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Characteristic of non-adiabatic tapered fiber towards humidity

***Abstract**. This paper reported the characterization of non-adiabatic tapered fiber using flame brushing technique towards humidity. The tapered fibers were exposed to relative humidity concentrations level ranging from 35%RH to 85%RH to observe the optical characteristic. There are several criterions considered for this study such as scattering coefficient (αmf), transmission loss (TL), output light intensity and enhancement factor (ɣ). The relationship between the waist diameter and the other criterions towards the %RH level has been successfully investigated.*

***Streszczenie.** W tym artykule opisano charakterystykę nieadiabatycznego włókna stożkowego przy użyciu techniki szczotkowania płomieniowego w w zastosowaniu do pomiaru wilgotności. Włókna stożkowe badano przy różnych poziomach wilgotności względnej w zakresie od 35% RH do 85% RH, aby obserwować charakterystykę optyczną. W tym badaniu bierze się pod uwagę kilka kryteriów, takich jak współczynnik rozproszenia (αmf), strata transmisji (TL), natężenie światła wyjściowego i współczynnik wzmocnienia (ɣ). Pomyślnie zbadano związek między średnicą talii a innymi kryteriami w stosunku do poziomu %RH. (**Badania nieadiabatycznego włókna stożkowego w zastosowaniu do pomiaru wilgotności**)*

Keywords: non-adiabatic, tapered fiber, humidity
Słowa kluczowe: nieadiabatyczne, stożkowe włókno, wilgotność

Introduction

Single mode fiber in its original form is less sensitive to the variation of external environment refractive index changes. When there are tapered, the core/cladding act as multimode fiber which improve the evanescent field interaction with the surround environment. The large fraction evanescent wave energy dispersed outside the tapered fiber enhanced the response towards refractive index change. This is due to the analyte that bind at the surface of the tapered fiber will increase the surround refractive index and modify the guided light [1].

According to [2], a perfect tapering process would produce a fraction power (η_{eff}) of the evanescent field that increase proportionally with increment of λ/r. λ will cause the transversal dimensions of the fundamental mode to propagate outside the tapered fiber to a relatively smaller value than the radiation wavelength. However, these criteria are barely achieved due to the technological constraint of the tapering machine using flame brushing technique. Even though there is an effort to formulate theoretical modelling of the tapered fiber diameter using flame brushing technique, it required a highly precise mixture of butane and oxygen, position and motor speed to pull the flame torch need to be controlled accurately [3].

There are several encountered problems that lead to this study. It is well known that the flame brushing technique has disadvantages of random turbulence of the oxygen and flame during the burning process. Non-adiabatic tapered fiber occurred when the taper machine abruptly change the taper angle so that the coupling occurs between the fundamental mode with the higher order modes as it propagate along the tapered fiber due to large effective refractive index between core and cladding modes [4]. If the taper is too steep, a non-adiabaticity will occur that cause low transmission. The mode propagation becomes more adiabatic when the tapering angle reduced [5]. In this paper, the characteristic of non-adiabatic tapered fiber waist diameter and the relationship with other criterions have been investigated for the first time to our knowledge. This work would beneficial in various vapour based sensing application using tapered fiber.

Theoretical analysis

Due to the constraint of tapering machine using flame brushing technique, the adiabaticity criteria were hardly fulfilled. Therefore, the excessive loss from the tapered fiber is uncontrollable lead to irrelative light transmission. It is noteworthy to mention that the evanescent wave and scatter light is a part of transmission loss. Since the tapered fiber employed the evanescent wave to couple with the humidity, the higher transmission loss could contribute to the enhancement of sensing response. However, since our goal is to characterize the tapered fiber, the relationship between the tapered fiber with the other criterions need to be figure out. This is due to the transmission loss is hardly reliance with the tapered fiber diameter. The first criterions considered in this study is the transmission loss (T_L). It is measured by using the equation (1):

$$T_L = T_{L2} - T_{L1} \tag{1}$$

where T_L is the transmission loss after deducting transmission after tapering (T_{L2}) and transmission before tapering (T_{L1}).

The light transmitted through the taper fiber is highly affected by the absorption coefficient and fraction power inside the evanescent field. The light attenuation through the tapered fiber is described by the Lambert-Beer law as described in equation (2) [6]:

$$I = I_o e^{-\alpha L} \tag{2}$$

where I is the intensity of the light leaving the sensing region, I_o is the intensity of light entering the sensing region, α is the scattering coefficient and L is the length of the sensing region. This equation shows that the output light intensity relied to scattering coefficient at the surface of tapered fiber [7]. Based on equation (2), the scattering coefficient of the tapered fiber can be derived to produce equation (3) as follows:

$$\alpha_{mf} = \frac{-ln\left(\frac{I_{mf}}{I_{omf}}\right)}{L} \tag{3}$$

where α_{mf} is the scattering coefficient of the tapered fiber, I_{mf} is the light leaving the tapered fiber, I_{omf} is the light entering the tapered fiber and L is the tapering length.

When water molecules attached at the surface of tapered fiber, surround refractive index increase. The output light intensity fluctuates when expose to different humidity concentration level [8]. The couple light across the sensing region varies with the changes of water molecule concentration [6]. The intensity could be measured by using the optical transmittance (T) formula as shown in equation (4) [9]:

$$T = \frac{I}{I_o} = e^{-\alpha L} \qquad (4)$$

Enhancement factor (ɣ) is calculated to investigate the influence of taper fiber samples towards humidity sensing. ɣ is ratio between the optical transmittance at the lowest target %RH and the highest target %RH. The tapered fiber is exposed at minimum humidity (T_{min}) and maximum humidity (T_{max}) for all samples. It can be derived by dividing T_{max} and T_{min} to produce equation (5) [10].

$$ɣ = \frac{T_{max}}{T_{min}} = e^{L(\alpha_{min}-\alpha_{max})} \qquad (5)$$

Sensing Mechanism

The SMF is tapered using flame brushing technique to enhance the evanescent field coupling between the fiber and the surrounding environment [8, 11]. The evanescent wave would attenuated with respect to the absorption, refractive index variation and scattering [12, 13]. The taper region increases the excitation events in the cladding region [10]. The intensity of the evanescent wave could be enhanced by increasing the penetration depth of the region surround by the core. It would increase the power fraction of the evanescent wave in the cladding region which enhanced the sensitivity to the environmental changes [14]. The energy transfers from the fundamental mode to the closest few higher order modes depend on the change rate of diameter. The number of higher-order modes determines the propagation loss. Less number of higher-order modes produce low loss of light [15].

The evanescent field will be absorbed and attenuate in the amplitude of the propagating signal to any absorbing molecule exist within the interaction depth of the evanescent field. It is affected by the length of the sensing region, concentration of the molecule, absorption coefficient and wavelength of the light. Sensing response to the evanescent wave is a combined effect of absorbance, loss due to V-number mismatches and refraction loss [16]. The air medium is replaced by the water molecules when the tapered fiber is exposed to the humidity due to weak hydrogen bonding [17]. This increase the refractive index of the cladding as compared to the core [7]. Hence more evanescent field presence around the tapered fiber. Thus, the output light intensity (I) will be attenuated when the light source (I_o) propagate through the length (L) of the sensing region as shown in Fig.1.

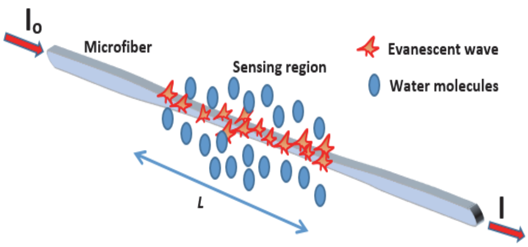

Fig.1. Sensing mechanism of the tapered fiber

Fabrication and experimental setup

Single-mode fiber (Corning SMF-28, USA) with 125 µm diameter was mechanically stripped and cleaned with an alcohol solution. Then, it was tapered into several diameters which are 5 µm, 6 µm, 8 µm, 12 µm and 20 µm with a constant tapered length of 2 cm as shown in Fig.2. The waist diameter of the tapered fibers was measured using the microscope (Medilux-12) with 20X magnification.

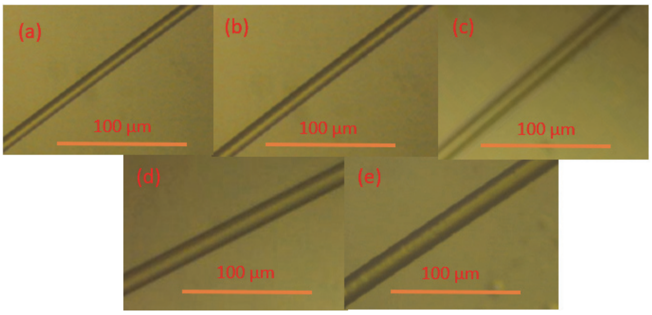

Fig.2. Tapered fiber waist diameter of; a) 5 µm, b) 6 µm, c) 8 µm, c) 12 µm and e) 20 µm

The tapered fiber was placed inside a sealed chamber. Amplified Spontaneous Emission (ASE) was injected at the input of the tapered fiber and the output was connected to the Optical Spectrum Analyzer (OSA) (Anritsu: The tapered fiber was placed inside a sealed chamber. Amplified Spontaneous Emission (ASE) was injected at the input of the tapered fiber and the output was connected to the Optical Spectrum Analyzer (OSA) (Anritsu: MS9710C) as shown in Fig.3. The light transmisson spectrum was recorded in the wavelength range between 1500 to 1600 nm in dBm unit. Sodium Hydroxide (NaOH) was used to increase the %RH due to the increment of water vapor from the salt solution. The concentration level was increased from 35%RH to 85%RH at almost constant room temperature, 27°C. The probe of a %RH meter (Hygrometer RS 1365, Sensitivity: 1%) was placed as close as possible to the tapered fiber to monitor the actual %RH around the sample's surface.

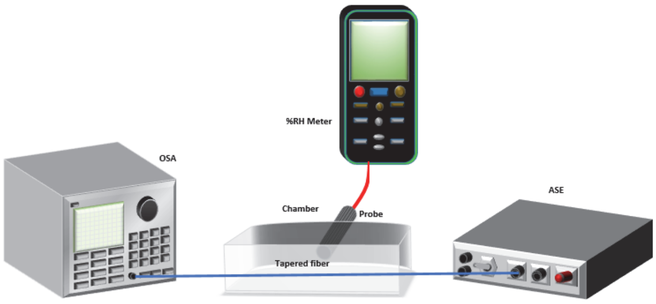

Fig.3. The experimental setup of humidity sensing

Result and discussion

Fig.4 shows the normalized transmission loss (T_L) and the scattering coefficient (α_{mf}) of difference tapered fiber's diameter. It shows that the T_L and α_{mf} exhibit similar output trend. Thus T_L and α_{mf} can be correlated as shown in Fig.5 where the α_{mf} rise proportionally as the T_L increases. As aforesaid, the tapering process would induce light scattering on the surface of the tapered fiber that influence the propagation loss. Thus, substantial loss of light would happen when energy transfer along the tapered fiber. The excessive loss could be minimized if the adiabaticity criteria are fulfilled along the tapered fiber with careful taper transitions [18]. On the other hand, since the adiabaticity criteria could not be realized during the tapering process, the excessive loss is uncontrollable which lead to irrelative transmission loss in smaller tapered fiber's diameter. For that reason, the T_L and α_{mf} were hardly reliance with the tapered fiber diameter using imperfect tapering machine. Since the T_L and α_{mf} has a direct relationship, the factor (ɣ) could be related with either T_L or α_{mf}.

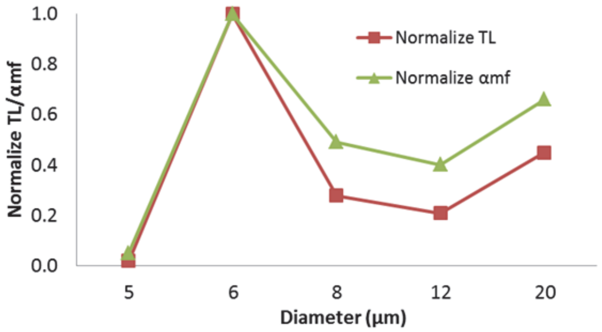

Fig.4. Normalize T_L and α_{mf} for difference tapered fiber's diameter

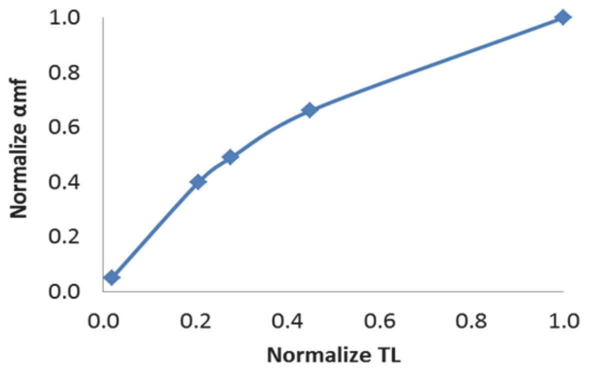

Fig.5. Normalize α_{mf} rise as the T_L increases.

Enhancement factor (ɣ) is influenced by two major factors which are scattering and the evanescent wave dispersion of the tapered fiber. These two factors are part of component in T_L. Fig.6 shows that ɣ exhibit an obvious correlation with the T_L in which ɣ increases proportionally with T_L. The 6 µm sample which has the highest T_L value produce optimum ɣ result and improve by almost 2% as compared to the nearest sample. The effective index decreased in the tapered region which expanding the light transmitted through the tapered fiber. This is due to the tapered fiber yield greater evanescent field coupling coefficient [18]. Higher T_L would influence the sensing response. This is because the tapered fiber produce light scattering and evanescent wave coupling that interact with the surround humidity level. Based on the result in Fig.6, the higher T_L would influence the sensing response. This is because the tapered fiber produce light scattering and evanescent wave coupling that interact with the surround humidity level. Fig.7 shows the output intensity of difference tapered fiber's diameter. The 6 µm tapered fiber produce largest intensity drop as compared to the others tapered fiber. Note that 6 µm represent the tapered fiber with highest T_L and α_{mf} as shown in Fig.4. It exhibits largest light leakage and evanescent coupling with the increment of surround water molecules [19]. There is only little variation of light intensity at low concentration level but it begins to show sharp drop at 40%RH onwards. This is due to only evanescent wave absorbance phenomenon occurred at low concentrations but more intensity loss happened at a higher concentrations level due to the larger effective index between the tapered fiber and the surround water molecules [16, 20].

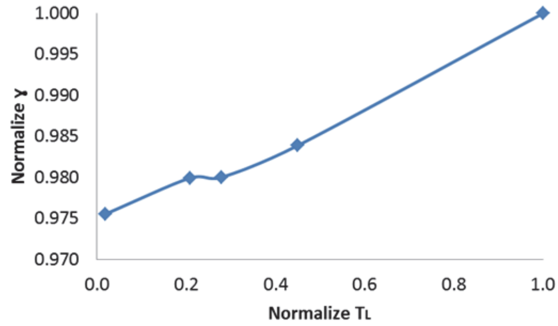

Fig.6. Normalize ɣ versus T_L graph

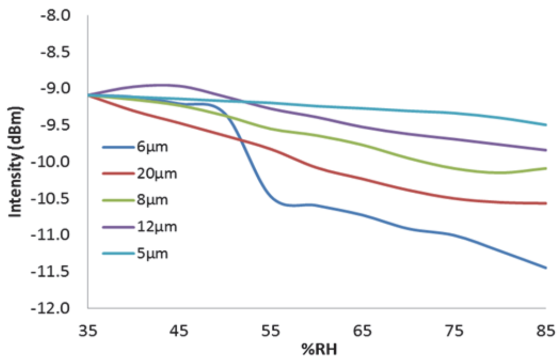

Fig.7. Measured output light intensity of the samples

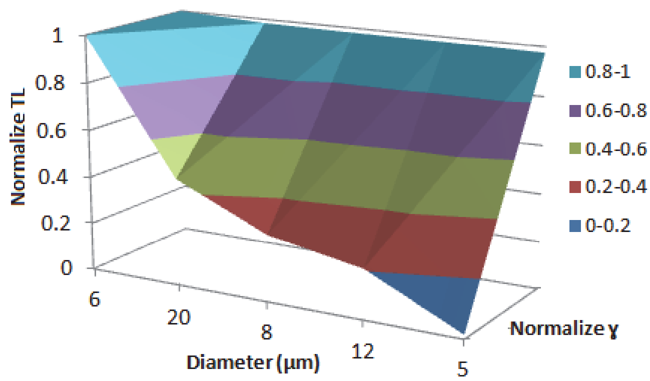

Fig.8. Three dimensional graph of the tapered fiber's diameter, T_L and ɣ

Eventually the relationship between tapered fiber's diameter, T_L and ɣ are depicted in Fig.8. This would become applicable if the tapering process could not adhere to the adiabaticity criteria which exhibit uncontrollable propagation loss along the tapered fiber. The three-dimensional graph shows that the tapered fiber's diameter with the highest T_L would produce the highest ɣ regardless of their diameter. This is because higher T_L means more light scattering at the surface of the tapered fiber and evanescent coupling with the surround analyte. Thus, in order to select the most optimum tapered fibers for humidity sensing, the highest value of T_L can be chosen to maximize the sensing response.

Conclusion

We have successfully characterized the non-adiabatic tapered fiber using flame brushing technique towards humidity sensing. It is performed by investigating several criterions such as scattering coefficient (α_{mf}), transmission loss (T_L), enhancement factor (ɣ) and output light intensity. It is noteworthy to mention that the selection of the tapered fiber is not entirely relied on the tapered fiber waist diameters, but is dependent on the T_L and α_{mf}. This is applicable to the tapering machine which could not comply with the adiabaticity criterion of a well-controlled propagation loss fiber. This research contributes a new characterization approach to understand the relationship of non-adiabatic tapered fiber with other criterions towards humidity sensing. This approach can be applied to other tapered fibers structure such as optical interferometer [21].

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