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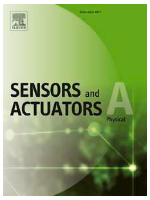

# Chemical modified fiber Fabry–Pérot interferometer by silver mirror reaction for hot-wire anemometry

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## ABSTRACT

This study reports the first chemically modified polymer air-gap fiber Fabry–Pérot interferometer (PAGFFPI) with a silver-coated film by silver mirror reaction (SMR) for achieving the hot-wire anemometry (HWA). The main sensing element, PAGFFPI based on a high thermal expansion polymer has a high temperature (T)-sensitivity; however, if it is simply fabricated with NOA65 polymer and fused silica the heating process with a commercial pumping laser diode (LD) can not be applied. Thus, a chemically modified PAGFFPI with Ag thin film based on SMR is proposed to significantly improve the absorption efficiency of laser heating energy and to obtain the steady-state high T which exceeds that of the surrounding. The PAGFFPI's interference wavelength fringes shift due to its T decrease when being cooled by the airflow. The cooling effect on heated PAGFFPI is largely determined by the airflow speed and it is converted into a wavelength shift in the interference fringes. According to experimental results, the chemically modified PAGFFPI by SMR can be successfully heated by LD with rise and fall times of 0.14 s and 0.98 s, respectively. The SMR with an Ag thickness of 270 nm can achieve a better airflow measurement than that with the 150 nm. Over the airflow range of 0–20 m/s, SMR-thickness of 150 and 270 nm achieve average sensitivities of 0.702 nm/(m/s) and 3.302 nm/(m/s), respectively.

## 1. Introduction

Over the past few decades, the development of industrial sectors and advanced technologies have been heavily dependent on adequate energy, typically petroleum energy. Yet, fossil fuels are harming the environment and the health of human beings in many aspects. As a result, most countries in the world have developed renewable energy resources such as wind power, solar energy, and geothermal energy. Of various renewable energy sources, wind power (energy) is a popular one. In operation, the wind (airflow) power is firstly converted into mechanical power via wind turbines and then used to operate electric generators for generating electricity. It has been well accepted that the development of wind energy, with technically matured and much smaller impact on the environment, in many developing and emerging countries is very substantial. It is also economically viable to produce electricity from wind energy in comparison to conventional energy sources such as coal and diesel in many places. In practice, the best amount of power output from a wind energy conversion system depends upon the accuracy of real-time wind speed measurement with which the peak power points can be tracked by the maximum power point tracking control algorithm [1,2]. Thus, the measurement of wind speed is a significant task for enhancing wind-energy conversion efficiency. There are various airflow measurements devices and anemometers currently available and most of them are based on hot-wire anemometry (HWA) [3]. The measuring principle of the HWA is based on the heat transfer from the anemometer to the surrounding environment for reducing its T. Normally, the heat transfer is primarily related to the fluid/wind velocity since the heat transfer is directly proportional to the T difference between the sensor and the fluid/wind. The HWA technique is reliable and has a good response in measuring rapid wind flows. Optical fiber made by the fused silica has intrinsic properties of low thermal optics coefficient (TOC), low thermal expansion coefficient (TEC), and endures high humidity ability that can be developed as a new kind and improved HWA-based fiber-optic anemometers. In recent years, with a number of

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advantages, i.e., small size, fast response, high accuracy, long-distance remote monitoring, reliability in harsh environments, and immunity to electromagnetic interference, many fiber-optic anemometers have been proposed [4–16]. To improve the HWA technique, the fiber anemometers should have a high T measurement capability. Using a pig-tail laser diode (LD) to heat the fiber-optic anemometers that exhibited controllable sensitivity, effectiveness, and simple configuration makes the approach particularly valuable [4–9,11–16]. However, fused silica fiber has an extremely low absorption coefficient from the wavelength of 400 nm~ 2 µm (visible ~ near IR regions) in room T so that it can not be effectively heated with common LDs [17]. To solve this problem, these fiber optic HWA-based anemometers have to be fabricated by using complicated techniques, like vacuum coating silver [4,5,9,13,15], silicon [12], and carbon nanotube [7]. Some special fibers are used for achieving the hot-wire, for example, cobalt-doped fiber [8,16], high-absorption fiber [6], and metal-filled microstructured optical fiber [14] those used metal elements can absorb the light carried by optical fibers for achieving the high T measurement. The configurations of fiber-optic anemometers based on the fiber Bragg gratings [4–9,13–16] and Fabry–Pérot interferometers [10,11,18] have been proposed to investigate their sensing sensitivity to the fluids. Although the above-reported sensing devices have high thermal responses and have a high correlation to the measured flow speed, complicated fabrication processes have strongly cramped their wide application.

To make a contribution in this sensing mechanism, a fiber-optic HWA based on a chemically modified polymer air-gap fiber Fabry–Pérot interferometer (PAGFFPI) is proposed in this paper, in which the SMR technique is applied to overlay a silver (Ag) thin film for achieving LD heating. The polymer air-gap fiber Fabry–Pérot interferometer has been demonstrated to have a very high T sensitivity performance [18]. To further improve the performance and simplify the fabrication processes, we further cleave the sensor's endface with a slant before filling the polymer to prevent the undesired Fresnel reflection from the PAGFFPI end. In addition, the Ag-film of the chemically modified PAGFFPI by the SMR can be made with different thicknesses to significantly improve the laser heating to obtain a steady-state high T exceeding the surrounding. When the laser-heated PAGFFPI is cooled by the testing airflow, interference wavelength fringes shift due to its T decrease. The cooling effect on the heated sensor greatly depends on the wind speed and it is converted into wavelength shifts (Δλ). Experimental results demonstrated that the proposed new approach can be effectively heated by an LD with high responses of rising and fall times of only 0.14 s and 0.98 s, respectively. When the 980 nm-LD heating, the device with a thicker Ag-film of SMR will have better sensitivity. That is because that it can get a higher temperature on the inner wall of the Ag-film based on heat conduction of the Fourier's law under the thermal equilibrium [19]. Average sensitivities of 0.702 nm/(m/s) and 3.302 nm/(m/s) over the airflow range of 0–20 m/s are obtained by using the thickness ($d_{SMR}$) of SMR-150 nm and SMR-270 nm, respectively.

## 2. Sensor fabrication and Operating Principle

The structure of the proposed chemically modified PAGFFPI based airflow sensor is shown in Fig. 1(a). A single-mode fiber (SMF) was firstly spliced with a tiny section of hollow-core fiber (HCF) having the inner diameter D= 50 µm by using a special fusion method for avoiding hollow-core destruction. Then, the endface of the HCF was cleaved a slant and then filled with the high T-sensitivity monomer NOA65 by the capillary action. The filled lengths and the quantity of the monomer NOA65 can be controlled by varying the duration of the capillary action [18]. The polymer of NOA 65 has a high TEC of about + 2.2 × $10^{-4}$ (°$C^{-1}$) for providing thermal sensitivity, enough elasticity, and stabilized performance, and is a good candidate for performing the experiment [20]. In our design, an airgap can be readily formed inside the HCF that gives rise to interference fringes in the reflection spectrum, the microphotograph is shown in Fig. 1(b). The sensor structure was configured as a simple type of airgap fiber Fabry–Perot interferometer (FFPI), and its interferometric mechanism was based on two-beam interference with low finesse [10,11,18]. As mentioned previously, the NOA65 was filled into the HCF and formed a microcavity, after filling, the end face of the HCF was exposed to UV light. In the UV-curing process, the polymer NOA65 with a refractive index of about 1.515 gradually transformed into a solid polymer with a refractive index of 1.524, which established the solid-state of the NOA65. Finally, we chemically modified the sensor head by using the SMR with coating different $d_{SMR}$ of Ag thin film for effectively absorbing light from the 980 nm LD, as shown in Fig. 1(c). The used 980 nm pump LD is one of the most cost-effective light sources to deliver high-power output via optical fiber due to the rapid progress of fiber laser technology.

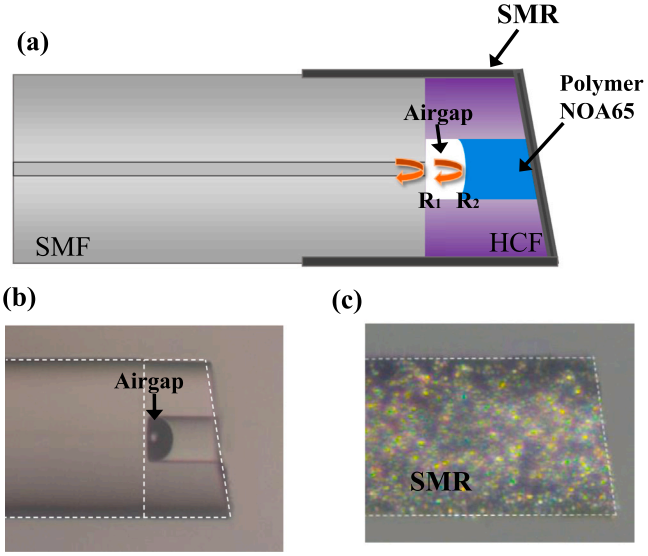

**Fig. 1.** (a) Schematic illustration of the proposed chemical modified PFAGFFPI anemometer. (b) Optical micrograph of the PFAGFFPI (c) Optical micrograph of the PFAGFFPI with SMR.

The chemical modification of the SMR is a very simple and rapid process [21]. The processes of the SMR are shown in Fig. 2. The preparation of the SMR involves three steps. First of all, as shown in Fig. 2(a), two drops of 2.5 g dilute sodium hydroxide are added to 2.5 g silver nitrate solution ($AgNO_3$). The $OH^-$ ions combined with the $AgNO_3$ aquo complex form into silver oxide ($Ag_2O$), which are precipitated from the solution as a brown-black precipitate in the solution, as shown below in Eq. (1). In the second step, as can be seen in Fig. 2(b), the sufficient 33% aqueous ammonia was added drop-by-drop into the silver oxide ($Ag_2O$) until the brown-black precipitation dissolves to give a clear solution of diamine silver (I) complex ($[Ag(NH_3)^2]^+$), known as Tollen's reagent (Eq. (2)). Finally, as shown in Fig. 2(b), the end surface of the fiber sensor was dipped into the Tollen's reagent. The 0.1 mL of 10% glucose was rapidly added, and then the fiber was kept in the reagent for a period of time to coat the silver mirror as bellow in Eq. (3). Afterward, the sensor is taken out from the reagent, then rinsed with deionized water (DI water), and dried for the airflow sensing tests. The $d_{SMR}$ of the Ag thin-film on the chemically modified PAGFFPI can be controlled by the time duration of the process as expressed in Eq. (3). The Ag thin-film thickness (dSMR) with 150 nm and 270 nm can be obtained by the duration of ~1.5 min and ~3 min, respectively. Here, the thin-film thickness were confirmed by an Atomic Force Microscope (Multi Mode, Veeco).

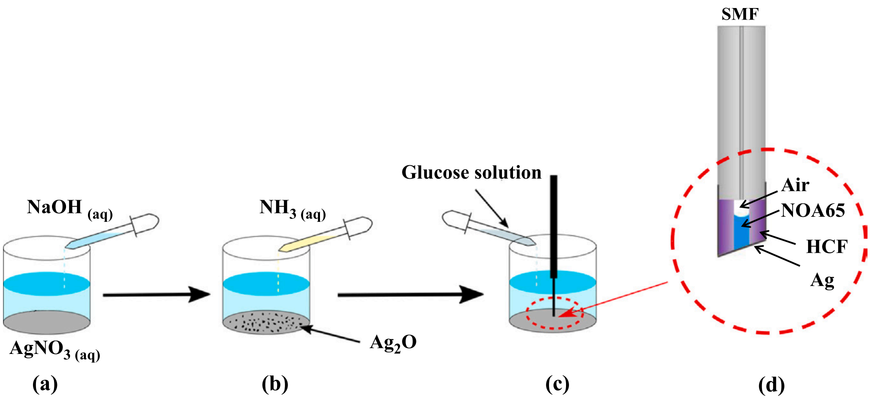

**Fig. 2.** Silver mirror reaction (SMR).

$$2AgNO_3(aq) + 2NaOH(aq) \rightarrow Ag_2O(S) + 2NaNO_3 + H_2O(l) \tag{1}$$

$$Ag_2O(s) + 4NH_3(aq) + 2NaNO_3(aq) + H_2O(l) \rightarrow 2[Ag(NH_3)_2]NO_3(aq) + 2NaOH(aq) \tag{2}$$

$$C_6H_{12}O_6(aq) + 2[Ag(NH_3)_2]NO_3(aq) + 3NaOH(aq) \rightarrow 2Ag(s) + C_6H_{11}O_7Na(aq) + 4NH_3(aq) + 2H_2O(l) + 2NaNO_3(aq) \tag{3}$$

Fig. 3 shows the experimental setup for the airflow tests. To achieve a steady-state high T, a 980 nm pump LD was utilized to heat the SMR-PAGFFPI through a 980/1550 nm wavelength division multiplexer (WDM) for achieving the desired sensor features. As can be predicted that the thin film of Ag metal can effectively absorb the energy of the wavelength of 980 nm. The measurement system also includes an optical spectrum analyzer (OSA, ADVANTEST-Q8381A), a broadband light source (BLS), and a 2 × 2 optical fiber coupler. When the BLS is propagated into the SMR-PAGFFPI, the three Fresnel reflective beams from the $R_1$, and $R_2$ are combined and returned to the SMF to produce multiple interference patterns over a very wide range of wavelengths, which can be detected by the OSA. The optical response of the PAGFFPI would be the interference of two beams of the $R_1$ and $R_2$, achieving the air-gap Fabry Perot interference with a sinusoidal interference pattern.

## 3. Experimental results and discussion

To demonstrate the effectiveness of the proposed 980 nm-LD heated, chemically modified PAGFFPI, different SMR thicknesses ($d_{SMR}$) of the sensors are fabricated and tested. Fig. 4 displays optical spectra responses of the proposed PAGFFPIs with different $d_{SMR}$ by 980 nm LD heating. The interference fringes are estimated to be blue-shift, shifting to the shorter wavelength region, with the increase in heating power (P) as well as T since the polymer is expanded to compress the airgap. The threshold current ($I_{th}$) of the used LD is near 40 mA, thus the wavelength shift was gradually increased when the driving current ($I_{LD}$) of LD was higher than 38 mA, as shown in Fig. 4(a)-(b) It indicates the chemical modified sensor by SMR enables Ag film to absorb the light even in the spontaneous emission of LD. It is worthwhile noting that for a PAGFFPI without chemically modified by the SMR, its interference fringes stay unchanged when it is heated by the 980 nm LD, as plotted in Fig. 4(c). The insets of Fig. 4(a)-4(c) respectively show the detailed interference shifts. We can see the interference spectra are very flat due to the sensor's endface cleaving to a slant and further optimizing the spectral interference by a simple signal processing (fast Fourier transform, FFT) [22]. Regarding the efficiency of different $d_{SMR}$ heated by the LD with the same pumping power, the measured results for the $d_{SMR}$ = 150 and 270 nm are presented in Fig. 4(a) and (b), respectively. Based on the results obtained, the PAGFFPI with thicker thin film can have much better heating sensitivity. The wavelength shifts increased immediately when the $I_{LD}$ of LD was higher than $I_{th}$ with a steadily linear response to current. The heating performance with high sensitivity of −2.34 and −3.33 nm/mA are shown in Fig. 4(a) and (b), respectively to demonstrate the relationship between the Ag-film thickness and the absorption of heat. Total wavelength shifts with − 51 nm and − 80 nm are obtained by LD heating with $I_{LD}$= 60 mA for the $d_{SMR}$= 150 and 270 nm, respectively.

Based on the above results, it has been proved that the laser heating effect is feasible for the chemically modified PAGFFPI by the

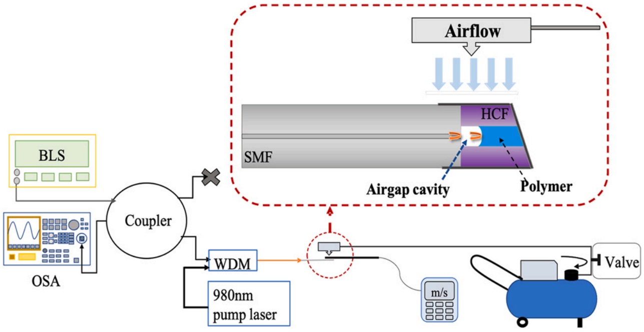

**Fig. 3.** The schematic of experimental setup for measuring airflow speed. Inset shows the hot-PAGFFPI acted by the wind.

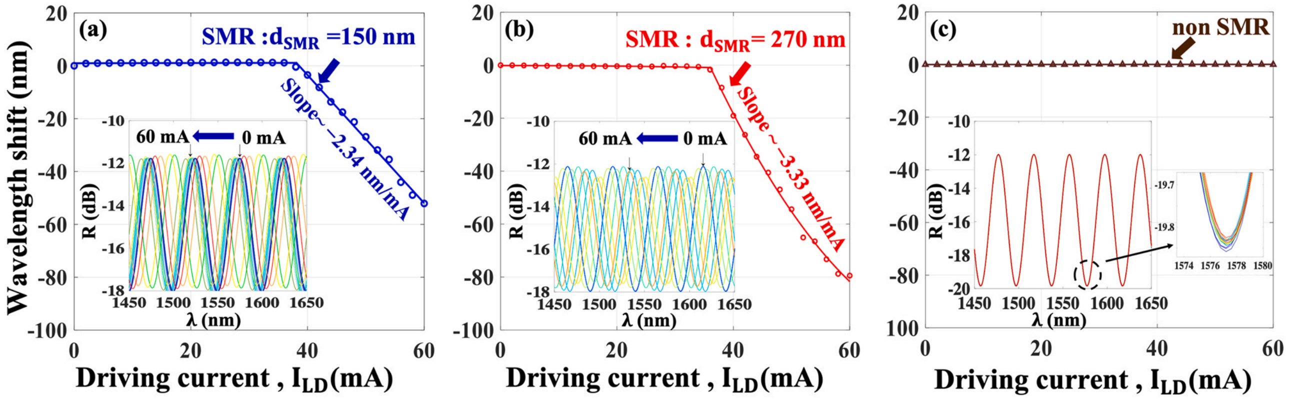

**Fig. 4.** Wavelength shifts of the interference spectra of the PFAGFFPIs heating by LD with different $I_{LD}$ for the $d_{SMR}$ with (a) 150 (b) 270 nm, and (c) non-SMR, respectively. The insets respectively show the detailed interference shifts.

SMR. Exploiting the favorable thermal responsive characteristics of the NOA65 polymer and the high absorption of LD by the SMR-Ag metal, the proposed PFAGFFPI sensor can reach high T and achieve the HWA performance. Next, the proposed PFAGFFPI sensor was applied to measure airflow to evaluate the effectiveness of its HWA sensing scheme. Initially, the proposed sensor was packaged on a thermal insulation plate with a commercial hot-wire anemometer for obtaining the T reference. Before the airflow was measured, the T of the sensor was effectively increased by the LD heating with a fixed $I_{LD}$. Airflow with different speeds was then delivered to the PFAGFFPI anemometer by an air compressor, controlled by a gauge monitored steady flow valve. When the air flowed directly over the sensor device to take away its heat (reduce T), thereby shrinking the polymer cavity to increase the airgap cavity to cause the interference wavelength shifts to the longer wavelength region (red-shift). The interference spectra were individually recorded by OSA with different settings of the airflow speed, which affected the T of the PFAGFFPI anemometer.

To investigate the influence of the wind speed on the proposed PFAGFFPI with different $d_{SMR}$ under different LD driven power. The PFAGFFPI with airgap of about 23 µm with $d_{SMR}$ of 150 and 270 nm are heating by the LD with fixed $I_{LD}$ of 40, 50, and 60 mA and the corresponding power (P) of 0.7, 2.4, and 4 mW, respectively. Fig. 5 shows the measuring results of airflow for the cases of $d_{SMR}$= 150 nm, (a)-(c), and $d_{SMR}$= 270 nm, (d)-(f), heated by the LD with $I_{LD}$= 40, 50, and 60 mA, respectively. It can be clearly seen from the experimental results, the

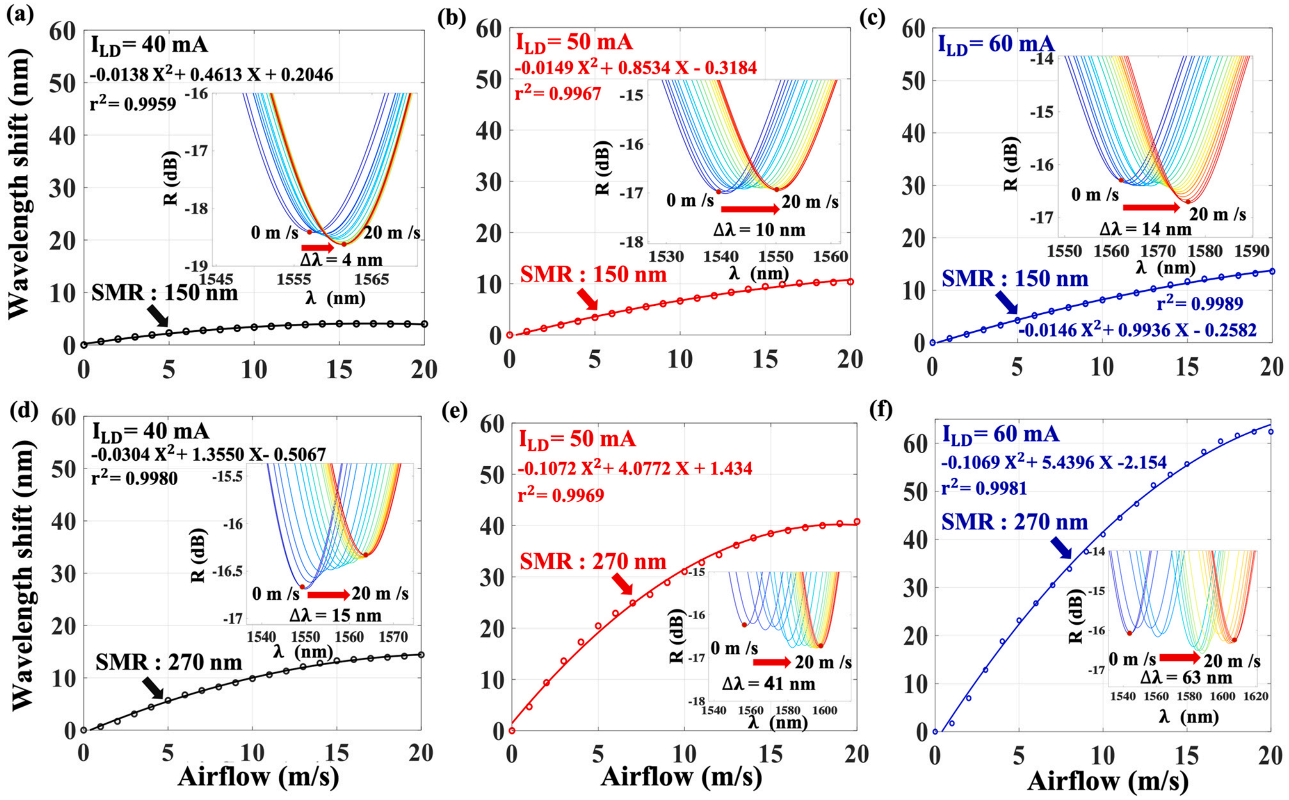

**Fig. 5.** Wavelength shifts of the interference spectra under airflow range of 0 ~ 20 m/s in the cases of (a)-(c) $d_{SMR}$= 150 nm, and (d)-(f) $d_{SMR}$= 270 nm corresponding heated by the LD with P = 0.7, 2.4, and 4 mW ($I_{LD}$=40, 50, and 60 mA), respectively. Insets respectively show the detailed wavelength shifts.

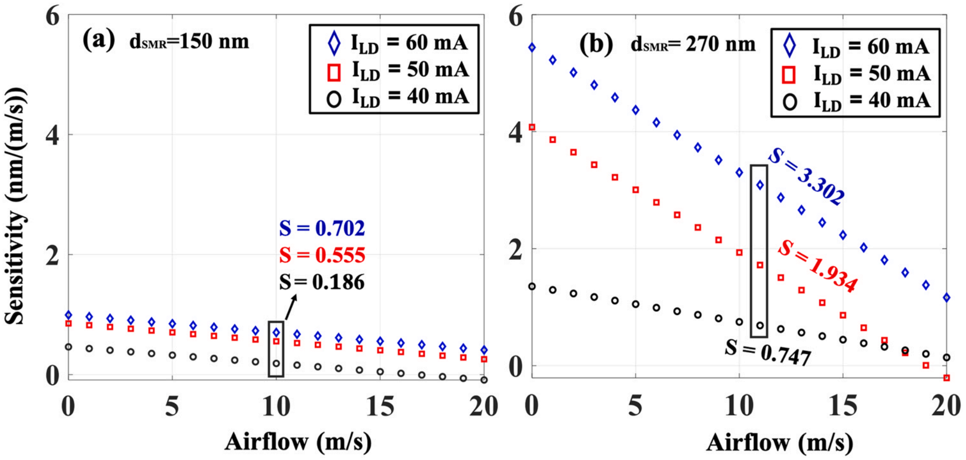

**Fig. 6.** Sensitivity changes of (a) SMR= 150 nm and (b) SMR= 270 nm PFAGFFPIs under various airflows in the different input current 40, 50, and 60 mA with P = 0.7, 2.4, and 4 mW.

sensor with thicker $d_{SMR}$ and larger $I_{LD}$ can be heated to a higher T to obtain a better airflow sensitivity. The total Δλ of the PFAGFFPIs over the wind speed range of 0–20 m/s are 4, 10, 14, 15, 41, and 63 nm for the conditions of (a) $d_{SMR}$ = 150 nm, $I_{LD}$= 40 mA, (b) $d_{SMR}$ = 150 nm, $I_{LD}$= 50 mA, (c) $d_{SMR}$ = 150 nm, $I_{LD}$= 60 mA, (d) $d_{SMR}$ = 270 nm, $I_{LD}$= 40 mA, (e) $d_{SMR}$ = 270 nm, $I_{LD}$= 50 mA, (f) $d_{SMR}$ = 270 nm, $I_{LD}$= 60 mA, respectively. The insets of Fig. 5(a)-(f) show the detailed wavelength shifts (Δλ) in the reflection spectra corresponding to the wind speed.

In the measurement range of airflow speed with 0–20 m/s, the experimental results indicated that wavelength shifts vary substantially within the airflow speed below 10 m/s. However, in this design case, the airflow sensing sensitivity weakened at high airflow rates of 10–20 m/s. The variation of wavelength shifted Δλ gradually approach to unchanged at high airflow speed when the equilibrium of thermal interaction occurs. The experimental results also reveal that the higher $I_{LD}$ for the heated PFAGFFPI with thicker $d_{SMR}$ can

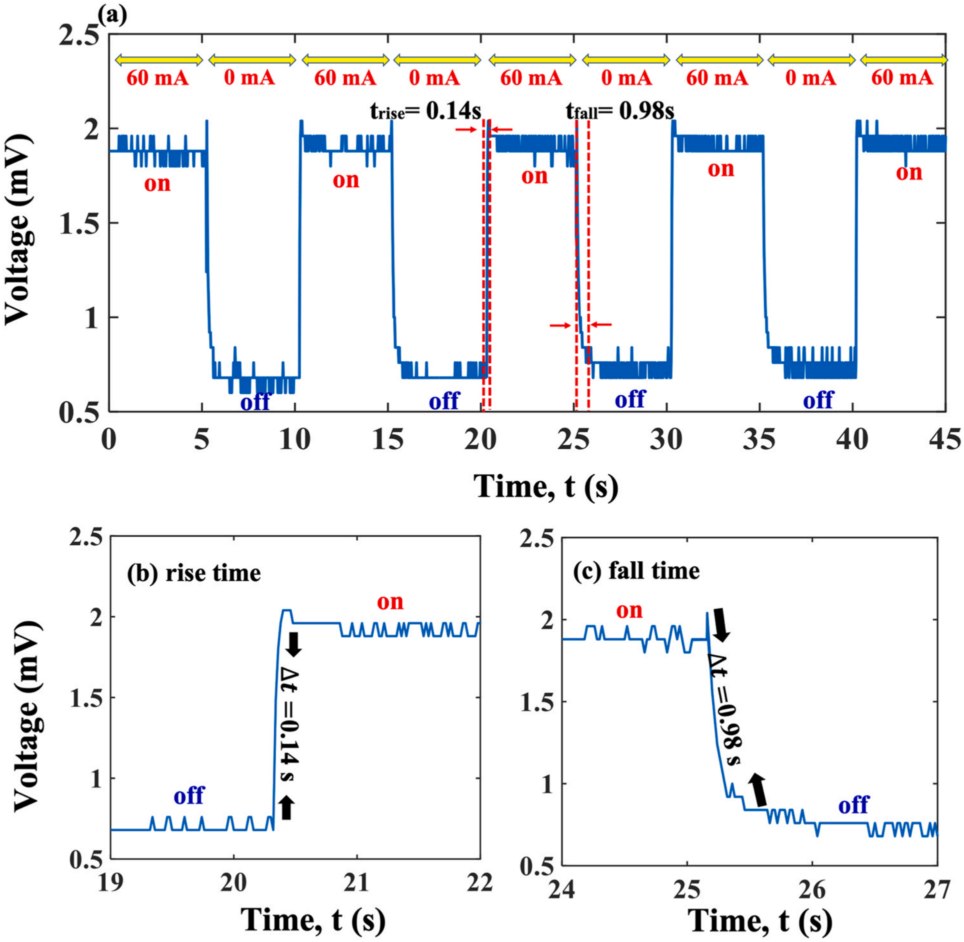

**Fig. 7.** (a) Transient response of the SMR-PFAGFFPI by $I_{LD}$= 60 mA, P = 4 mW LD heating in successive switch cycles. The corresponding (b) rise and (c)fall times of 0.14 s and 0.98 s, respectively.

achieve the best sensitivity at the airflow measurement. Based on the results shown in Fig. 6, we can evaluate the sensing effectiveness of different conditions of $I_{LD}$ and $d_{SMR}$, and determine the sensitivity (S) with respect to the wind speed ($v$), as below:

$$S \equiv \left| \frac{d(\Delta\lambda)}{dv} \right| \tag{4}$$

Based on Eq. (4) and the results shown in Fig. 6, it is verified that the sensitivities of the proposed sensor that are strongly correlated with $v$.

Compared to the results shown in Fig. 6(a) and 6(b), the heated PFAGFFPIs with a thickness of $d_{SMR}$ = 270 nm can have a higher S than that of the thickness of $d_{SMR}$ = 150 nm by the same $I_{LD}$ of LD due to the former can have higher T. Moreover, the S to $v$ of the proposed sensor at different heating powers ($I_{LD}$) of 40, 50, 60 mA with the symbols of black-○, red-□, and blue-◊ are also presented. The S decreases with the increase of wind speed until it approaches zero. This means that the enhanced wind speed cannot further effectively decrease the T of the sensor at that sensing condition. It also can be easily realized that the higher $I_{LD}$ the better S can be achieved in the proposed PFAGFFPI. In the $v$ measurement range from 0 m to 20 m/s, the averaged S for the conditions of (a) $d_{SMR}$ = 150 nm and (b) $d_{SMR}$ = 270 nm by $I_{LD}$ of 40, 50, 60 mA are 0.186, 0.555, and 0.702 nm/(m/s) and 0.747, 1.934, and 3.303 nm/(m/s), respectively.

The above results show that the sensor with a thicker $d_{SMR}$ of 270 nm will have better sensitivity by 980 nm-LD heating. However, two sensors with $d_{SMR}$ = 270 nm and 150 nm should have the same laser light absorption due to their similar skin depth of tens nanometers. Based on the Fourier's law for heat conduction, via the continuous absorption of a 980-nm laser, the rate of thermal flux (q) flowing into these two fiber devices with different thicknesses ($d_{SMR}$) should be the same, as defined below Eq. (5).

$$q = -k\,\nabla T \sim -k\left(\frac{T_2 - T_1}{d_{SMR}}\right) \tag{5}$$

where q is the heat flux. $k$ the thermal conductivity is always constant in the same material, and ∇T is the temperature gradient. $T_2$ and $T_1$ are high and low temperatures at the inner and outer surfaces of the Ag-films, respectively. We can see the Eq. (5), in thermal equilibrium, the ∇T across the Ag-film with different $d_{SMR}$ are also the same due to the same of q. The temperature of the outer surface of Ag film is approaching room temperature ($T_1$). Thus, based on Eq. (5), with the same ∇T and the same boundary condition ($T_1$: room temperature) at the Ag-film/air interface (outer surface), thicker $d_{SMR}$ can have a higher temperature difference ($T_2 - T_1$). Thus, it can be inferred that high temperature ($T_2$) on the inner wall of the Ag-film with $d_{SMR}$ = 270 nm thickness will be higher than that with 150 nm thickness.

In order to evaluate the transient response of the proposed PFAGFFPI heating by the LD, a signal light was launched into the sensor and its response is detected and measured by an oscilloscope. When the 980 nm laser is launched into the sensor, the proposed chemically modulated PFAGFFPI takes a rapid response to the light heating. This phenomenon resulted from the metal Ag which modified on the sensor head can quickly absorb the energy of laser light. In the experiment, the driving current was set to 60 mA for the 980 nm LD. The “on” and “off” switch alternates every 5 s and its responses are displayed in Fig. 7.

Fig. 7(b) and (c) indicate the rise and fall times of the sensor simply takes 0.14 and 0.98 s for switch on and off, respectively. It can also be seen from Fig. 7(a) that the results show excellent repeatability, and the steep slope of the optical response also shows the stability of the sensor. Note that using pig-tail LD heating to quickly control the T of the sensor is much convenient and fast, thereby achieving high efficiency of the heating process.

## 4. Conclusion

We have proposed a novel, chemically modified polymer air-gap fiber Fabry–Pérot interferometer (PAGFFPI) which is coated with a silver (Ag) film by silver mirror reaction (SMR) to achieve a performance improved hot-wire anemometry (HWA). The proposed PAGFFPI was heated by the LD to reach a high T state, then it was cooled by the airflow for shifting its interference wavelength due to T decrease. In practice, the wavelength shift of the laser-heated PAGFFPI greatly depends on the airflow speed. It has been found that the proposed chemically modified PAGFFPI with the metal Ag film can efficiently absorb the laser diode (LD) energy and can be effectively heated to reach the steady-state high T which exceeds that of the surrounding. Compared with conventional high vacuum coating applied on the fiber-optic HWA, the proposed chemically modified fiber sensor device with the SMR approach exhibits a number of merits, i.e., simplicity, high sensitivity, fast response, and low cost. In this paper, a comprehensive experimental test has been carried out, and results with comparative quantitative analysis have been presented. Results have demonstrated that a higher driving current ($I_{LD}$) and the SMR with thicker Ag film can achieve a better airflow measurement performance. It should be noted that the transient responses of the proposed PFAGFFPI heating by the LD with $I_{LD}$= 60 mA, P = 4 mW can achieve the rise and fall times of 0.14 s and 0.98 s, respectively. Fabrication details and experimental results presented in this paper also verify that the proposed chemical modified fiber sensor by the SMR technique is simple, reliable, and efficient for achieving broader fiber-optic-based HWA applications.

## Author contributions

This work was carried out in collaboration between all authors. The first author Chen-Ling Lee led the study, performed the analysis of the results, and wrote the first draft of the manuscript. Authors, Yi-Ching Chang, the student in the Department of Electro-Optical Engineering, NUU, performed the experiments, managed data, and figures. The author, Chao-Tsung Ma, performed the experiments and provided discussions in preparation of the paper. The author, Chien-Hsing Chen, from the Department of Biomechatronics Engineering, NPUST, performed the experiments of Chemical Modified-SMR. The last author, Wei-Wei Hsiang, provided the 980 nm LD heating techniques in the experiment.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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