large waveguide dispersion [7] and low optical loss through sharp bends [8].

The sensor's evanescent field can be modified by changing the refractive index of the coating material. This will decrease or increase the light coupled into the cladding modes. One of the dominant factors for the sensing is the penetration depth of the evanescent wave which depends on the refractive index of both core and coating material [9].

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Metal oxides have been employed as sensing material because they are thermally robust, have good resistance or chemical degradation and not affected by aging. Zinc oxide (ZnO) is a persuasive material for sensing application due to its chemical adsorption, electronic features and numerous available synthesis processes. It is an n-type semiconductor with band gap energy is 3.37 eV. O_2 is capable to adsorb into the metallic oxide and produces oxygen ions by taking electrons from the conduction band, which results in a reduction of the material conductivity [9]. It has become eminent materials in high-technology applications such as biological detector [10], field-effect transistor [11], light-emitting diode [12] and sensing applications [13]. It shows exciting manners such as room temperature ferromagnetism, piezoelectric behavior, huge magneto-optic and chemical sensing properties [14]. Optical detection of the ZnO nanorods towards humidity is based on the changes of the electrical conductivity of the material due to the adsorption of water molecules and changes of surrounding effective refractive index [15,16]. The change in electrical conductivity modifies the complex refractive index of the ZnO nanostructures. [17]. These factors affect the optical scattering characteristics of light incident on the ZnO nanorods [18].

As aforementioned, in order to maximize the evanescent wave generation and the interaction with the surrounding medium in the sensing region, the waist diameter of the silica microfiber and the ZnO nanorods growth need to be optimized [19]. Ideally, if the waist diameter reduction process can be perfectly conducted, the fraction power (η_{eff}) propagating in the evanescent field would depend on the ratio of λ/r. η_{eff} increases monotonically when λ/r increases [20]. λ will lead to the dramatic growth of the transversal dimensions of the fundamental mode that propagates outside the microfiber by reducing the diameter of the microfiber to the values significantly smaller than the radiation wavelength. The corresponding evanescent field is applicable for sensing the ambient medium and trapping atoms [21]. As for ZnO nanorods, there are several crucial parameters need to be optimized. One of the most important parameters is growth duration because it will influence the nanorods dimension such as density, length, and optical scattering cross section. These dimensions could change the optical response of the nanostructures in term of attenuation coefficients and scattering [22]. Several efforts have been conducted to optimize the ZnO nanorods parameters. Fallah et al. studied the effect of aqueous growth condition of nanorods for optical fiber coupling power [23]. Bora et al. found that 2.2um tall ZnO nanorods were optimum height for ZnO nanorods to produce maximum average coupling efficiency of classing mode light side coupling [24]. Rahim et al. discovered the optimum width for spiral patterned ZnO nanorods coating based on light side coupling for alcohol vapors detection [14]. To date, there were no studies have been conducted to optimize both the ZnO nanorods growth and microfiber waist diameter for humidity sensing application.

There are numbers of optical humidity sensing mechanism has been introduced such as using microfiber bottle resonator [25], long-period grating coated with gelatin [26], electrostatic self-assembly of tapered optical fiber [1], PMMA microfiber doped with agarose gel [27], silica fiber interferometer [28] and side polish fiber coated with tungsten disulphide [29]. However these directly coated nano-materials humidity sensors onto the fiber required vigilant handling process during synthesis procedure especially for diameter up to micron meter. It also have possibility to deteriorate the long term performances of the microfiber [30]. In this paper, an optimum microfiber waist diameter and ZnO nanorods coated glass surface for the proposed humidity sensing scheme has been investigated for the first time to our knowledge. It is based on the integration of the ZnO nanorods coated glass surface and the silica microfiber. This work would not only solve the issues pertaining to microfiber based optical sensor such as the portability of the sensor and the hassle during synthesis process [30,31], it also realized the optimal parameters to access the evanescent wave from microfiber and ZnO coating layer for humidity sensing.

2. Theorethical analysis

2.1. Sensing mechanism

The intensity-modulated technique is a suitable technique for humidity sensing since it is easily affected by the external environment factor while most of the other methods are intended to eliminate the interferences [32]. Evanescent fields were employed to develop the intensity modulated fiber optic. Power carried by the evanescent wave would interact with the surround measurand and attenuated with respect to the scattering, absorption and refractive index change [33]. Taper region on fiber increases the strength of the evanescent waves in the cladding region that lead to the increase of the excitation events in the cladding. Refractive loss occurs when an increase in the surrounding of a sensing region will decrease the local numerical aperture (NA) and results in attenuation of light. When the surrounding refractive index (RI) changes, the critical angle also changes. This would cause the new critical angle is greater than the existing incidence angle, resulting in refraction loss [34]. When analyte molecules attached to the surface of the ZnO nanorods, physical adsorption and interaction between the evanescent field region and receptor on the medium surfaces will occur. The molecule interacts depend on its size and optical parameters such as the extinction coefficient and refractive index. The evanescent waves absorbance is highly related to the concentration of the analyte if other parameters are known [34].

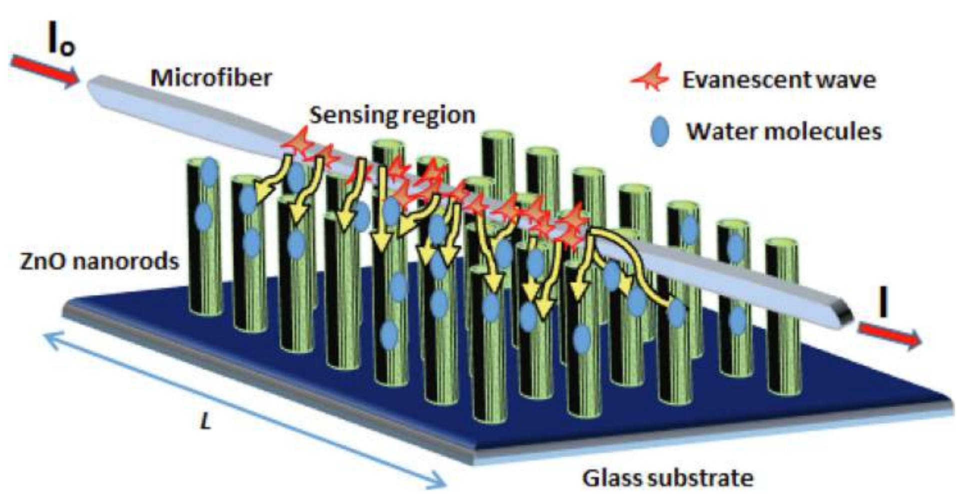

Fig. 1. Sensing mechanism of the proposed sensor.

Fig. 1 illustrates the sensing mechanism of the proposed sensor. When the sensing region is exposed to the humidity, the refractive index of the ZnO becomes larger compared to the microfiber because the air medium is replaced by humidity and the water molecules chemisorbed on the ZnO nanorods surface due to weak hydrogen bonding [35]. This will result in light coupling into the ZnO nanorods waveguides. This phenomenon will increase more evanescent field appearance in the sensing region. Thus, when the light source (I) propagates through the length (L) of the ZnO coated glass substrate, the output light intensity (I_o) will be reduced. At low %RH, the refractive loss is negligible since it is a very slight difference of RI between sensing material and analyte molecule. Therefore, at low RH, most change is due to the evanescent wave absorbance phenomenon. While at high concentration, refractive loss normally happens due to the significant difference in RI between two medium [34]. Noted that when %RH increases, effective index of the ZnO nanorods and surrounding medium increases as well. Thus, the forward scattering coefficient will increase due to the reduction of light transmission through the sensing region [36]. The ZnO nanorods morphological structure affected the forward-scattering and back-scattering of the proposed sensor. The backward scattering lowers the leakage of light while the forward scattering increases the light leakage. Backward scattering would dominate with shorter rods and lower rod density. Thus, the response reduced with lower nanorods length and smaller density of nanorods [36]. Therefore the best trade-off between the rods length and density would determine the optimum output response.

2.2. Optimization of ZnO nanorods growth and microfiber waist diameter

Based on literature, microfiber with small diameter provides higher sensitivity as more evanescent field exposed to the surrounding medium and larger external refractive index will produce. Geometrical characteristics such as diameter, length, type and density could affect the fractional power that ultimately influences the sensitivity of the fiber [20]. Furthermore, the smaller diameter could affect light scattering on the surface of the taper waist that induced the propagation loss. This is because of effective refractive index reduced in the waist region that broadening the mode of light propagating through the microfiber. As mention in [37], thinner taper fiber also yields stronger evanescent field and higher coupling coefficient between microfiber and surround analyte. However, the handling process of the thinner microfibers becomes more sophisticated due to its fragility and lossy [38]. Generally, the intensity of the guided light inside the microfiber is depended on the absorption coefficient of the coating material and the portion of total fraction power carried in the evanescent field. The mechanism to describe the attenuation of light propagating through the sensing medium has been described by the Lambert-Beer law as shown in the following equation [39]:

$$I = I_o e^{-\alpha L} \tag{1}$$

where I is the intensity of the light leaving the medium after interaction of sensing region with the analyte, I_o is the intensity of the light entering the medium before interaction of sensing region with the analyte, α is the scattering coefficient and L is the length of the sensing region. It also the function of the effective fraction of the total guided power, concentration and bulk absorption coefficient of the absorbing material [35]. As light transmits through materials, it may be weakened by absorption and scattering. The combined effect of this phenomenon is called extinction. Scattering occurs when incident light interacts with an atom. The atom will be excited to a higher energy level and immediately drops down to its original level and emits a photon at the same frequency as the one it absorbed. It occurs when there are refractive index mismatches at boundaries. Based on equation (1), the scattering coefficient (α) can be derived as :

$$\alpha = \frac{-ln\left(\frac{I}{I_o}\right)}{L} \tag{2}$$

Optical transmittance (T) reduced as the humidity level increased. Refractive index increase with the increment of water molecules around the ZnO nanorods. This induces higher light leakage that improves the response towards humidity [36]. The output intensity of the coupled light into the ZnO nanorods around the sensing region fluctuates during the exposure to the different concentration of humidity [19]. The intensity of the coupled light across the absorbing medium varies under exposure to different %RH level. It correspondent to the changes of analyte (water molecule) concentration around the sensing region [39]. Optical transmittance (T) could be measured at the sensor's output using equation (3) [36]:

$$T = \frac{I}{I_o} = e^{-\alpha L} \tag{3}$$

In order to observe the effect of %RH towards the ZnO nanorods growth time, sensing performance factor (γ) is introduced. γ will reveal the enhancement ratio between the scattering coefficient (α) at the lower %RH and higher %RH numerically. The sensor is tested at maximum humidity (T_{max}) and minimum humidity (T_{min}) for each ZnO nanorods growth time samples. Subsequently, γ can be derived by using equation (3) by dividing T_{max} and T_{min} to produce equation (4)

$$\gamma = \frac{T_{max}}{T_{min}} = e^{L(\alpha_{min} - \alpha_{max})} \tag{4}$$

Growth time will affect several ZnO nanorods parameters such as rods shape, diameter, and length. Based on the first order scattering model [23], the light intensity propagates over a distance L of the sensing region is shown in Eq. (5). C_{sc} is the scattering cross-section of one nanorod ($C_{sc} = \alpha/\rho_v\rho_v$) is the average rods density per unit volume, $\rho_v = \rho_a/ \int$ and P_a is the average number of nanorods per unit area. $\int$ is the average rods' length and I_o is light source intensity entering the medium. Therefore, the average intensity is depicted in Eq. (5).

$$I_{ave} = -C_{sc}\rho_v I_o L \tag{5}$$

3. Material, fabrication and characterization

3.1. Glass substrate and microfiber preparation

Initially, waist diameter of single-mode fiber (Corning SMF-28, USA) with a diameter of 125 µm was reduced into a diameter of 6 µm, 8 µm, 10 µm and 12 µm (Fig. 2) at a fix tapered length of 2 cm using flame brushing technique. The hydrothermal synthesis process of the ZnO nanorods was performed onto microscope glass substrates (Heathrow Scientific LLC, USA). It starts with ultrasonic cleaning process where the glass substrates were immersed in a container of soap water and clear water for the duration of 15 min sequently. The glass substrates were then immersed in acetone [C_3H_6O] (Bendosen Laboratory Chemical, Germany) through water bath procedure for 15 min and placed in an oven at 90 °C for 1 h to remove organic material. Then, the seeding process took place where 0.0132 g zinc acetate dehydrate [$Zn(O_2CCH_3)_2{\cdot}2H_2O$] (Friendemann Schmidt, Germany) were dissolved in 60 ml of pure ethanol [C_2H_5OH] (HmbG Chemical, Germany) to form a 1 mM solution under continuous stirring at temperature of 60 °C. In order to increase pH in alkaline, aliquots of 0.0003 g sodium hydroxide pellets [NaOH] (Friendemann Schmidt Chemical, Germany) was added to the solution. It is then kept in a water bath at 60 °C for 3 h followed by annealing process under 300 °C for 3 h [40]. Subsequently, ZnO growth solution was prepared where 1.4875 g zinc nitrate hexahydrate [$Zn(NO_3)_2{\cdot}6H_2O$] (Sigma-Aldrich) and 0.7 g of hexamethyleneteramine or HMT [$(CH_2)_6N_4$] (Sigma-Aldrich) were dissolved in 500 ml of deionized (DI) water to form 10 mM aqueous solution. The seeded glass substrates were then placed in 200 ml of the solution and heated in an

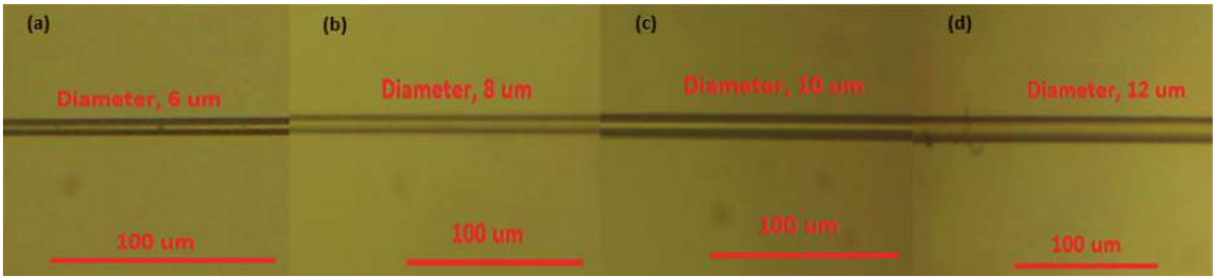

Fig. 2. Microscopic view of a microfiber with diameter of; a) 6 μm, b) 8 μm, c) 10 μm and d) 12 μm.

oven at temperature of 90 °C. It is important to change the synthesis solution for every 5 h to guarantee constant growth rate of the nanorods. In the experiment, the ZnO nanorods were grown for 6 h, 9 h, 12 h, 15 h and 18 h. Eventually, the samples were removed from the solution and severally rinsing in DI water.

3.2. Characterization & experiment

Field emission Scanning electron microscopy (FESEM) was performed using the Hitachi model 3400 N to view the morphology of ZnO nanorods growth on the glass surfaces. In the meantime, Energy dispersive X-ray (EDX) was conducted to determine the chemical constituent of the samples. Fig. 3 illustrated the experimental setup of the humidity sensing. The sample was placed inside a sealed chamber (22 × 12 × 12 cm) where the nanorods coated surface was directed upwards. Subsequently, the microfiber was laid on the coated glass surface. Amplified Spontaneous Emission (ASE) from an erbium doped fiber amplifier (EDFA) was excited at one end of the microfiber and the other end was connected to the Optical Spectrum Analyzer (OSA) (Anritsu: MS9710C) for intensity and transmitted power measurement. The output spectrum was measured in the bandwidth between 1500 and 1600 nm measured in dBm using Optical Spectrum Analyzer (OSA).

Sodium Hydroxide (NaOH) was placed inside the sealed chamber to increase the relative humidity. The relative humidity increases when the water vapor from the salt solution increases. In this work, the humidity level was varied from 35%RH to 85%RH (due to the limitation of our equipment) while the temperature was maintained at the constant room temperature of 27 °C. This is because if temperature rises at the particular %RH condition, the amount of absorbed water molecules from the surrounding reduces due to entropy increase of water molecules [41]. This scenario will slightly change the refractive index of the medium. According to Tan et al., the increment of temperature would lead to wavelength shift [28]. However, it is worthy to note that the temperature cross sensitivity is rather low for silica fiber taper (~-0.048 %RH/°C). This is due to the photon energy, which mostly resides in silica fiber and thus the change of the propagation light mode and refractive index with the temperature are occurring at almost the same rate. This allows the thermal optic effect to be self-compensated and the sensor is almost insensitive to the ambient temperature which leads to the insignificant transmitted output power response change. In order to monitor the actual humidity level around the sample's surface, the probe of a %RH meter (Hygrometer RS 1365, Sensitivity: 1%) was placed as close as possible to the proposed sensor. In order to ensure the stability and repeatability of the sensing, the readings were recorded several times. Eventually, the optical characterization was evaluated based on several criterions such as light scattering, transmission loss and intensity with the goal of achieving optimum parameters value of both microfiber and ZnO nanorods growth time.

4. Result and discussion

4.1. Morphology of the ZnO nanorods growth

ZnO nanorods coating: Fig. 4 depicted the EDX elemental analysis that examines the coating layers on the glass surface consist of only zinc (81.21%) and oxygen (18.79%). Fig. 5 shows FESEM image of ZnO nanorods grown on the glass surface at different growth time which are 6 h, 9 h, 12 h, 15 h and 18 h at 20.00 kX magnification and 50.00 kX,

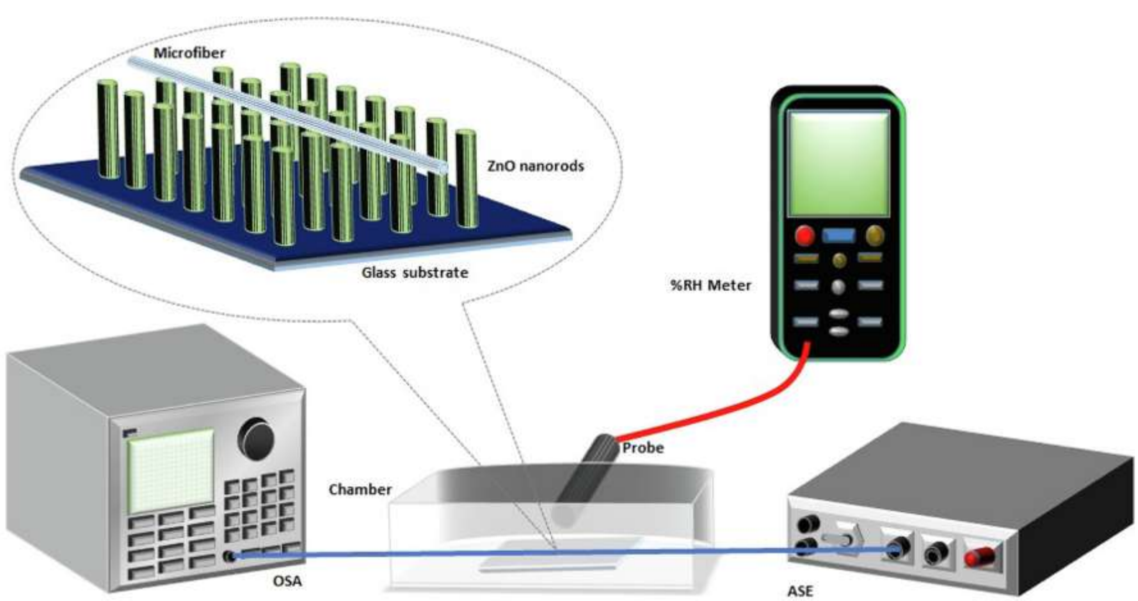

Fig. 3. The experimental setup of humidity sensing.

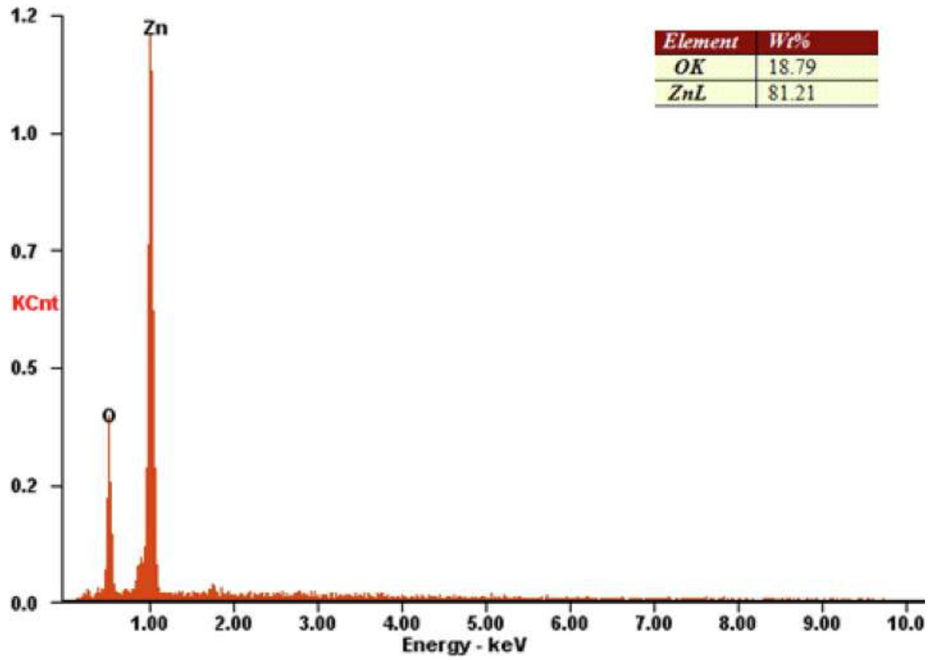

Fig. 4. EDX elemental analyses of ZnO coating comprise of zinc and oxygen peaks.

respectively. It can be seen growing vertically on the surface of the glass substrate. It can be observed that each growth sample exhibit a variety of morphology structure such as length, diameter and density. Based on Fig. 6, the average nanorods length and diameter rise monotonically with the increment of growth time while the average nanorods density declines monotonically when the growth time increases.

4.2. Optimizing ZnO nanorods growth time

The experiment was first conducted with the microfiber with 10 μm diameter which was laid on the different growth time samples. Normalize scattering coefficient (α) was calculated based on experimental results using Eq. (2). Fig. 7 shows that the normalize α increase proportionally with the increment of %RH for most samples. When the sensing region is exposed to the humidity, the air medium is replaced by humidity and the water molecules chemisorbed on the ZnO nanorods surface due to weak hydrogen bonding [35]. The additional water molecules would increase the absorption coefficient and the effective index of the ZnO composite and surrounding medium [42]. Noted that if other parameters are known, the evanescent waves

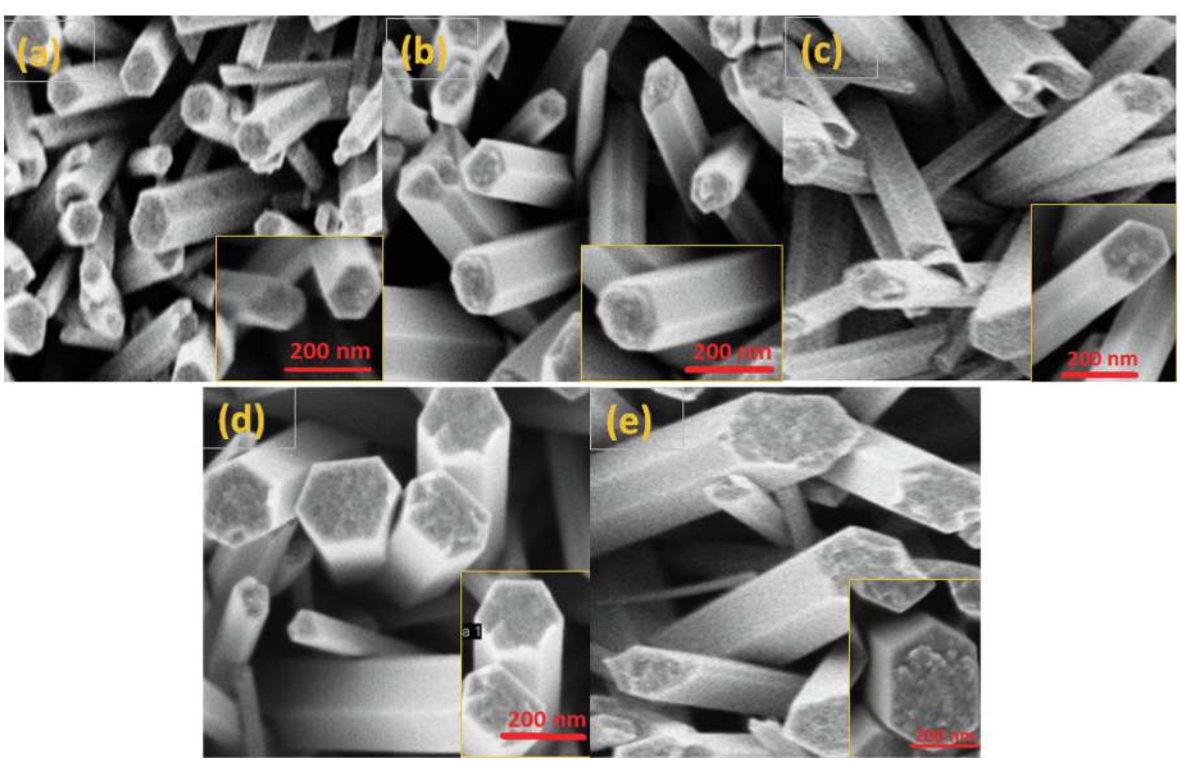

Fig. 5. Morphology of the ZnO nanorods coated glass with growth duration of; a) 6 h, b) 9 h, c) 12 h, d) 15 h and e) 18 h.

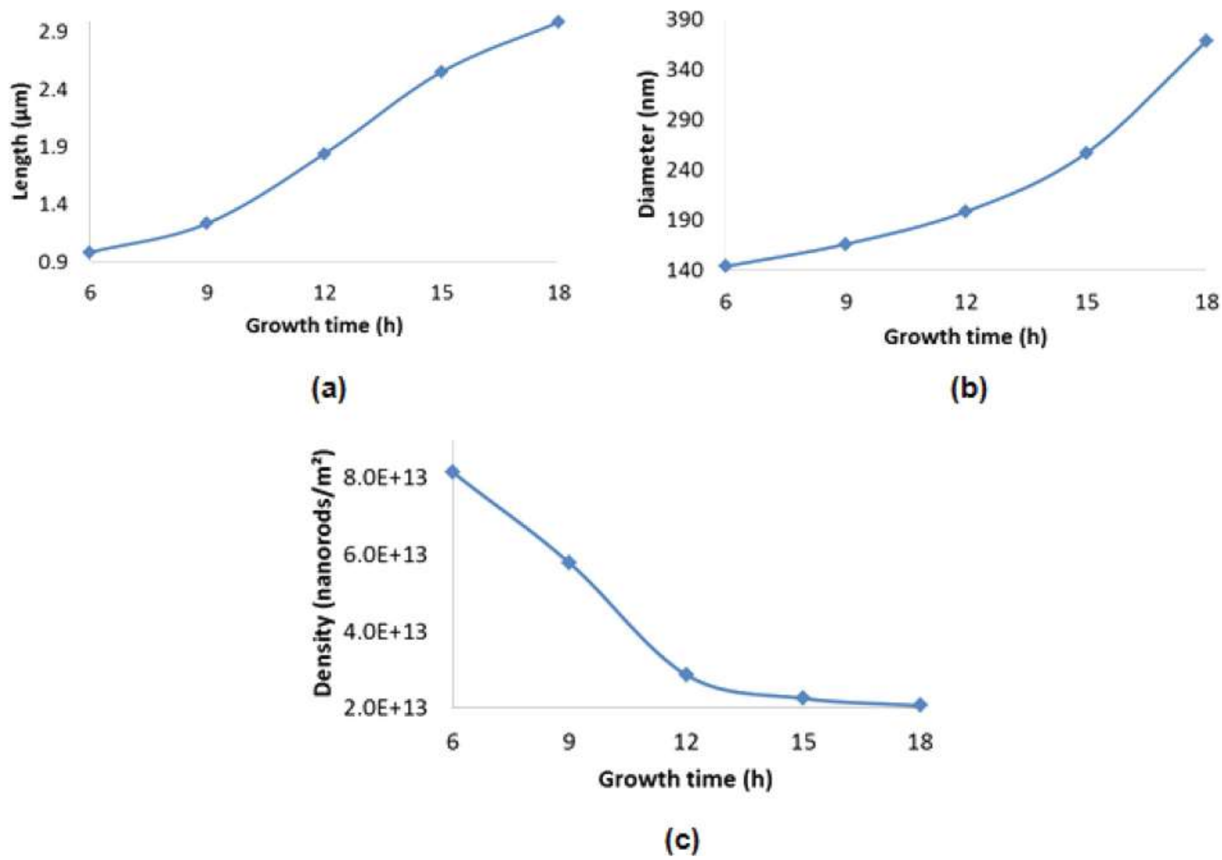

Fig. 6. Difference physical structure of the ZnO nanorods coated glass when the growth increase in term of; a) Length, b) Diameter and c) Density.

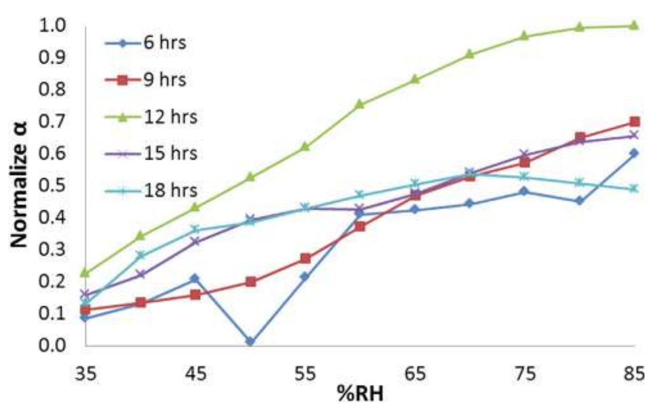

Fig. 7. Normalize α for every growth time samples when the %RH increases.

absorbance is mostly dependent on the concentration of the analyte [34]. Thus evanescent field appearance would increase around sensing region and resulting in light coupling into the ZnO nanorods waveguides. Therefore, the normalize α will increase due to the combined effect of forward scattering and surface absorption into the ZnO nanorods. Based on Fig. 7**,** the 12 h sample exhibit the highest α due to its optimum nanorods physical dimension that encourage more light absorption inside the nanorods [36].

Sensing performance factor (γ) is calculated by substituting measured result in using Eq. (4). It is an essential parameter to identify which samples produce the best response when they are exposed to the minimum %RH to maximum %RH. When the relative humidity increases, rapid surface adsorption would cause more water molecules onto the ZnO nanorods surfaces. Y.Liu et al. reported that the effective index increased from 1.698 to 1.718 when relative humidity varies from 10% to 95% [43]. This weakening the light transmission and resulted in a larger leakage of light. Therefore, the response to humidity increases when the %RH increases. Furthermore, longer growth times reduced the ZnO nanorods density (refer Fig. 6) on the glass substrates which induce more backscattering. This will cause a greater barrier of light absorption inside the nanorods which reduce the response [14]. Hence, based on Fig. 8, growth duration of 12 h was optimal in limiting backscattering and improving the response thus produce highest normalize γ as compared to other samples.

It is observed that both forward-scattering and back-scattering affected the output intensity of the proposed sensor. Backward scattering lowers the leakage of light while the forward scattering will increase the light leakage. Backward scattering would dominate with shorter rods and lower rod density. Thus, the response reduced with lower nanorods length and smaller density of nanorods [36]. However, nanorods lengths increased when the growth time increased meanwhile nanorods density reduced when the growth time increase, based on

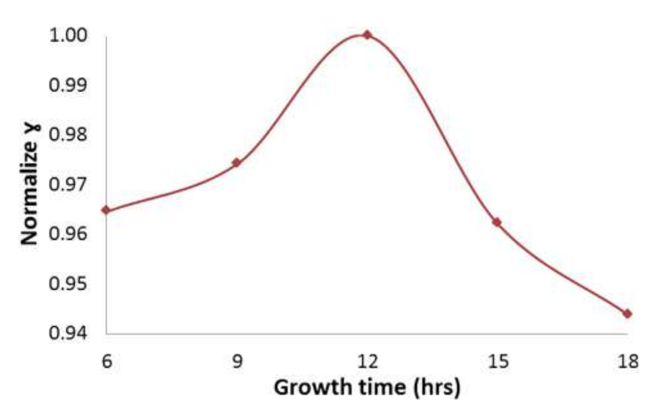

Fig. 8. Normalize γ of every growth time samples at ambient temperature.

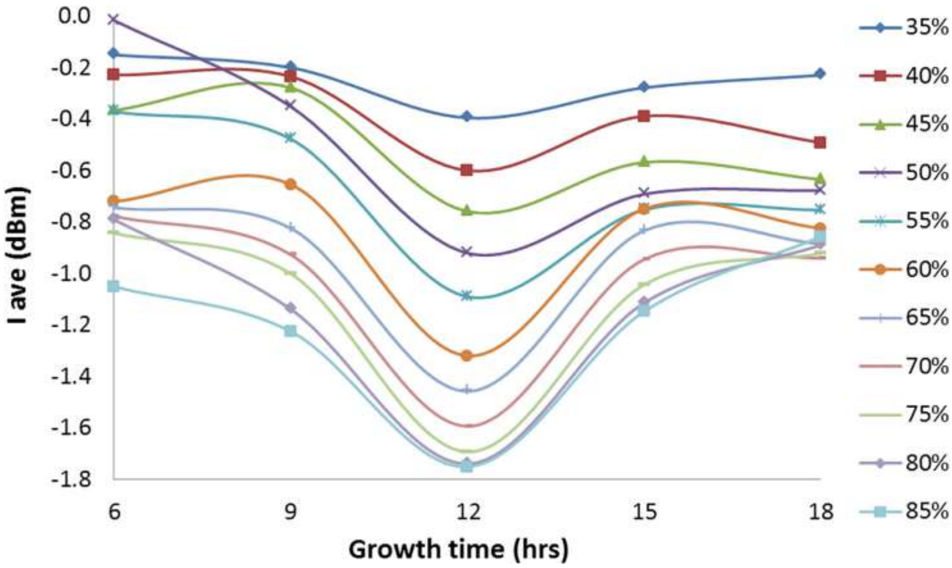

Fig. 9. Average intensity of every growth time samples when %RH increases based on theoretical formulation.

results in Fig. 6. Therefore the best trade-off between the rods length and density would determine the optimum output response. The average intensity is calculated using equation (5) based on the experimental result in Fig. 5. Output intensity that coupled into the ZnO nanorods around the sensing region fluctuates during the exposure to the different concentration of humidity [19]. Based on Fig. 9, the best trade-off between the length and density is 12 h grow time sample. The intensity significantly reduced due to light leakage for almost all %RH range. It also can be observed that the intensity varies in a small magnitude at low %RH and further reduced when %RH increases. This is because, at low %RH, the refractive loss is negligible since it is a very slight difference of refractive index (RI) between sensing material and analyte molecule. Therefore, at low %RH, most change is due to the evanescent wave absorbance phenomenon. While at high concentration, refractive loss normally happens due to the significant difference in RI between two medium [34]. Thus, the 12 growth time sample was chosen for the rest of the experiments because it exhibits the highest light absorption inside ZnO nanorods which was the utmost criteria for the proposed sensing mechanism. Eventually, the response towards the humidity sensing for every growth time samples from 35%RH to 85% RH was obtained as shown in the trendline graph in Fig. 10. The result shows that 12 h grow time sample has the best sensitivity as compared to the other samples. It improved by a factor of 1.3 as compared to the closest best sample.

4.3. Optimizing microfiber waist diameter

The experiment was conducted with difference microfiber waist diameter samples which was laid on the 12 h grow time sample. Fig. 11 shows that normalize α of most samples rise proportionally when %RH increase. However, the smallest diameter sample which is 6 µm produce highest raise as compared to other samples. As aforesaid, smaller waist diameter could increase the light scattering effect on the surface of the taper waist that induced the propagation loss. This is due to effective refractive index reduced in the waist region that broadening the mode of light propagating through the microfiber [34]. Fig. 12 shows sensing performance factor (γ) of the samples. It was measured at the output of the proposed sensor after exposure to the maximum and minimum humidity level. Two major factors would affect the γ are the scattering and the surface absorption when the light propagating through the

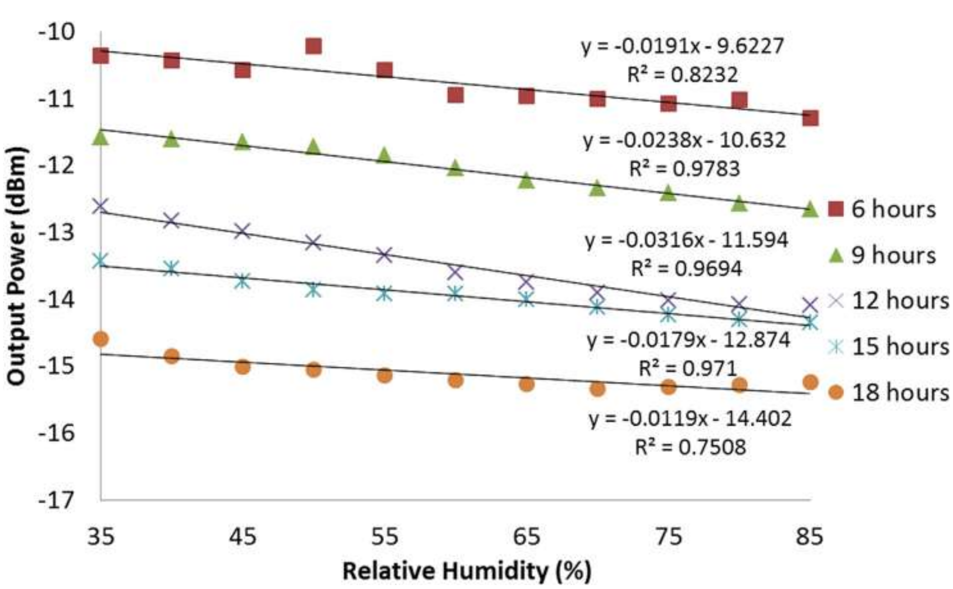

Fig. 10. Trendline of every growth time samples when %RH increases.

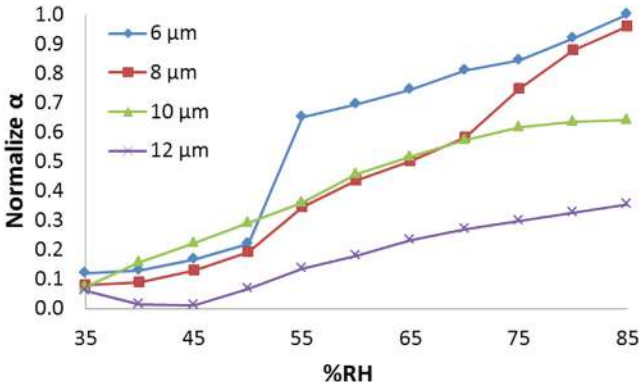

Fig. 11. Normalize α of microfiber waist diameter increased when the %RH increase.

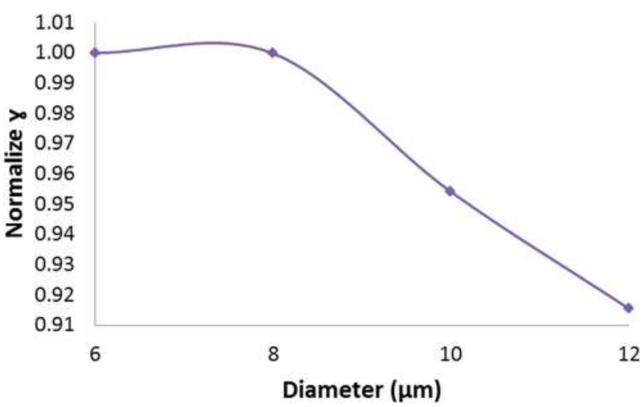

Fig. 12. Normalize γ reduced with the increment of microfiber waist diameter.

microfiber via the ZnO nanorods coated glass. The result shows that normalize γ display a direct relationship with microfiber waist diameter in which γ decrease proportionally when the diameter increases. This is because bigger microfiber diameter provides lower evanescent field exposed to the surrounding medium and smaller external refractive index will produce. This phenomenon reduced the propagation loss as the diameter increase [37].

Based on the result in Fig. 12**,** smaller microfiber waist diameter sample would be beneficial to improve the sensing response. This is because the proposed sensor employed the evanescent wave and light scattering from the microfiber to couple with the humidity. Fig. 13 shows the trendline graph **of** the output response towards the humidity sensing for every microfiber's diameter samples from 35%RH to 85% RH. Microfiber with diameter of 6 µm produce significant power drop as compared to the others microfiber. It produces larger light propagation outside as evanescent waves and couple with the water molecules as the %RH increase. Furthermore, it has higher order modes leak out of the fibers and cause more lights interacts with the surrounding medium [4]. The intensity only varies in a small magnitude from 35% RH to 50%RH and start to drop significantly from 50%RH onwards. This is because at low %RH most change is due to the evanescent wave absorbance phenomenon due to small effective index between sensing material and the analyte molecules. Whereas at higher %RH the intensity loss was due to the larger effective index between the low mediums [34]. Thus, 6 µm sample exhibit the best sensitivity as compared to the other samples. It improved by a factor of 1.1 as compared to the closest best sample. As for resolution, it can be measured by dividing standard deviation (SD) with sensitivity (S). Based on the calculation, the proposed sensor is found to produce a good resolution value of around 2 %RH and thus it becomes suitable for applications in many fields including agriculture, incubators, production and environmental control system. In order to verify the long term stability, the output power against time of the proposed sensor and conventional sensor (normal microfiber) were examined at ambient %RH (55%RH) in room temperature for a total period of 15 min (900 s) in every 1 s. Based on Fig. 14, it is found that the output power of the proposed sensor exhibit better stability as compared to the conventional sensor throughout the tested period. For long term design, an appropriate packaging of the proposed sensor could be considered to avoid the microfiber from polluted and damaged. Furthermore, if the microfiber damage, it is easily replace with an uncoated microfiber by just laying it on the coated glass substrate. Therefore, the proposed sensor has better serviceability as compared to other directly coated microfiber based sensor.

Table 1 summarizes the humidity sensing performance as the parameters change. For ZnO nanorods growth time optimization, normalize α, normalize γ and sensitivity rise as the growth time increase. However they reach peak at 12 h sample and the performance start degrading for 15 h and 18 h sample. As explained previously, it is due to the morphological change of the nanorods as the growth time increase which changes the amount of light absorption inside the rods. As for microfiber waist diameter optimization, normalize α, normalize γ and sensitivity reduce as the waist diameter increase. This is because the bigger diameter provide lower amount of evanescent field exposed to

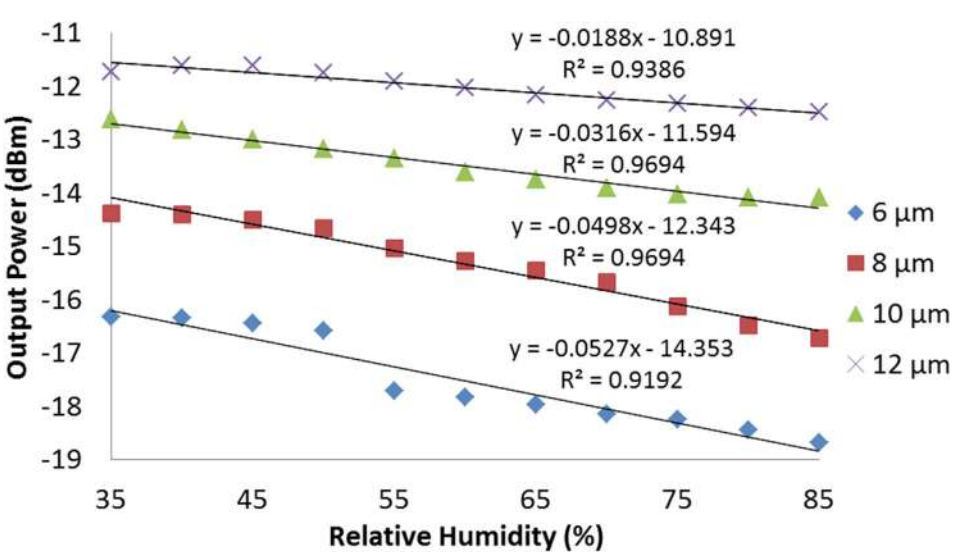

Fig. 13. Trendline of every microfiber waist diameter samples when %RH increases.

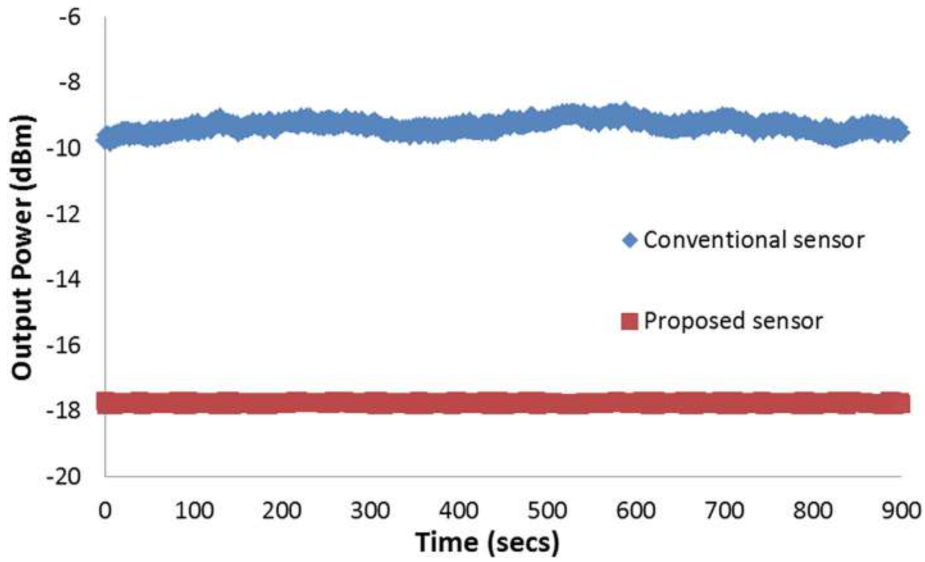

Fig. 14. Stability of the proposed and conventional sensor.

Table 1
The humidity sensing performance as the parameters change.

ZnO nanorods growth time					
Growth time (hrs)	6	9	12	15	18
Normalize α (max)	0.6002	0.6994	1	0.6552	0.4889
Normalize γ (max)	0.9645	0.9741	1	0.9621	0.9438
Sensitivity (dBm/%RH)	0.0191	0.0238	0.0316	0.0179	0.0119
Linearity (%)	< 95%	> 95%	> 95%	> 95%	< 95%
Microfiber waist diameter					
Diameter (µm)	6	8	10	12	
Normalize α (max)	1	0.9591	0.6410	0.3559	
Normalize γ (max)	1	0.9998	0.9541	0.9156	
Sensitivity (dBm/%RH)	0.0527	0.0498	0.0316	0.0188	
Linearity (%)	> 95%	> 95%	> 95%	> 95%	

the surrounding medium and less light scattering which is paramount criteria for sensing performance. Therefore, based on results in Table 1, it can be summarize the optimum parameter for ZnO nanorods growth time is 12 h sample and the optimum parameter for microfiber waist diameter is 6 µm. Both parameters also have acceptable linearity values which is > 95%.

5. Conclusion

We have successfully optimized the sensing performance factor (γ) based on microfiber-coupled ZnO nanorods humidity sensing scheme. It is conducted by investigating several performance parameters such as scattering coefficient (α), output light intensity and sensitivity. ZnO nanorods with 12 h' growth time produce the optimum result. The sample produces the highest value of α, γ and sensitivity as the %RH increase. Besides that, it exhibits significant intensity loss in almost all %RH range. The sensitivity improved by a factor of 1.3 as compared to the closest best sample. Whereas microfiber with 6 µm diameter produces the optimum results in humidity sensing. The sample exhibits the optimum value of α, γ and sensitivity when exposed to the %RH. The sensitivity improved by a factor of 1.1 as compared to the closest best sample. This work provides new optimization method for selecting the most optimal microfiber and ZnO nanorods samples for the proposed humidity sensing scheme. This method is also able to be applied to other microfibers evanescent wave that integrates with other nanomaterials coated glass surface. This method is based on first order principles which assume uniform ZnO nanorods growth and microfiber diameter. There are several other parameters could be considered as a second order approximation such as penetration depth, wavelength of light source and incident angle to refine future analysis.

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Appendix A. Supplementary data

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