

Design and Fabrication of Tapered Optical Fiber Related Devices

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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. 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).

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1. 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 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].

2. 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. Equation (1) describes the interference spectrum that results [5].

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

The intensities of the interference signal, core, and cladding modes are denoted by I_{out} , I_1 , and I_2 , respectively. Equation (2) expresses $\Delta\varphi$ as the phase difference between the core and cladding modes.

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

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

$$\Delta n_{eff} = n_{eff}^{core} - n_{eff}^{cladding} \quad (3)$$

From Equations (1) and (2), it's 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 Equation (4):

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

where $n_{eff}^{cladding}$ and Δn_{eff} vary with changes in the refractive index RI of the measured solution.

Describing the m^{th} order shift of the interference spectrum, Equation (5) is derived:

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

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

2. 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. 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. of internal structure of Microfiber MZI that was fabricated by employing the long uniform tapering.

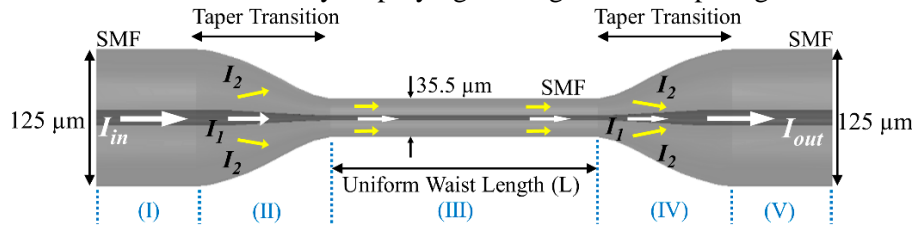


Fig 1. Schematic diagram of the internal structure of a microfiber MZI that was fabricated by employing the long uniform tapering.

The measuring device's schematic diagram is used in the experimental setup, which is shown in Figure 1. The ASE light source emits light with a wavelength of 976 nm, which is directed towards the (1+1) x 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].

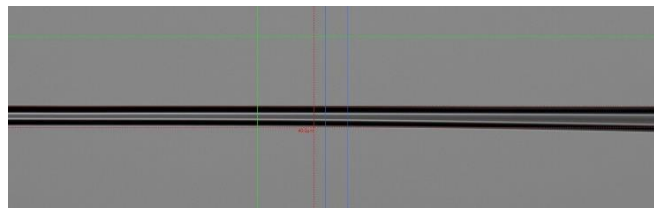


Fig 2: Tapered down fiber of diameter 40 μm.

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 125μm was first tapered to 60μm 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 40μm, as shown in Fig. 2.

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

Table 1: Parameters of single tapering fibers

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.

3.1 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.

4. RESULT

Both single and double-taper designs with a waist diameter of $40\mu\text{m}$ and a waist difference of $60\mu\text{m}$ 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.

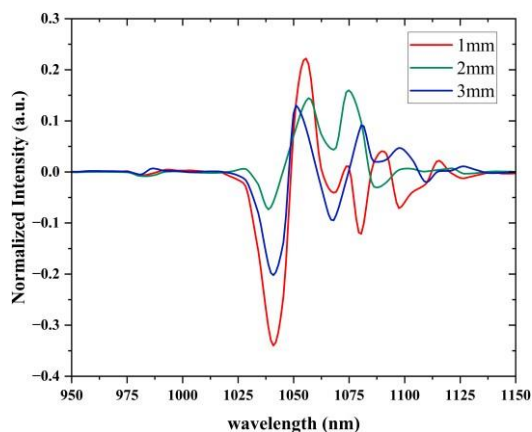


Fig 3: Attenuation Spectrum for different lengths for single taper

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

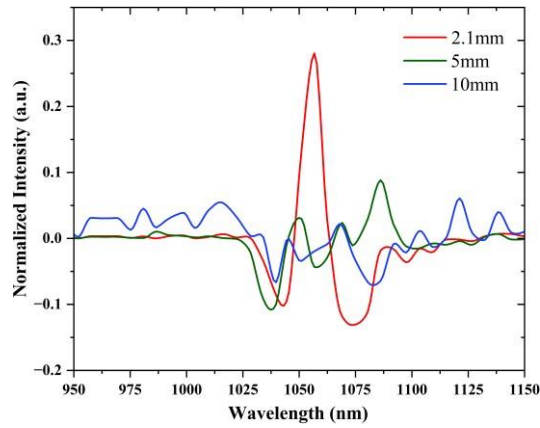


Fig 4: Attenuation Spectrum for different lengths between two tapers

The attenuation spectrum for different distances between two tapers inside a single fibre is shown on the graph in Figure 4. The lengths that were chosen for analysis were 2.1 mm, 5 mm, and 10 mm, in that order. The refractive index for 10mm 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 fibre setup.

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

Table 2: R.I. for 10mm length between taper and different molarity of NaCl solutions

5. 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's 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.

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