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Fabrication and characterization of cascaded tapered Mach-Zehnder interferometer for refractive index sensing

Vanita Bhardwaj*, Vinod Kumar Singh

Department of Applied Physics, Indian School of Mines, Dhanbad 826004, India

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ABSTRACT

A highly sensitive glucose detection refractometer based on Mach- Zehnder Interferometer (MZI) formed by two cascaded tapered joints by using a fusion splicer was proposed and experimentally demonstrated. A section of 40 mm single mode fiber is spliced by arcing function with cascaded tapered joint between two single mode fibers to construct MZI. Experimental results show that the transmission spectrum of the proposed cascaded device has a blue shift with the decreasing concentration of glucose. The sensitivity coefficient of 380 nm/RIU was acquired within the refractive index range from 1.333 RIU to 1.349 RIU. This result shows that the proposed structure can be used as a sensor to detect glucose concentration, which enables its importance in physiological and biomedical applications. Its ease of fabrication makes this device itself a low-cost alternative to existing sensing applications.

1. Introduction

Optical fiber sensors have been widely developed and used for the refractive index, temperature, pH, pressure, magnetic field sensing, liquid level sensing etc. [1–12]. Compared to other conventional sensors, optical fiber sensors offer many advantages such as low cost, ease of fabrication, high sensitivity and resistance to corrosion. There are many kinds of optical fiber sensors based on interferometer principle. However, Mach-Zehnder interferometer based optical fiber sensors are widely used for many purposes [13–15]. Various types of optical fiber sensors have been reported by using photonic crystal fiber [16], U bends fiber structures [17], fiber tapered structures [18,19], interference structures [20] and Chemical etched optical fiber [21]. For instance, Yinping *et al.* proposed characteristics of bend sensor based on two-notch Mach-Zehnder fiber interferometer [22]. Xiaoyan Sun *et al.* demonstrated a robust, high refractive index sensitivity fiber Mach-Zehnder interferometer fabricated by femtosecond laser machining and chemical etching [23]. These techniques are not easy to handle. Measurement of refractive index of glucose has great importance in chemical, physical parameter and especially to biosensor [24]. The measurement of glucose in different concentrations is performed in various fields, including biochemistry, clinical biochemistry, microbiology, chemistry sensing field and physical sensing fields. The determination of glucose in blood and urine is an important measurement of the functioning in the human body. Now a day, many people are affected by diabetes that is a dangerous and complicated disease. For this purpose some technologies have been emerged to monitor glucose level. Various kinds of biosensors have been reported for glucose detection [25–27].

In our present work we have used tapered fiber for sensing refractive index of glucose. The tapered sections in the fiber play an important role in improving sensitivity. The fiber tapering involves only fiber splicing and the fabrication process can be achieved by using arc function of fusion splicer. The glucose samples have been prepared in deionized water. The novel contribution of our work is that this kind of cascaded sensor structure is obtained in simple procedure and it can be used to detect refractive index of glucose at different concentrations. The whole sensing probe is fabricated by very simple technique. The sensitivity obtained for RI sensing is higher than mentioned work [28,29]. An advantage of fiber optic sensor is the small size of the optical fibers, which enables its importance in physiological and biological applications.

2. Fabrication of cascaded tapered Mach-Zehnder interferometer

The proposed double taper like fiber probe is fabricated by using three pieces of single mode fiber (SMF), while coupling ends are formed by simple arc function of fusion splicer. The first step in fiber probe

* Corresponding author.
E-mail addresses: vanitabhardwaj@ap.ism.ac.in (V. Bhardwaj), singh.vk.ap@ismdhanbad.ac.in (V.K. Singh).

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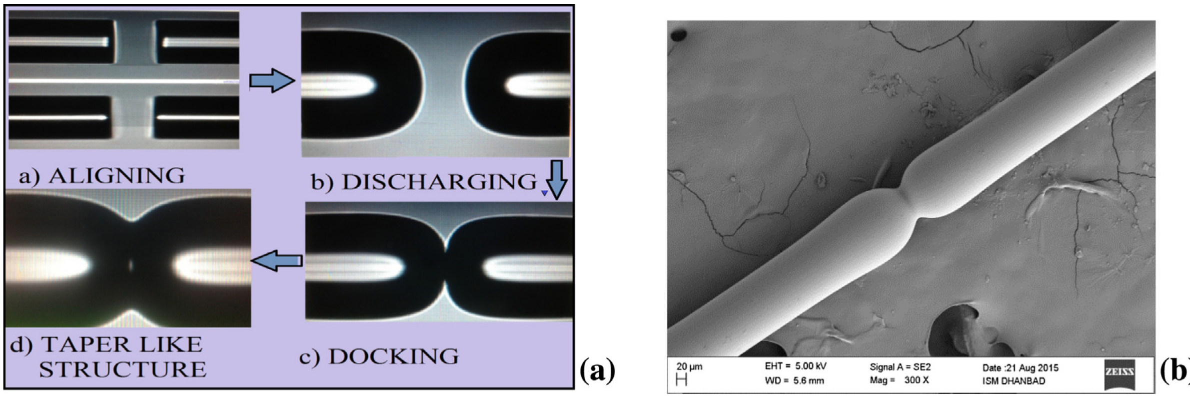

Fig. 1. Fabrication process and FESEM image of the proposed sensing structure of double tapered fiber probe.

fabrication is to strip and cleave all three pieces of SMF, with flat and smooth surface were spliced by using a commercial fusion splicer machine (SUMITOMO ELECTRIC, TYPE 39). First, the fusion splicer softens the ends of the fiber section by heat. Because of heat end faces of fibers melt into the spherical shape. Then fusion splicer exerts pressure on both ends of fiber to bring them together to merge in the middle and fuse them back into a single fiber. Once the first splice joint is formed, the linked fiber is again cleaned and cleaved. Then the cleaved sections of fiber are fused again using a same splicer function. The middle SMF acts as the sensing section for glucose detection and the separation between two splicing joints is 40 mm. The completed fabrication process and FESEM image of fabricated probe is shown in Fig. 1(a) and Fig. 1(b). The tapers are cylindrically symmetric like the joints. The optimized conditions used for this fabricated structure set at fusion time 1.65 s, perfusion time 0.05 s, Arc check, Arc gap 25 μm, Overlap 80 μm. After arc discharging, fiber is stretched inside the fusion splicer and then the cascaded tapered joint formed. To get interference, 3 dB taper is preferred.

The sensitivity of this structure depends on the distance between splicing joints, waist diameter and fusion loss. By decreasing fusion loss we can increase the sensitivity of the device. Thus, in the fabrication of tapered structure the fusion loss should be minimized. For compact device, it is difficult to increase the length of fiber. Then the performance of the device depends on how to enlarge the effective refractive index difference and to excite higher cladding modes. The excited cladding mode depends on the taper parameters. The evanescent field of the selected cladding mode can be increased by decreasing tapering diameter. The sensitivity of the device can further improve by introducing tapering between tapered joints.

3. Principle

In optical fiber devices, the MZI concept can also be realized by using SMF sandwiched by two SMFs consisting of input and output fibers as shown in Fig. 2. By drawing a section of SMF into a taper, a very simple MZI can be implemented. Decrements of the fiber cladding or core diameter allow the increment of evanescent field effect.

The light outputted from an input SMF splicing joint to an SMF diffracts and produces multimode lights. Totally reflecting multimode lights on the outer surface of the SMF are transmitted several times and then interfered at the end of the SMF. Different modes have different propagation constants, thus different modes have different mode effective RI. Thus, when different modes get into the output SMF splicing joint, the inter- modes interference occurs. The interference light coupled with the output SMF splicing joint can be observed with an optical spectrum analyzer (OSA). A strong evanescent field was formed near the tapered region and made the sensitive to external RI variations. In other words, we can say that this phase change shifts the interference condition of the spectrum. Therefore, this shift reflects the change in RI.

The transmission intensity can be expressed as:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\,\mathrm{Cos}\,\Delta\varphi \tag{1}$$

Where I_1 and I_2 are the intensities of different modes. $\Delta\varphi$ is the intermodal phase difference, which can be defined as,

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n_{\mathrm{eff}} L = (2m+1)\pi \tag{2}$$

Where λ and Δn_{eff} are the central wavelength and intermodal effective refractive index differences, respectively. L is the length of sensing arm. The phase difference between core and cladding mode enables the MZI to measure various environmental parameters. Δn_{eff} is the difference between the effective refractive indices of the core and cladding modes.

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

The separation of attenuation maxima wavelengths $\Delta\lambda_m$ is given by

$$\Delta\lambda_m = \lambda_m - \lambda_{m-1} \approx \frac{\lambda^2}{\Delta n_{eff} L} \tag{4}$$

With the increment of RI of the environment, the effective RI of the cladding mode increases by δn_{eff}, while that of core mode is almost constant, so Δn_{eff}. With Eq. (2), λ_m has to shift to the shorter wavelength by $\delta\lambda_m$.

$$\delta\lambda_m \approx 2\pi L \delta n_{eff} \tag{5}$$

Using $\delta\lambda_m$, one can detect the RI of unknown sample [30]. When the fiber probe is immersed in liquids of different concentration having different RI, the effective RIs of cladding modes will be influenced but the fundamental mode is unaffected. A small core diameter leads to high sensitivity by two factors; first one is an enhancement of diffraction and the second is sharper angle dependence. The light propagating from a small core diameter, at first tapered region enhanced the diffraction. This results the higher mode light with high intensity. Whereas the sharper angle dependence of coupling efficiency occurs in the second tapered region.

4. Experimental

The experimental setup for investigating RI of Glucose of the sensing structure for biomedical application is shown in Fig. 3. It consists broadband source with operating wavelength range from