

REFRACTIVE INDEX SENSING EVALUATION OF MULTI-TAPERED OPTICAL FIBERS PREPARED BY CARBON DIOXIDE LASER PROCESSING

Nurul Hidayat^{1,*}, Arif Hidayat¹, Muhammad Safwan Abd Aziz² and Hazri Bakhtiar²

Received: March 28, 2024; Revised: June 01, 2024; Accepted: June 12, 2024

Abstract

Tapered optical fiber sensor technology has offered highly sensitive monitoring solutions to a wide range of applications, from environmental to biomedical fields. Until today, many experts have been working on tapering optical fibers to produce an optical-based viable monitoring system based on light-matter interaction. Refractive index (RI) sensing is one of the most basic sensing mechanisms in photonics. Herein, a simple, fast, and controllable tapering process was acquired by means of a carbon dioxide (CO₂) laser tapering system. The use of CO₂ laser allowed constant heating temperature with which clean and symmetrical multi-tapers could be produced. The interaction of CO₂ laser beam and silica-based optical fiber was discussed to explain the formation of tapered fiber along with the RI sensing mechanism based on evanescence wave and analyte interaction. Sensors with 2, 3, and 4 tapers showed extremely linear responses to the refractive index change, indicated by degree of linearity values close to unity. The sensitivity increased from around 8a.u./RIU (2 and 3 tapers) to 9a.u./RIU (4 tapers). In addition, all sensors had excellent reversibility. Since MTOFs were reversible and sensitive in the wide range of refractive index, then they could be further proposed as RI-based environmental and biomedical sensors.

Keywords: CO₂ laser; Tapered fiber; Refractive index; Sensor technology

Introduction

Up to now, refractive index (RI) detection has been crucial because diverse chemical and biological substances can be identified via RI measurement (Bui *et al.*, 2018; Hidayat *et al.*, 2023a). Provided the fact that environmental and biomedical analyte RI values are typically between 1.3 and 1.5 (Butt *et al.*, 2022; Razani *et al.*, 2022),

RI sensors have been recently applied in environmental and biomedical fields. For example, RI sensing can function for glucose sensing (Azargoshasb *et al.*, 2020), gas sensing (Alkhabet *et al.*, 2022), water pollution monitoring (Halkare *et al.*, 2019), cancer early detection (Razani *et al.*, 2022), single-cell growth investigation (Cetin *et al.*,

¹ Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Negeri Malang, Jl. Semarang 5, Malang 65145, Indonesia. E-mail: nurul.hidayat.fmipa@um.ac.id

² Laser Center, Ibnu Sina Institute for Scientific and Industrial Research, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia.

* Corresponding author

2021), and COVID-19 spike antigen quantification (Dai *et al.*, 2022). Amongst many types of RI sensors, optical fiber-based RI sensors have been recently preferable since they perform many benefits, such as low weight, high stability, compact size, protection against electromagnetic interference, and many more (Taha *et al.*, 2021).

Tapered optical fibers (TOFs) have become highly effective systems for RI sensors due to evanescent waves that penetrate the tapered region and interact with the analyte. Various approaches have been made to taper optical fibers, for instance using flame brush technique (Ahmad *et al.*, 2021), chemical etching approach (Son *et al.*, 2022), arc-discharge route (Karimi-Alavijeh *et al.*, 2022), and CO₂ laser heating method (Bianco *et al.*, 2022). Thus, many scientists have extensively attempted to produce high-quality TOFs.

From those various tapering approaches, a review paper has explored their advantages and disadvantages (Wang *et al.*, 2022). According to Wang *et al.* (2022), flame heating technology is the most classical and low-cost tapering approach, but it requires long preheating treatment to acquire silica-based fiber softening temperature, and it is problematic to keep the constant heat temperature. The chemical etching method can be applied to any type of optical fiber; therefore, its superiority is in its simple procedure and low fabrication cost. Unfortunately, the acid concentration steadily decreases, which influences the corrosion rate. Besides the waist diameter being difficult to control, some residues may be attached to the corroded tapered surface region. The arc-discharge technique produces taper through a controlled electrode and accurately sets the discharge time to prepare tapered structures. However, continuous discharge may lead to electrode power loss and reduce the quality of the final tapered fiber. In contrast, CO₂ laser may reach exceptionally high heating control accuracy to prepare cleaner and more symmetrical TOFs with a fast-tapering process. Taking all these considerations into account, the CO₂ laser was chosen as the heating source to create tapered fibers in this present study.

While all the above-proposed fiber structures had only one taper, multi-tapered fibers are also important to study since, according to the theory, more evanescence waves can be generated by increasing the number of tapers (Wu *et al.*, 2021). Therefore, a comparative RI sensing of three different multi-tapered optical fibers fabricated by the CO₂ laser tapering approach is discussed herein. In order to meet the criteria for future environmental and biomedical applications, which require RI sensing range of 1.3-1.5 (Butt *et al.*, 2022; Razani

et al., 2022), the multi-tapered fibers were subjected to test on water ($n = 1.33$) and ethylene glycol solutions ($1.35 \leq n \leq 1.43$).

Materials and Methods

Initially, multi-tapered optical fibers (MTOFs) were prepared using CO₂ lasing approach. Large core multimode fiber with core, cladding, and jacket diameters (in micrometers) respectively of 200, 225, and 500 was selected as the material of interest because it could promote more evanescent waves than those of single mode fibers (Wu *et al.*, 2019). The process of tapering the large core fiber is shown in Figure 1.

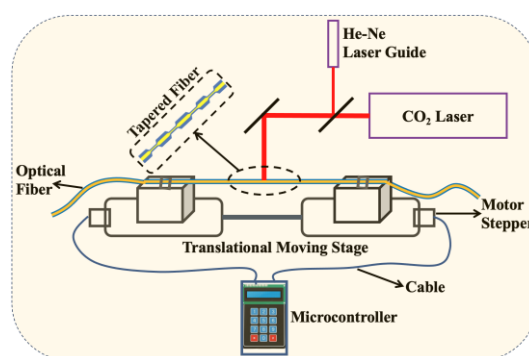


Figure 1. Experimental set-up for tapering process using CO₂ laser

CO₂ laser with a wavelength of 10.6μm in the infrared region was employed as the fiber heating source. Since the CO₂ laser beam cannot be detected by human eyes, the HeNe laser operating at a wavelength of 632.8nm, which is in the red part of the visible light spectrum, was introduced as the laser guide. Optical mirrors appropriate for CO₂ laser and HeNe laser were used to direct the laser beams to the targeted large core optical fiber. The optical fiber was placed on a translational motorized stage. At this stage, the fiber could be pulled automatically by an Arduino-based microcontroller with the desired pulling time and speed. Thus, with this CO₂ laser tapering system, controllable preparation of tapered fibers could be achieved by controlling the heating and pulling parameters. The fiber was tapered by heating its small section with a CO₂ laser with a power of 36W. After 2 seconds of lasing, the fiber was pulled at a speed of 1000 rpm to reach a distance of 3mm. The process was repeated to create multi-tapered regions.

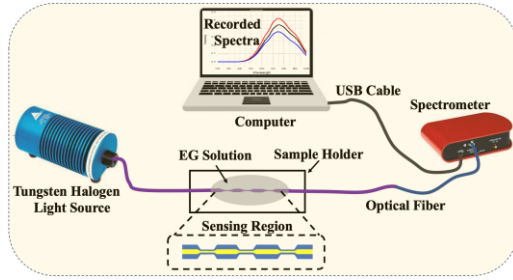


Figure 2. Optical spectral measurement set-up

Table 1. EG solutions with different refractive indices

EG:DIW (volume ratio)	RI (rounded value)
0:100	1.33
20:80	1.35
40:60	1.37
60:40	1.39
80:20	1.41
100:0	1.43

Next, the profiles of MTOFs were evaluated using an AmScope microscope. The MTOFs were tested as RI sensors using the experimental setup shown in Figure 2. The tapered region was placed on a glass-based sample holder. One end of the fiber was connected to a Tungsten Halogen light source, while the other end was plugged into a CCS 200 Thorlabs spectrometer. The optical spectra from the spectrometer were recorded by a computer. MTOFs sensing sensitivity, limit of detection, and reversibility were evaluated. The sensor sensitivity was tested from the optical spectra recorded under different RI media. In this case, ethylene glycol (EG) solutions with different refractive indices were prepared by modifying deionized water (DIW) and EG ratio (see Table 1). The RI values of the prepared solutions were measured using a digital Krüss refractometer K-05268. The sensor sensitivity was calculated from the slope of transmitted intensity vs. RI graph. Meanwhile, the limit of detection (LOD) was calculated from the ratio of the standard deviation and sensitivity (Al-Hayali *et al.*, 2021). In addition, the MTOFs sensing reversibility was evaluated by comparing the optical spectra in ascending and descending RI measurements.

Results and Discussion

Schematic diagram of the tapered fiber profile is given in Figure 3(a). The core and cladding diameters of an optical fiber are reduced through heating and pulling mechanism. The reduced fiber

diameter is defined as waist diameter and the length of the tapered region is expressed as tapered length. The transition region lies in between the tapered and untapered region. Figure 3(b) displays the typical taper profile of the prepared MTOFs. It is seen that the taper profile produced by CO₂ heating was symmetrical, in the sense that it had uniform waist diameter and equal transition regions. The original fiber had core and cladding diameters of 200 μm and 225 μm , respectively. The resulting tapered fiber featured a waist diameter of 43 μm and a tapered length of 794 μm .

Tapering silica-based fiber is possible by pulling the fiber while heated by CO₂ laser. The CO₂ laser power is the direct heating parameter to control the heat temperature on the fiber. The light energy from the CO₂ laser working at a wavelength of 10.6 μm is absorbed by the silica optical fiber providing localized heating (Harvey *et al.*, 2021) and can reach its softening temperature, which is around 1600°C for silica (Amouzad Mahdiraji *et al.*, 2014). Therefore, the final tapered waist diameter can be controlled via CO₂ laser power. The light-matter interaction between CO₂ laser radiation and an optical fiber is covered by Mie Theory which includes absorption and scattering (Chryssou, 1999). Taking into account the bell-shaped of the CO₂ laser beam and an approach of light absorption and scattering from a thin rod, the power density intercepted by silica fiber can be expressed as (Chryssou, 1999):

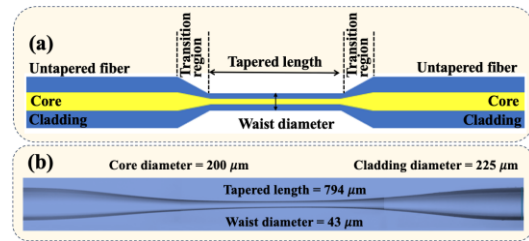


Figure 3. (a) Schematic diagram of tapered fiber profile and (b) microscope image of the produced tapered fiber using CO₂ laser heating

$$I(z) = \frac{P_{tot}}{\pi\omega^2} \operatorname{erf}\left(\frac{d}{\sqrt{2}\omega}\right) \exp\left(-\frac{2z^2}{\omega^2}\right) \quad (1)$$

where P_{tot} , ω , d , and z respectively represent the total power of the CO₂ laser, the CO₂ beam radius, the fiber diameter, and the position where the fiber is perpendicularly irradiated by CO₂ laser beam. Since the CO₂ laser beam profile is Gaussian, then the beam power decreases to e^{-2} along the

perpendicular (z) axis. During the interaction, Q_{abs} representing the fiber absorption efficiency factor plays an essential role because it directly affects the energy absorbed by the fiber. Q_{abs} strongly depends on the fiber diameter, r . Furthermore, the energy from the CO_2 laser absorbed by the silica optical fiber per unit time and per unit volume, $q(z)$, is then defined as (Chryssou, 1999):

$$q(z) = \frac{2Q_{\text{abs}}P_{\text{tot}}}{\pi^2\omega^2r} \operatorname{erf}\left(\frac{d}{\sqrt{2}\omega}\right) \exp\left(-\frac{2z^2}{\omega^2}\right) \quad (2)$$

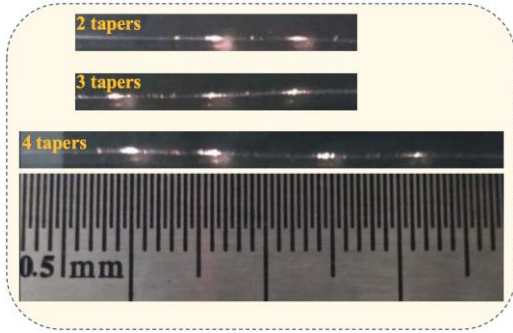


Figure 4. MTOFs produced by CO_2 laser tapering approach. The white light spreading at the tapered regions showed the existence of evanescent waves

Figure 4 shows the MTOFs with different numbers of taper. The presence of evanescent wave in the tapered regions was proven by the white light leaking in the fibers. Evanescent wave is generated in the optically lower refractive index, the fiber cladding, which attenuates after around the wavelength order of the transmitting light (Chao and Wang, 2022). When the propagating light passes through the first taper, some of the transmitted light in the core is coupled into the cladding that generates evanescent wave, while the other part remains transmitted in the core (Wu *et al.*, 2021). The remaining evanescent wave in the cladding is recoupled into the fiber core when entering the second taper for further transmission. The same mechanism occurs in the third and fourth tapers. Thus, multi-tapered regions in the optical fiber may act as couplers. The light interference in the MTOFs can be expressed as

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{2\pi(n_{\text{co}} - n_{\text{cl}})L}{\lambda}\right) \quad (3)$$

where I_1 and I_2 respectively represents the transmitted light intensity in the core and cladding, n_{co} and n_{cl} respectively denotes the effective RI of

the core and cladding, L is the effective length of taper, and λ is the incoming light wavelength. During the light propagation in the tapered region, the evanescent wave penetrates the cladding. The penetration depth, d_p , for a particular light mode enters at the core-cladding interface at an angle θ_i is expressed in Equation (4).

$$d_p = \frac{\lambda}{2\pi\sqrt{(n_{\text{co}}\sin\theta_i)^2 - (n_{\text{cl}})^2}} \quad (4)$$

Figures 5-7 depict the graphs of relative transmitted light intensity against wavelength for MTOFs with 2, 3, and 4 tapers at different refractive indices. In this experiment, it is revealed that the RI sensing mechanism is based on the amplitude modality. From the optical spectra, there are no wavelength shifts detected for all RI measurements. The transmitted light intensity decreased as the EG concentration increased, or optically speaking, due to the RI increase. The optical spectra for all positions of the peaks were identical for all sensors. This suggested that adding number of tapers did not degrade the optical properties.

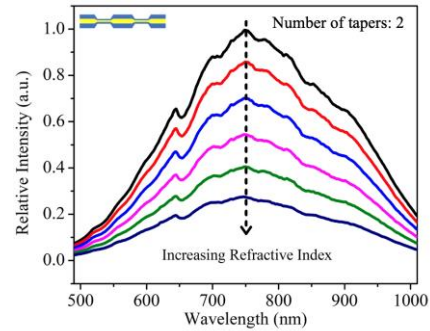


Figure 5. Optical spectral dependence of MTOF (2 tapers) due to RI changes

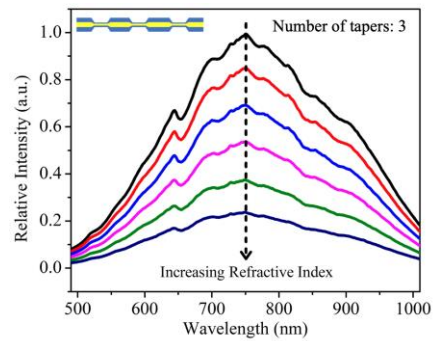


Figure 6. Optical spectral dependence of MTOF (3 tapers) due to RI changes

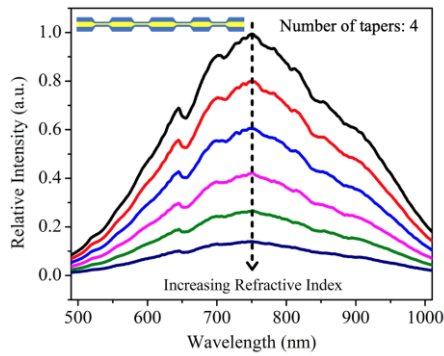


Figure 7. Optical spectral dependence of MTOF (4 tapers) due to RI changes

The relative (highest) intensity at a certain wavelength was plotted for every value of RI, as depicted in Figures 8-10, for further linear regression. Selecting the intensity at 750nm for sensitivity calculation was appropriate because this wavelength corresponded to the maximum intensity observed in the recorded spectra. This approach is widely adopted for intensity-based optical fiber sensing; see, for example, studies reported in (Zhu *et al.*, 2024) and (Hidayat *et al.*, 2023). This peak indicated a strong and consistent optical response to changes in the refractive index (RI), making it a reliable and sensitive indicator for RI sensitivity analysis through linear regression.

The dotted lines in the graphs represent the linear fitting curves where the slope indicates the MTOF sensitivity. The degree of linearity, R^2 , for all sensors, was close to 1, implying that the linear relationship nearly perfectly fit the observed data. Thus, the transmitted light intensity in the MTOFs was linearly dependent on the refractive index of the medium. This result implied the MTOFs had high linearity. The sensitivity values for MTOFs with 2, 3, and 4 tapers were respectively 8.092a.u./RIU, 7.718a.u./RIU, and 9.117a.u./RIU. Here, RIU means refractive index unit. It was found that the MTOF with 4 tapers performed the highest sensitivity.

The lower sensitivity of the 3-tapered structure compared to the 2-tapered and 4-tapered structures was likely due to a combination of increased optical losses (Karimi-Alavijeh *et al.*, 2022), suboptimal evanescent field interaction (Azargoshasb *et al.*, 2020), and less favorable interference effects (Biazoli *et al.*, 2012). In a 3-tapered design, light transmission might be more disrupted due to scattering and absorption. The interaction of the evanescent field with the surrounding medium in this structure might also be less efficient, and the interference patterns in a 3-tapered structure might

not align as optimally as in other tapered fibers. These factors together resulted in the lowest sensitivity for the 3-tapered configuration.

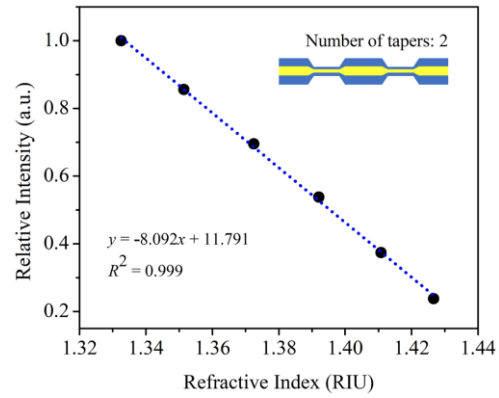


Figure 8. Linear fitting of MTOF (2 tapers) for RI sensitivity determination

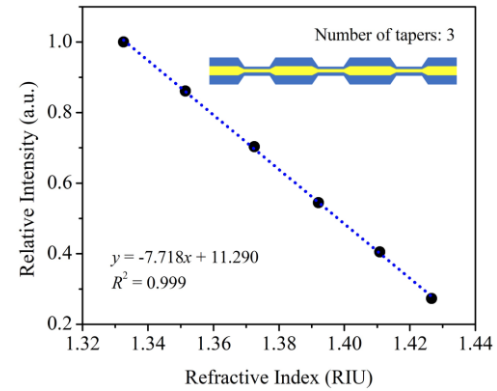


Figure 9. Linear fitting of MTOF (3 tapers) for RI sensitivity determination

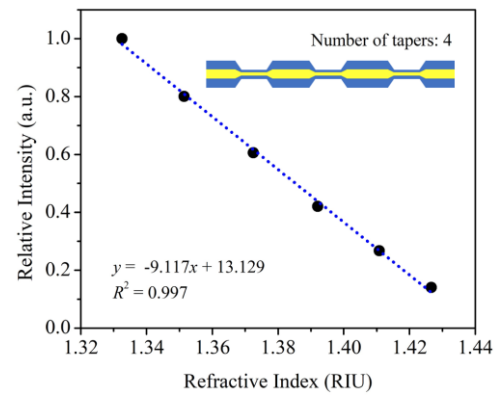


Figure 10. Linear fitting of MTOF (4 tapers) for RI sensitivity determination

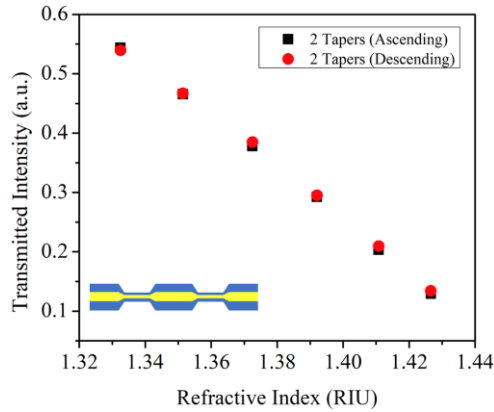


Figure 11. Reversibility of MTOF (2 tapers) measured by ascending and descending RI values

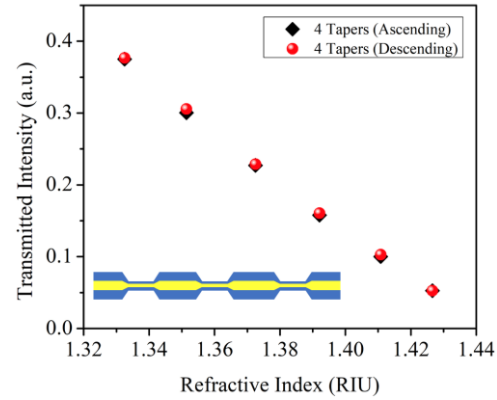


Figure 13. Reversibility of MTOF (4 tapers) measured by ascending and descending RI values

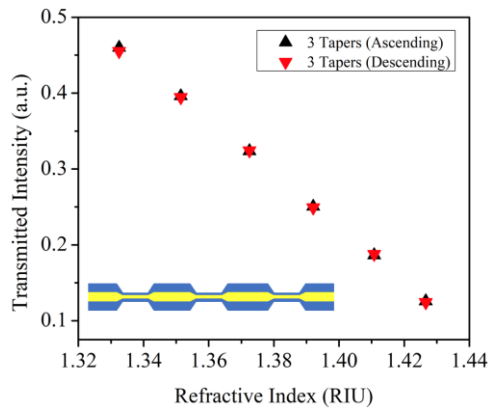


Figure 12. Reversibility of MTOF (3 tapers) measured by ascending and descending RI values

Furthermore, the reversibility performances of the MTOFs are given in Figures 11-13. It is noticed that all the data points lie at the same value, indicating that the MTOF sensors were able to recover to the original condition after exposure to EG solutions. Sensor tests for both ascending and descending order of RI values produced similar results. Reversibility is crucial to ensure that the sensor can further detect RI with consistent results. In principle, a sensor with good reversibility represents its ability for practical operation (Al-Hayali and Al-Janabi, 2020). As depicted in Figures 11-13, the transmission light intensity decreased as the number of tapers increased, implying that more evanescence waves were promoted in the fiber sensors with a higher number of tapers. Similar results were reported by other researchers (Wu *et al.*, 2021). The mechanism of light interference, as expressed in Equation 3, applied in the tapered fibers.

In addition, the limit of detection that describes the minimum analyte that can be sensed by the sensor is also plotted in Figure 14. The limit of detection increased as the number of tapers increased. Although the sensitivity of the 3 tapers structure was lower than those of the 2 and 4 tapers, it could still be used as an RI sensor because the sensitivity value was not too far from the other two tapered fibers. Another study (Wu *et al.*, 2021) reported that their optical fiber sensors with 2 tapers and 3 tapers showed very low extinction ratios of transmission spectra as compared to 4-taper fiber. Therefore, they only picked up the 4-taper fiber as it was suitable for sensing (Wu *et al.*, 2021). In our work, all the sensors with 2, 3, and 4 tapers could be applied as RI sensing, within the range of 1.33 - 1.43, with high sensitivities.

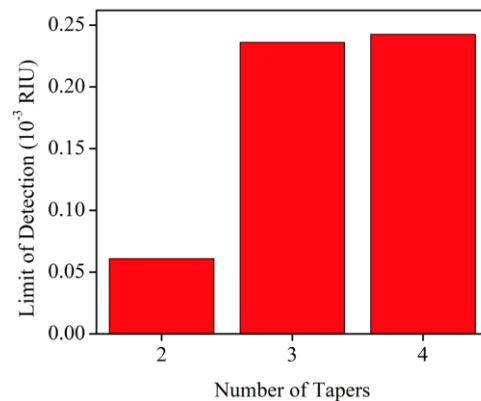


Figure 14. Limit of detection of MTOFs

Conclusions

MTOFs have been successfully prepared by direct CO₂ laser heating. It was demonstrated that 2, 3, and 4 tapers exhibited excellent linearity (0.99) and high reversibility. The sensitivity of the MTOFs tended to increase as more tapers formed. The light-matter interaction in the silica fiber with CO₂ laser electromagnetic wave was explained by Mie Theory which includes absorption and scattering. More evanescence waves or deeper penetration depth promoted in the higher number of tapers was shown by the decreasing transmission light intensity as the number of tapers increased. The highest RI sensitivity in the range of 1.33-1.43 was achieved by 4 tapers optical fiber, i.e., and 9.117a.u./RIU. Recalling that the sensitivity range lies in the biomedical analyte RI values, MTOFs are, therefore, promising to be applied in biomedical fields.

Acknowledgement

We would like to acknowledge Universiti Teknologi Malaysia (UTM) for MSA under UTMFR (Fundamental Research) with cost center number Q.J130000.3809.22H43 and UTM Matching Grant (MG2-6.1) with cost center number Q.J130000.3009.04M29.

References

- Ahmad, H., Azri, M.F.M., Ramli, R., Samion, M.Z., Yusoff, N., and Lim, K.S. (2021). 2 μ m passively mode-locked thulium-doped fiber lasers with Ta₂AlC-deposited tapered and side-polished fibers. *Scientific Reports*, 11(1):1. <https://doi.org/10.1038/s41598-021-99928-z>
- Al-Hayali, S.K., and Al-Janabi, A.H. (2020). All fiber-optic temperature sensor based on cladding etched no-core fiber coated with nanostructured copper oxide-polyvinyl alcohol thin film. *Optik*, 220:165154. <https://doi.org/10.1016/j.ijleo.2020.165154>
- Al-Hayali, S.K., Salman, A.M., and Al-Janabi, A.H. (2021). Effect of hygroscopic polymer-coatings on the performance of relative humidity sensor based on macro-bend single-mode fiber. *Optical Fiber Technology*, 62:102460. <https://doi.org/10.1016/j.yofte.2021.102460>
- Alkhabet, M.M., Yaseen, Z.M., Eldirderi, M.M.A., Khedher, K.M., Jawad, A.H., Girei, S.H., Salih, H.K., Paiman, S., Arsad, N., Mahdi, M.A., and Yaacob, M.H. (2022). Palladium/graphene oxide nanocomposite for hydrogen gas sensing applications based on tapered optical fiber. *Materials*, 15(22):22. <https://doi.org/10.3390/ma15228167>
- Amouzad Mahdiraji, G., Chow, D.M., Sandoghchi, S.R., Amir Khan, F., Dermosesian, E., Yeo, K.S., Kakaei, Z., Ghomeishi, M., Poh, S.Y., Yu Gang, S., and Mahamid Adikan, F.R. (2014). Challenges and solutions in fabrication of silica-based photonic crystal fibers: An experimental study. *Fiber and Integrated Optics*, 33(1-2):85-104. <https://doi.org/10.1080/01468030.2013.879680>
- Azargoshasb, T., Navid, H.A., Parvizi, R., and Heidari, H. (2020). Evanescent wave optical trapping and sensing on polymer optical fibers for ultra-trace detection of glucose. *ACS Omega*, 5(35):22,046-22,056. <https://doi.org/10.1021/acsomega.0c01908>
- Bianco, M., Pisanello, M., Balena, A., Montinaro, C., Pisano, F., Spagnolo, B., Sabatini, B.L., De Vittorio, M., and Pisanello, F. (2022). Orthogonalization of far-field detection in tapered optical fibers for depth-selective fiber photometry in brain tissue. *APL Photonics*, 7(2):026106. <https://doi.org/10.1063/5.0073594>
- Biazoli, C.R., Silva, S., Franco, M.A.R., Frazão, O., and Cordeiro, C.M.B. (2012). Multimode interference tapered fiber refractive index sensors. *Applied Optics*, 51(24):5,941-5,945. <https://doi.org/10.1364/AO.51.005941>
- Bui, H., Pham, T.B., Nguyen, V.A., Pham, V.D., Do, T.C., Nguyen, T.V., Hoang, T. H. C., Le, H. T., and Pham, V. H. (2018). Novel method of dual fiber Bragg gratings integrated in fiber ring laser for biochemical sensors. *Measurement Science and Technology*, 29(5):055105. <https://doi.org/10.1088/1361-6501/aaa8b0>
- Butt, M.A., Voronkov, G.S., Grakhova, E.P., Kutluyarov, R.V., Kazanskiy, N.L., and Khonina, S.N. (2022). Environmental monitoring: A comprehensive review on optical waveguide and fiber-based sensors. *Biosensors*, 12(11):11. <https://doi.org/10.3390/bios12111038>
- Cetin, A.E., Topkaya, S.N., Yalcin-Ozuysal, O., and Khademhosseini, A. (2021). Refractive index sensing for measuring single cell growth. *ACS Nano*, 15(6):10,710-10,721. <https://doi.org/10.1021/acsnano.1c04031>
- Chao, X., and Wang, D.N. (2022). Surface plasmon resonance sensor based on a tapered multimode fiber with a long inner air-cavity. *IEEE Photonics Technology Letters*, 34(15):799-802. <https://doi.org/10.1109/LPT.2022.3188314>
- Chryssou, C.E. (1999). Theoretical analysis of tapering fused silica optical fibers using a carbon dioxide laser. *Optical Engineering*, 38(10):1,645-1,649. <https://doi.org/10.1117/1.602271>
- Dai, Z., Xu, X., Wang, Y., Li, M., Zhou, K., Zhang, L., and Tan, Y. (2022). Surface plasmon resonance biosensor with laser heterodyne feedback for highly-sensitive and rapid detection of COVID-19 spike antigen. *Biosensors and Bioelectronics*, 206:114163. <https://doi.org/10.1016/j.bios.2022.114163>
- Halkare, P., Punjabi, N., Wangchuk, J., Nair, A., Kondabagil, K., and Mukherji, S. (2019). Bacteria functionalized gold nanoparticle matrix based fiber-optic sensor for monitoring heavy metal pollution in water. *Sensors and Actuators, B: Chemical*, 281:643-651. <https://doi.org/10.1016/j.snb.2018.10.119>
- Harvey, C.M., Mühlberger, K., Oriekhov, T., and Fokine, M. (2021). Low-loss silicon-core optical fibre fabrication using a CO laser-based furnace without an interface layer. *Frontiers in Optics + Laser Science 2021*, Paper FW1C.2, FW1C.2. <https://doi.org/10.1364/FIO.2021.FW1C.2>
- Hidayat, N., Aziz, M.S., Krishnan, G., Johari, A.R., Nur, H., Taufiq, A., Mufti, N., Mukti, R.R., and Bakhtiar, H. (2023a). Tapered optical fibers using CO₂ laser and their sensing performances. *Journal of Physics: Conference Series*, 2432(1):012013. <https://doi.org/10.1088/1742-6596/2432/1/012013>
- Hidayat, N., Safwan Abd Aziz, M., Nur, H., Taufiq, A., Mufti, N., Rakhmata Mukti, R., and Bakhtiar, H. (2023b). Sensitivity enhancement of gold nanospheres assisted CO₂ laser tapered optical fiber for refractive index sensor. *Optical Fiber Technology*, 77:103275. <https://doi.org/10.1016/j.yofte.2023.103275>

- Karimi-Alavijeh, H., Taslimi, A., Maghsoudian, M.H., Poorghadiri, M.H., and Kazemzadeh, M. (2022). Fabrication of low-loss adiabatic optical microfibers using an attainable arc-discharge fiber tapering setup. *Optics Communications*, 522:128669. <https://doi.org/10.1016/j.optcom.2022.128669>
- Razani, A.H.N., Rezaei, P., Zamzam, P., Khatami, S.A., and Daraei, O.M. (2022). Absorption-based ultra-sensitive RI sensor based on the flower-shaped graphene resonator for early detection of cancer. *Optics Communications*, 524:128775. <https://doi.org/10.1016/j.optcom.2022.128775>
- Son, G., Pradono, R.A., Choi, J., Jeong, Y., Han, D.S., Syahadi, M., Jung, Y., Kwon, K., Bae, H., and Yu, K. (2022). Chemically-etched optical fiber tapers for adiabatic fundamental mode evolution over O-and C-bands. *Journal of Lightwave Technology*, 40(14):4,832-4,840. <https://doi.org/10.1109/JLT.2022.3166774>
- Taha, B.A., Ali, N., Sapiee, N.M., Fadhel, M.M., Mat Yeh, R.M., Bachok, N.N., Al Mashhadany, Y., and Arsad, N. (2021). Comprehensive review tapered optical fiber configurations for sensing application: Trend and challenges. *Biosensors*, 11(8):8. <https://doi.org/10.3390/bios11080253>
- Wang, Z., Zhang, W., Liu, X., Li, M., Lang, X., Singh, R., Marques, C., Zhang, B., and Kumar, S. (2022). Novel optical fiber-based structures for plasmonics sensors. *Biosensors*, 12(11):11. <https://doi.org/10.3390/bios12111016>
- Wu, Q., Zhao, Y., Zhang, Y., and Yang, Y. (2019). High sensitive applied load measurement using optical fiber tapered-loop probe with SPR effect. *Optics & Laser Technology*, 114:95-102. <https://doi.org/10.1016/j.optlastec.2019.01.045>
- Wu, Y., Liu, B., Nan, T., Wu, J., Mao, Y., Ren, J., Zhao, L., Sun, T., Wang, J., Han, Y., and Zhang, Y. (2021). Improved optical fiber Mach-Zehnder high-sensitivity refractive index sensor. *Optik*, 229:166214. <https://doi.org/10.1016/j.ijleo.2020.166214>
- Zhu, T., Chah, K., Chiavaioli, F., Villatoro, J., and Caucheteur, C. (2024). Gold-coated optical fiber supermode interferometer for insulin bio-sensing. *Optics & Laser Technology*, 168:109878. <https://doi.org/10.1016/j.optlastec.2023.109878>