Strain-Insensitive Biocompatible Temperature Sensor Based on DNA Solid Film on an Optical Microfiber

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***Abstract*— We demonstrated a biocompatible and highly sensitive temperature sensor using DNA-CTMA (DNA-Cetyl trimethyl ammonium) solid film deposited on micro-tapered fiber. The micro-tapered silica fiber provided a built-in interferometer that was inherently sensitive to the environment variation due to the enhancement of evanescent wave interaction. The tapered region was coated with DNA-CTMA film with a high thermo-optic coefficient enabling a high-temperature sensitivity higher than −0.9 nm/°C in the bio-medically important region from 35 to 80 °C in a water bath. The cross-sensitivity problem between the temperature-sensing and the strain-sensing was successfully resolved since the elastic properties of the DNA-CTMA film on the micro-tapered silica fiber resulted in a very low strain sensitivity of −7 pm/$\mu\varepsilon$. Detailed procedures for device fabrication and optical characterization of the proposed device were described.**

***Index Terms*— Biomaterial, DNA-CTMA, optical fiber sensors, temperature sensors.**

I. Introduction

OPTICAL fiber sensors are immune to electromagnetic interference, mechanically flexible, light-weighted, and can be miniaturized with a small footprint. With these advantages, optical fiber sensors have found various types of applications in measurement and monitoring physical properties [1]–[3] such as temperature [4], strain [5], refractive index (RI) [6], and humidity [7], to name a few. Especially, temperature sensing has been based on key fiber optic technologies including fiber Bragg grating (FBG) [8], photonic crystal fiber (PCF) [9], [10], external Fabry-Perot interferometer on fiber tip (EFPI) [11] and tapered micro/nanofiber [12], which are still being actively pursued in recent years. Biomedical applications have been growing rapidly in fiber optic sensors and biocompatibility has been the fundamental and critical problem [13]–[16]. Non-toxic bio-polymeric materials have been intensively studied for fiber optic applications in sensing and monitoring of live specimens [17]–[19]. In particular, recent in situ biosensing has required a high-temperature sensitivity in the range from 35 °C to 55 °C for in vivo and in vitro diagnosis and treatment [20], [21].

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Recently the authors' group has reported a fiber optic temperature sensor using biocompatible DNA-Cetyl trimethyl ammonium (DNA-CTMA) solid films integrated into an all-fiber interferometer achieving a high-temperature sensitivity of −0.22 to −0.15 nm/°C [15], [17]. The sensors have shown good sensing performances but they have required a delicate fusion splicing of a coreless fiber segment whose length had to be precisely controlled and the overall sensor length was in the range of 15 mm [15], [17]. Note that this sensor length might be too long to raise the strain-temperature cross-sensitivity problem as in FBG sensors [8].

In this letter, we proposed and experimentally demonstrated a new type of all-fiber temperature sensor that showed a high-temperature sensitivity exceeding those of prior reports by four folds and a suppressed strain response to achieve a strain insensitive temperature sensor. The proposed device had a micro-tapered fiber structure to enhance the evanescent interaction on which DNA-CTMA film was deposited. The film provided two key roles; 1) a high thermo-optic coefficient (TOC), dn/dT, to modulate RI of the layer sensitive to the temperature variations, 2) an elastic buffer to reduce the strain-induced RI change, $dn/d\varepsilon$, over the micro-taper. Utilizing these unique features, we achieved a high-temperature sensitivity over −0.9 nm/°C in the biomedically important region from 35 to 80 °C immersed in a water bath whilst successfully suppressing the strain sensitivity to −7 pm/$\mu\varepsilon$, for the first time to the best knowledge of the authors. The sensing head had a length of 2.5 mm, which is shorter than prior reports by several folds.

II. Principle of Operation

A schematic diagram of the proposed sensor structure is shown in Fig. 1. A single mode fiber (SMF) was heated and elongated to form an adiabatic micro-taper. Over the tapered region DNA-CTMA film was deposited using a drop-casting method similar to prior reports [15], [17] A white light source was launched into the SMF input and propagated along the core of SMF then into the taper, where higher-order cladding modes were excited to form a Mach–Zehnder interferometer (MZI) in reference to the optical path of the fundamental core mode. As the temperature changed the RI of DNA-CTMA changed to result in a spectral shift as schematically shown in the inset diagram on the center of Fig. 1.

The intensity (I) of the interferometric pattern is given by

$$I = I_{core} + I_{clad} + 2\sqrt{I_{core} I_{clad}} \cos \Delta(\phi). \quad (1)$$

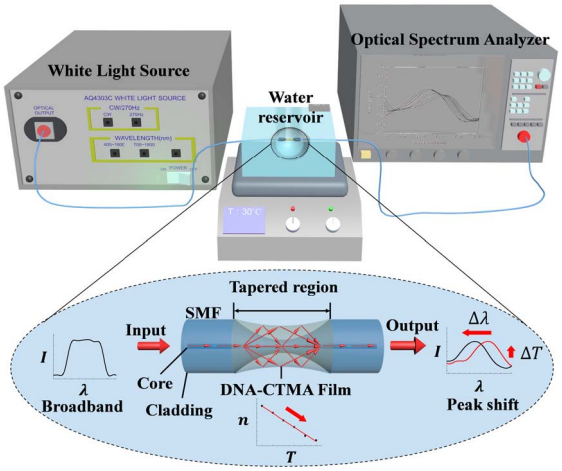

Fig. 1. Schematic diagram of the proposed device and the working principles. The white light is feed into the input of the fiber. The output spectrum is temperature sensitive due to the designed microstructure with thermo-optic properties of DNA-CTMA.

where I_{core} and I_{clad} are the intensity of the fundamental core mode and the higher-order cladding modes, respectively. $\Delta(\phi)$ is the phase difference between the core mode and the cladding mode [22]

$$\Delta(\phi) = \frac{2\pi}{\lambda}(\Delta n)L. \tag{2}$$

Here λ is the light wavelength, Δn is the effective index difference between the core mode and the cladding mode, and L is the taper waist length. When Δn changed by the TOC of DNA-CTMA film, the interferometric pattern shifted due to $\Delta(\phi)$ variation.

III. Fabrication of Sample & Experimental Results

In experiments, SMF (Corning SMF-28) was tapered using a commercial glass working system (Vytran, GPX-3000). The micro-taper had the waist dimeter of 15.7 μm and the waist length of 350 μm. The micro-tapered fiber was coated with DNA-CTMA by drop-casting of 5 wt.% DNA-CTMA:BuOH solution, followed by drying and baking in a nitrogen environment. The film thickness was ~20 μm and the total length of the sensor head was 2.5 mm, which was significantly reduced by a factor over 5 in comparison to prior sensors [15], [17]. DNA-CTMA solid film has an advantage of unique insolubility in water, and it has been reported by Hong et al. that the RI is n ~ 1.515, and a high TOC is $dn/dT \sim -4.1 \times 10^{-4}$/°C at the light wavelength λ ~1500 nm [17]. RI sensitivity of prior tapered interferometers has been reported previously [23]–[25]. Most of them had a common structure to extend the evanescent wave interaction outside the silica surface and further into the liquid to enhance RI sensitivity. This research, in contrast, confined the evanescent wave interaction within the DNA-CTMA solid film whose thickness is in the order of a few μm with the RI (n~1.52) significantly higher than the aqueous solution outside (n~1.33). Therefore, the optical field was successfully confined within the DNA-CTMA film to make the device nearly independent of the RI of the aqueous solution outside.

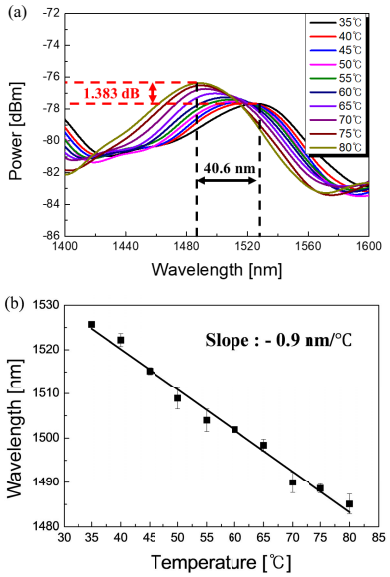

Fig. 2. (a) Spectral shifts in the output of the proposed device in the temperature range from 35 to 80 °C., (b) Spectral shifts as a function of the temperature variations.

The fabricated sensor was immersed in a water reservoir whose equilibrium temperature was varied from 35 to 80 °C and the output spectra were measured using an optical spectrum analyzer. We focused on the spectral range around 1500 nm which provided a low optical loss. As the temperature increased, the output spectrum blue-shifted consistent to the prior reports [17], [26] but the magnitude of spectral shift was significantly larger. Spectra corresponding to the temperatures from 35 to 80 °C are summarized in various colors in Fig. 2a. The peak shifted by as much as 40.6 nm for the temperature change of 45 °C, to result in high temperature sensitivity of −0.90 nm/°C. See the black curve fit in Fig. 2b. Note that this temperature sensitivity is 4-6 fold higher than prior DNA-CTMA temperature sensors [15], [17] and orders of magnitude larger than that of FBGs. For the same temperature change, the optical power of the peak increased by 1.383dB as shown in Fig. 2a.

In order to investigate the strain-dependence, we mounted the proposed device on fiber stages as shown in Fig. 3a. The sensor was fixed tight and one of the stages was translated in the fiber axial direction to provide a variable strain from 0 to 700 $\mu\varepsilon$ in the room temperature. The spectral shift of the peak was 4.9 nm at the maximum strain of 700 $\mu\varepsilon$. Spectral shifts with respect to the strain variation are summarized in the black graph of Fig. 3b. The proposed sensor showed good linearity in the spectral domain for both temperature and strain variations.

In Table I, we compared the temperature sensitivities of prior reports in the rapidly growing biosensor field. We could confirm that the proposed device achieved the highest sensitivity and the smallest footprint.

In order to find out the impacts of DNA-CTMA coating on the device sensitivity for both the temperature and the strain, we performed identical experiments for an identical bare silica micro-tapered fiber without DNA-CTMA coating. The bare micro-tapered fiber showed the temperature sensitivity

TABLE I
COMPARISON WITH PRIOR FIBER TEMPERATURE SENSORS

Structure	Spectral shift (nm/°C)	Power change (dB/°C)	Sensing medium	Length (mm)	Type	Ref
SMF-CSF	-0.22	+0.085	DNA-CTMA	14.5	Reflection	[17]
SMF-CSF-SMF	-0.15	+0.058	DNA-CTMA	15	Transmission	[15]
SMF-MMF-SMF	-0.10	-	Silicone rubber	80	Transmission	[36]
SMF-PDMS	+0.39	-	PDMS	-	Reflection	[37]
SMF-TiO_2-SMF	-	+0.13	PDMS	13	Reflection	[38]
SMF taper	-0.36	+0.040	Bare silica	2.5	Transmission	This work
SMF taper	-0.90	+0.061	DNA-CTMA	2.5	Transmission	This work

SMF: single mode fiber, CSF: coreless silica fiber, MMF: multimode fiber, PDMS : Poly-dimethylsiloxane

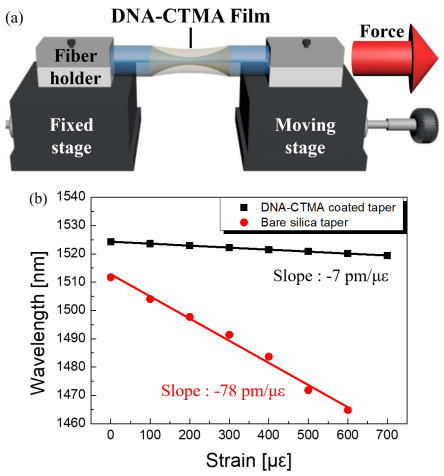

Fig. 3. (a) Schematic diagram of the strain dependence measurement., (b) Spectral shifts as a function of the strain variations for the DNA-CTMA coated taper and the bare silica taper. Both tapers had nearly the same geometrical shapes and dimensions.

of −0.36 nm/°C, which is only 40 % of the proposed device. See Fig. 2b and Table I. The TOC, *dn/dT*, of a typical SMF has been known to be $\sim 9 \times 10^{-6}$/°C [27], [28], whose magnitude is about 45 times smaller than that of DNA-CTMA film -4.15×10^{-4}/°C. DNA-CTMA film coating effectively enhanced the temperature sensitivity by 250 % due to its high *dn/dT*.

When a pulling force is applied to a bare silica tapered fiber along the axial direction, the taper waist region has the highest stress and becomes more sensitive to the strain [29], [30] than the pristine fiber. This has resulted in critical cross-sensitivity problems in tapered fiber sensors, which has hindered capability to discriminate a specific physical measurand from the strain responses [31]. The strain sensitivity of the bare micro-tapered fiber used in this study was measured to be −78 pm/$\mu\varepsilon$ which is more than 11 times larger than that of the proposed device, −7 pm/$\mu\varepsilon$. See Fig. 3b. This strongly indicated that the elastic behavior of DNA-CTMA film effectively reduced the strain sensitivity by an order of magnitude. Detailed investigations on fundamental elastic behavior of DNA films have been very scarce and it is only recently that elastic properties of biofilms have drawn intense research interests to understand the mechanism of how biofilms can cope with mechanical and chemical influences [32]–[34]. According to recent findings, some biopolymers behave like elastic solids to effectively resist external mechanical perturbations [35]. It is

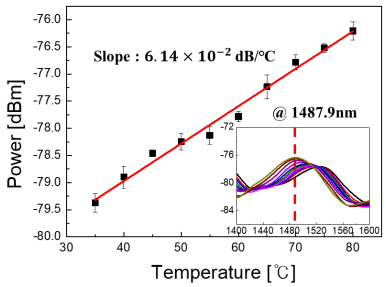

Fig. 4. The optical power variation at $\lambda = 1487.9$ nm.

speculated that the elastic behavior DNA-CTMA films coated around the taper effectively dispersed the stress to reduce the influence of strain in the proposed sensor. Detailed elastic properties of the DNA films are being investigated by the authors and the results will be reported in a separate paper in the future.

The main parameters to determine the sensor characteristics are the silica taper waist diameter, the taper length, and DNA-CTMA film thickness. In general, the smaller taper waist diameter and the longer taper length can provide the higher spectral temperature sensitivity but due to the nature of MMI, repeating dips and peaks in the spectral domain, these parameters showed certain limits. What we have emphasized more was the strain insensitivity by DNA-CTMA coating and we found thinner coating did not efficiently suppress the strain sensitivity. Further optimization of the structural parameters of the sensor is being pursued by the authors.

In practical sensor applications, the optical power measurements at a fixed light wavelength is highly preferred to the whole spectra measurements. However, optical power measurements should be done at the wavelength where commercially available light sources and photodiode exist. In our study, we found that optimal light wavelength $\lambda = 1487.9$ nm for the optical power monitoring over the temperature changes. The experimental results are summarized in Fig. 4, where a linear response with a slope of 6.14×10^{-2} dB/°C over the temperature range from 35 to 80 °C. Note that both laser diodes and photodiodes are commercially available at this wavelength. This slope was comparable to prior reports as shown in the second column of Table I.

IV. CONCLUSIONS

In conclusion, we successfully resolved the temperature-strain cross-sensitivity problem in a silica micro-tapered optical fiber utilizing DNA-CTMA thin solid

film coating over the tapered region. Utilizing the high TOC of DNA-CTMA film coated over the micro-taper, we significantly enhanced the temperature sensitivity to -0.9 nm/°C in the temperature range from 35 to 80 °C in a water bath, which is more than a factor of four increase compared to prior reports. The inherently high strain sensitivity of the silica micro-taper was efficiently suppressed to -7 pm/$\mu\varepsilon$ in the strain range of 0 to 700 $\mu\varepsilon$, which is an order of magnitude less than that of pristine silica micro-taper fiber with the same dimensions. At the light wavelength of 1487.9 nm, the proposed sensor also showed a linear response in the optical power with a sensitivity of 6.14×10^{-2} dB/°C. The sensor responses were highly linear and thermal hysteresis was not observed in repeated temperature cycles from 35 to 80 °C in the water bath. The sensor length was reduced to 2.5 mm, which is the shortest of the kind. This small-footprint, strain-insensitive and highly temperature sensitive sensor can find ample applications for local temperature measurements of living specimens immersed in aqueous solutions.

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