STM JOURNALS

Trends in
Opto-electro & Optical Communication

ISSN: 2231-0401 (Online)
ISSN: 2347-9957 (Print)
Volume 14, Issue 1, 2024
January–April
DOI (Journal): 10.37591/TOEOC

https://journals.stmjournals.com/toeoc

Research TOEOC

Design and Fabrication of Tapered Optical Fiber Related Devices

Keyur Raju Ninawe[1,*], Sahil Narendra Narlawar[1], Onkar Shivaji Jadhav[1], Ganesh N. Gaikwad[2]

Abstract

By joining conical single-mode fibers, a Mach-Zehnder interferometer with a refractive index (RI) sensor was produced. Sensors were made directly from conical SMFs using a Vytran engine. Compared to the single-taper sensor, the dual-taper sensor turned out to be more efficient. With a 10mm gap between the two taper sites in the dual-taper sensor arrangement, the RI fluctuation was quite noticeable. The principles underlying the design and fabrication of tapered optical fiber devices involve the manipulation of light propagation within an optical fiber through controlled geometrical changes. It enhanced light-matter interaction for improved sensing and photonics applications: High sensitivity to external parameters such as temperature and refractive index changes; and miniaturization and integration of complex optical functionalities into compact devices. Furthermore, the versatility of tapered fiber design allows for customization to specific application requirements, offering high precision and control over device properties. To enhance the sensor's effectiveness, we investigated how the sensitivity to changes in refractive index correlates with the diameter of the taper waist (TWD), while keeping the length of the taper waist constant. In particular, the sensor showed a RI sensitivity of 976 nm/RIU within a RI range of 0.018 to 0.071 with a taper width of 35.5 µm and a spacing of 10 mm.

Keywords: Fiber taper, Mach-Zehnder (MZ) interferometer, refractive index (RI) sensor, single mode fibers (SMF)

INTRODUCTION

In recent years, fiber refractive index (RI) sensors have garnered considerable attention in medical and biochemical analysis, owing to their advantageous properties. These include compact size, high-resolution detection capabilities, long-term stability, suitability for operation in harsh chemical environments, and resistance to electromagnetic interference. Researchers have dedicated significant efforts to enhancing the performance of fiber optic RI sensors, focusing on increasing sensitivity, improving resolution, streamlining design processes, reducing costs, enhancing sensor robustness, and minimizing penetration.

The fiber Mach-Zehnder interferometer (MZI) is a standout among the variety of fiber optic RI detection techniques due to its exceptional quality and simple production procedure. MZI sensors can be built using a range of fiber materials, including multimode, microfiber, and photonic crystal fiber (PCF), and a variety of designs, including surface plasmon resonance (SPR), core mismatch, and taper. For example, the MZI structure has been proposed to be formed by combining offset points

*Author for Correspondence
Keyur Raju Ninawe
E-mail: keyurninawe.scoe.entc@gmail.com

[1]Student, Department of Electronics & Telecommunication, Sinhgad College of Engineering, Savitribai Phule University, Pune, Maharashtra, India
[2]Professor, Department of Electronics & Telecommunication, Sinhgad College of Engineering, Savitribai Phule University, Pune, Maharashtra, India

Received Date: March 25, 2024
Accepted Date: May 23, 2024
Published Date: May 30, 2024

Citation: Keyur Raju Ninawe, Sahil Narendra Narlawar, Onkar Shivaji Jadhav, Ganesh N. Gaikwad. Design and Fabrication of Tapered Optical Fiber Related Devices. Trends in Opto-electro & Optical Communication. 2024; 14(1): 1–6p.

© STM Journals 2024. All Rights Reserved

with abrupt tapers within a single-mode fiber (SMF). But because of the complex fabrication process, the RI sensitivity is limited to 28.2 nm/RIU for a 30 mm fiber length [1–3].

In this work, we present a sensitive, easy to manufacture, cost-effective and mechanically robust MZI-based online RI sensor obtained by thinning a single-mode fiber (Single-mode fiber). Using the Vytran machine, we were able to create highly flexible and continuous long tapered blades in SMF to create MZI models. To optimize the performance of the sensor, we examined the relationship between the RI sensitivity of the sensor and the taper waist diameter (TWD) for a given taper waist length [4, 5].

PRINCIPLE

To accomplish its unique configuration, the MZI sensor made use of adiabatic tapering in both the down-taper and up-taper sections of the single-mode fiber (SMF). Interestingly, a few leaky modes were triggered in the down-taper area and merged more prominently with the core in the up-taper region, forming a unique interference pattern. In this design, higher-order modes coexist with the basic mode through the tapering area (III) as light moves from region (I) to (II). An interferometric pattern is produced in region (IV) by the fundamental and higher-order modes recombining as a result of the substantial refractive index disparity between glass and air. Eq. (1) describes the interference spectrum that results [5].

$$I_{out} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\varphi) \tag{1}$$

The intensities of the interference signal, core, and cladding modes are denoted by Iout, I1, and I2, respectively. Eq. (2) expresses $\Delta\varphi$ as the phase difference between the core and cladding modes.

$$\Delta\varphi = \frac{2\pi}{\lambda}(\Delta n_{eff})L \tag{2}$$

where λ is the central wavelength of the light source, and L represents the uniform waist length of the fiber. Δneff signifies the difference between the effective refractive indices of the core and cladding modes, given by Eq. (3):

$$\Delta n_{eff} = n_{eff}^{core} - n_{eff}^{cladding} \tag{3}$$

From Eqs. (1) and (2), it is evident that maximum transmission occurs when $\Delta\varphi=2\pi(\Delta n_{eff})L/\lambda=2m\pi$ (where m is an integer). Therefore, the transmission signal exhibits a peak at the wavelengths given by Eq. (4):

$$\lambda_m = (\Delta n_{eff})L/m \tag{4}$$

where $n_{eff}^{cladding}$ and Δn_{eff} vary with changes in the refractive index RI of the measured solution. Describing the mth order shift of the interference spectrum, Eq. (5) is derived:

$$\lambda_m = \frac{(\Delta n_{eff} + \Delta n)L}{m} - \frac{\Delta n_{eff} L}{m} = \frac{\Delta n L}{m} \tag{5}$$

where Δn represents the change in the RI of the measured solution. Thus, Eq. (5) indicates that the variation of the transmission signal is a function of Δn when the sensor length (L) is constant.

EXPERIMENTS

The Vytran Glass Processing System Workstation (GPX-3400) from Thorlabs is used in the production process. The fiber optic operator uses two fiber optic supports to pull the cable; the operation is facilitated, and the data is recorded by heating the optical fiber with graphite filaments.

© STM Journals 2024. All Rights Reserved

The taper on the single-mode fiber (SMF) platform has three adjustable lengths: waist, top, and bottom. The measurements of the modified SMF platform are confirmed in the Vytran office using a CCD camera. The fibers are prepped by stripping off their coats and removing an 8 cm portion of the coating. Tapering lengthens and decreases the diameters of the core and cladding, in contrast to etching. As such, in its original form, the core-to-sheath ratio of a tapered fiber does not alter [6, 7]. The schematic diagram in Figure 1 shows internal structure of Microfiber MZI that was fabricated by employing the long uniform tapering.

The measuring device's schematic diagram used in the experimental setup, is shown in Figure 1. The ASE light source emits light with a wavelength of 976 nm, which is directed towards the (1+1)×1 pump signal processor (PSC). A coupler connects the PSC's output to the ytterbium-doped laser fiber. The output bandwidth of this ytterbium-doped gain fiber is 30 nm, and it produces a signal at 1045 nm. The sensing head is flattened and placed on the glass surface for the experiment. Wavelength fluctuations are used to monitor changes in refractive index. Different molar concentrations of NaCl solutions are used in the experiment [8].

The initial step to create the sensor is to use a fiber stripper to remove the optical fiber. It is therefore necessary to thoroughly clean the monofilament (SMF) medium using isopropyl alcohol. The fiber is then firmly fastened onto a pair of linear motor stages. The Vytran system carefully configures critical operating parameters such phase speed, distance, and time delay for system activation or deactivation [9].

The spectrum of the light source is subtracted from the transmission spectrum of the tapered fiber device to determine the attenuation maxima or minima of the core and cladding modes. Attenuation maxima and minima were not seen when a fiber with a cladding diameter of 125 µm was first tapered to 60 µm and spliced with the ASE source. A variety of tapered waist lengths were then obtained, as indicated in Table 1, and the fiber was subsequently further tapered down to 40 µm, as shown in Figure 2.

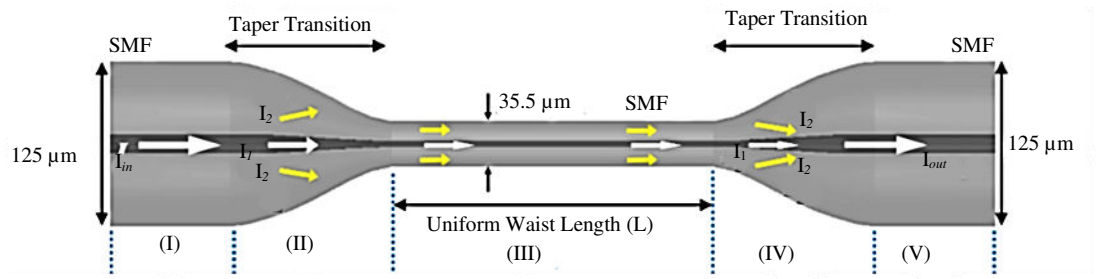

Figure 1. Schematic diagram of the internal structure of a microfiber MZI that was fabricated by employing the long uniform tapering.

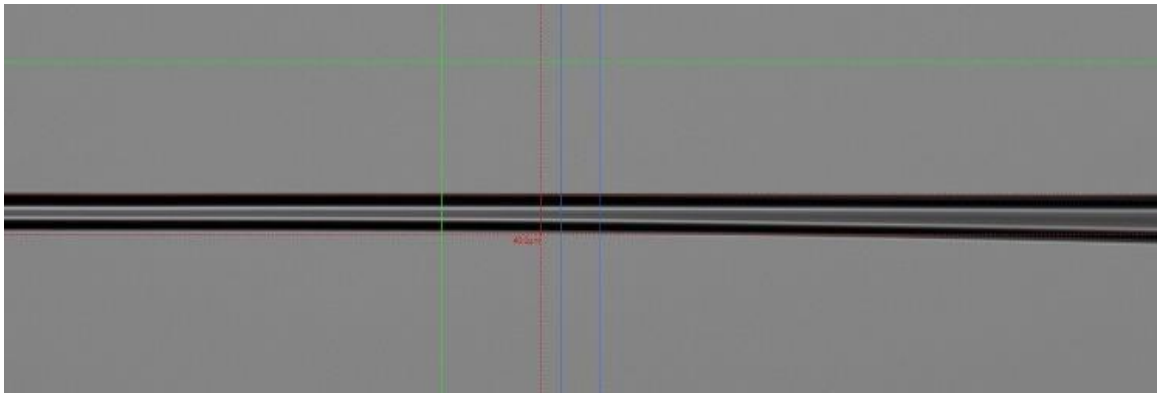

Figure 2. Tapered down fiber of diameter 40 µm.

© STM Journals 2024. All Rights Reserved

Table 1. Parameters of single tapering fibers.

Waist Diameter (μm)	Waist length (mm)	Down-taper Length (mm)	Up-taper Length (mm)
125	1	2	1
125	2	2	1
125	3	2	1

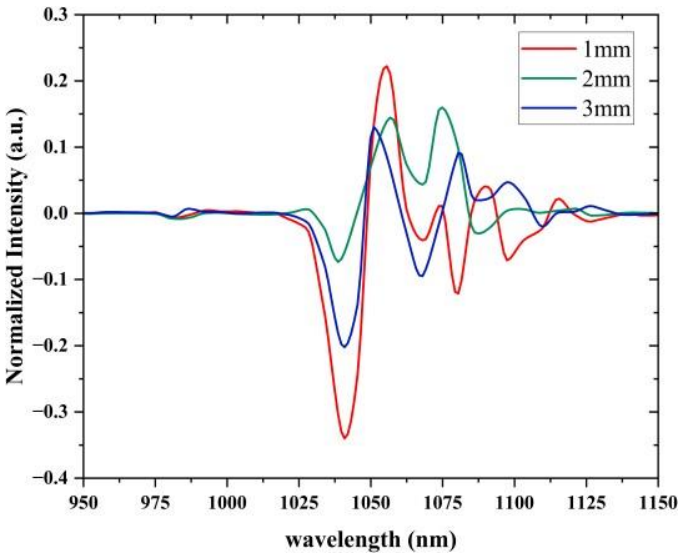

Figure 3. Attenuation Spectrum for different lengths for single taper.

As the drug's molar concentration rises, the wavelength shift for each wavelength might not be uniform, even after attenuation maxima have been identified. In fiber optics, a double-taper design is used to increase sensor sensitivity. Biconical arrangements were examined through testing with three different cone lengths, and they showed better sensitivity to changes in molar concentration than the single cone form.

Refractive Index Sensor

In this experiment, the sensor head was carefully immersed in identical NaCl solutions with different molar concentrations, as were electronic equipment set up in either a single or double configuration. It is easier to evaluate the sensor's reaction to changes in the environment, especially variations in the concentration of sodium chloride, when it is submerged in solutions containing sodium chloride. The Ocean Optics spectrometer was used to continually monitor and record the sensor's transmission during the immersion process. The bipyramidal configuration's minimal attenuation is shown in Figure 3. This makes it possible to track and examine any alterations or shifts in the transmission spectrum, giving information about the sensor's sensitivity and capacity to identify changes in the molar concentration of NaCl solutions. Furthermore, Figure 4 shows how various solutions alter the bipyramidal structure's wavelength. We may learn a great deal about the functioning of the sensor and its possible uses in sensing and detecting tasks by comparing spectra collected at different molar concentrations.

RESULT

Both single and double-taper designs with a waist diameter of 40 μm and a waist difference of 60 μm were investigated to study variations in molar concentration. The twin taper arrangement performed better at detecting these modifications. More precision and control over the sensing capabilities can be attained by modifying the taper settings.

The attenuation spectrum for different taper lengths is shown in a graph in Figure 3, where three different lengths were selected for analysis: 1, 2, and 3 months.

© STM Journals 2024. All Rights Reserved

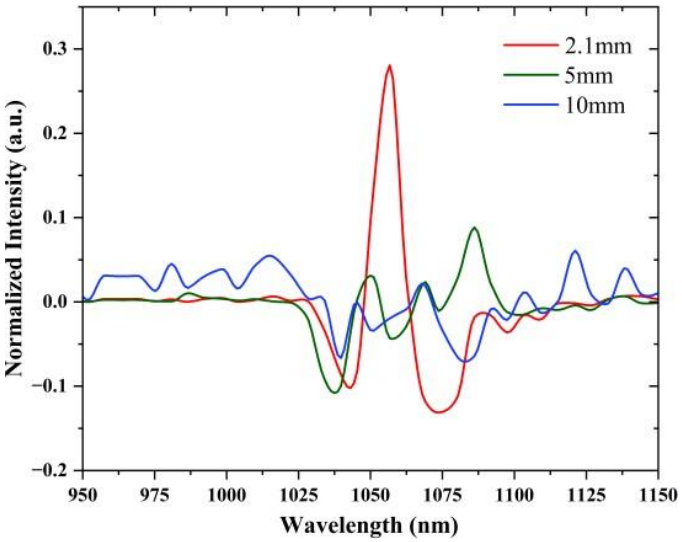

Figure 4. Attenuation Spectrum for different lengths between two tapers.

Table 2. RI for 10 mm length between taper and different molarity of NaCl solutions.

	1M	2M	3M	4M	5M
10 mm	0.018	0.018	0.018	0.036	0.071

Conspicuous changes in cone length are reflected in observable variations in intensity throughout the spectrum. This investigation successfully illustrates how length affects the stem's attenuation properties and shows how sensitive the sensor is to changes in taper length.

The attenuation spectrum for different distances between two tapers inside a single fiber is shown on the graph in Figure 4. The lengths that were chosen for analysis were 2.1, 5, and 10 mm, in that order. The refractive index for 10 mm length between taper and different molarity of NaCl solutions is shown in Table 2. There is a noticeable range of intensity variation that corresponds to variations in the separation between the two taper positions. This variation highlights how the inter-taper distance affects the system's attenuation characteristics and how sensitive the sensor is to changes in the spacing between tapers in a single fiber setup.

CONCLUSION

The work offers a simple and economical construction technique for a Fiber-optic Mach-Zehnder interferometer (MZI) that can detect refractive index (RI) with ultra-high sensitivity. To construct the MZI, a typical SMF-28 Fiber must be tapered. To examine the structural influence on RI measurement sensitivity, several MZIs with varying Taper Waist Diameters (TWDs) and taper lengths were constructed. It is interesting to note that the sensitivity of the RI sensors based on the two-taper interferometer was comparable to that of the single-taper interferometer. Furthermore, Mach-Zehnder interferometers can be used in chemical, biochemical, and biological sensing applications because to their intrinsic high sensitivity, especially in watery conditions.

Acknowledgment

For their steadfast support and advice throughout this study, the authors would like to thank the Department of Electronics and Telecommunication Engineering at Sinhgad College of Engineering, Pune. We would especially want to express our gratitude to our internal guide, Prof. Ganesh N. Gaikwad, and external guide, Mr. Shyamal Mondal, for their amazing knowledge and insights that made this project a huge success.

© STM Journals 2024. All Rights Reserved

REFERENCES

1. Ahsani Vahid, Farid Ahmed, Jun Martin BG, Colin Bradley. Tapered fiber-optic Mach- Zehnder interferometer for ultra-high sensitivity measurement of refractive index. Sensors. 2019; 19(7): 1652.
2. Tian Zhaobing, Yam Scott S-H, Jack Barnes, Wojtek Bock, Patricia Greig, Fraser James M, Hans-Peter Loock, Oleschuk Richard D. Refractive index sensing with Mach–Zehnder interferometer based on concatenating two single-mode fiber tapers. IEEE Photon Technol Lett. 2008; 20(8): 626–628.
3. Wang Qi, Lingxin Kong, Yunli Dang, Feng Xia, Yongwei Zhang, Yong Zhao, Haifeng Hu, Jin Li. High sensitivity refractive index sensor based on splicing points tapered SMF-PCF-SMF structure Mach-Zehnder mode interferometer. Sens Actuators B: Chemical. 2016; 225: 213–220.
4. Wu D, Zhu T, Deng M, Duan D-W, Shi L-L, Yao J, Rao Y-J. Refractive index sensing based on Mach–Zehnder interferometer formed by three cascaded single-mode fiber tapers. Appl Opt. 2011; 50(11): 1548–1553. [CrossRef] [PubMed].
5. Li L, Xia L, Xie Z, Hao L, Shuai B, Liu D. In-line fiber Mach– Zehnder interferometer for simultaneous measurement of refractive index and temperature based on thinned fiber. Sens Actuators A. 2012; 180: 19–24.
6. Smietana M, Korwin-Pawlowski ML, Bock WJ, Pickrell GR, Szmidt J. Refractive index sensing of fiber optic long-period grating structures coated with a plasma deposited diamond-like carbon thin film. Meas Sci Technol. 2008; 19(8): 085301.
7. Wu D, Zhao Y, Li J. PCF taper-based Mach–Zehnder interferometer for refractive index sensing in a PDMS detection cell. Sens Actuators B. 2015; 213: 1–4.
8. Taha BA, Ali N, Sapiee NM, Fadhel MM, Mat Yeh RM, Bachok NN, Al Mashhadany Y, Arsad N. Comprehensive review tapered optical fiber configurations for sensing application: trend and challenges. Biosensors. 2021 Jul 27; 11(8): 253.
9. Villatoro J, Monzón-Hernández D, Mejía E. Fabrication and modeling of uniform-waist single-mode tapered optical fiber sensors. Appl Opt. 2003 May 1; 42(13): 2278–83.

© STM Journals 2024. All Rights Reserved