Asymmetrical dual tapered fiber Mach-Zehnder interferometer for fiber-optic directional tilt sensor

Cheng-Ling Lee,* Wen-Cheng Shih, Jui-Ming Hsu and Jing-Shyang Horng

Department of Electro-Optical Engineering, National United University, No.2 Lien-Da, Miaoli city 360, Taiwan
TEL: + 886.37.381732, FAX: + 886.37.351575
**cherry@nuu.edu.tw*

Abstract: This work proposes a novel, highly sensitive and directional fiber tilt sensor that is based on an asymmetrical dual tapered fiber Mach-Zehnder interferometer (ADTFMZI). The fiber-optic tilt sensor consists of two abrupt tapers with different tapered waists into which are incorporated a set of iron spheres to generate an asymmetrical strain in the ADTFMZI that is correlated with the tilt angle and the direction of inclination. Owing to the asymmetrical structure of the dual tapers, the proposed sensor can detect the non-horizontal/horizontal state of a structure and whether the test structure is tilted to clockwise or counterclockwise by measuring the spectral responses. Experimental results show that the spectral wavelengths are blue-shifted and red-shifted when the sensor tilts to clockwise ($-\theta$) and counterclockwise ($+\theta$), respectively. Tilt angle sensitivities of about 335pm/deg. and 125pm/deg. are achieved in the $-\theta$ and $+\theta$ directions, respectively, when the proposed sensing scheme is utilized.

OCIS codes: (060.2340) Fiber optics components; (060.2370) Fiber optics sensors; (280.4788) Optical sensing and sensors; (120.3180) Interferometry.

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1. Introduction

Tilt sensors (inclinometers) are very important in engineering for accurately measuring the angular deflection/deviation of an object in a plane or on a line. Accordingly, a cost-effective, simple-structured and highly accurate tilt sensor that meets engineering requirements must be developed. Fiber-optic sensors are well known to be small, to transmit over long distances, and to be immune to electromagnetic interference; their ease of integration makes them especially suitable for tilt sensing applications. Various fiber-based tilt (inclined) sensors have been proposed [1–17]. However, most fiber-optic tilt sensors are based on grating-type fiber devices, for example: fiber Bragg grating (FBG) [1–9], long-period fiber grating (LPFG) [10, 11] or tilt fiber Bragg grating (TFBG) [12]. To sense the angle-dependence of tension or strain in a fiber grating, the tilt angle (strain) is determined by measuring shifts in the wavelength or power variation. Such grating-based fiber devices have recognized reliability and favorable sensing characteristics not only when applied as tilt sensors but also in many sensing applications. However, the fabrication of grating-type devices usually requires expensive UV-laser and phase masks, even requiring photosensitive fibers and hydrogen loading processes. Another group of fiber-optic tilt sensors that use interferometric configurations have been reported [11, 13–16]. Most fiber-optic interferometers are based on the optical interference of two beams that propagate along different optical paths in a single fiber or in different fibers. Optical beam-splitting and beam-combining processes can be used to obtain the interference in as Mach-Zehnder [11, 13, 14], Michelson [14], Fabry-Pérot [15] and polarized mode interference [16] fiber interferometers. Variations in the spectral response, optical phases or optical intensity can be detected to measure the remarkable sensing characteristics of fiber interferometric sensors, including large dynamic range, high accuracy, and high sensitivity. Other structures such as a simple fiber-optic tilt sensor that is based on the change in angle of the surface of a liquid with respect to the tilt angle of the used fibers have been presented [17]. According to two studies [12, 16], orientation-dependent fiber tilt sensors (inclinometers) are becoming increasingly popular owing to the high demand for monitoring accurately tilt angles and the direction of inclination of a structure. Information on the tilt angles and directions of inclination is extremely useful in architectural engineering and mechanical technology.

This paper proposes a novel type of highly sensitive directional and in-line fiber tilt sensor that is based on an asymmetrical dual tapered fiber Mach-Zehnder interferometer (ADTFMZI). The well-known fiber Mach-Zehnder interferometers (FMZIs) formed by cascaded two FBGs [18], LPFGs [19] and fiber tapers [20–22] have been widely used for many important applications. The proposed ADTFMZI in this study was effectively fabricated by asymmetrically tapering a pair of fiber tapers using an SMF-28 single-mode

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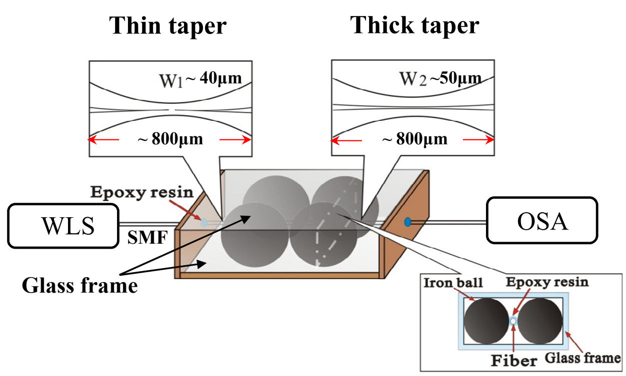
fiber. Tapering the fiber can strongly enhance the optical distribution of an evanescent wave, increasing the sensitivity of the device to changes in environmental parameters. In this investigation, asymmetrical dual fiber tapers with different tapered diameters are formed into an in-line TFMZI to detect a range of inclinations (from clockwise (−θ) to counterclockwise (+ θ). In the device was incorporated a set of iron spheres to produce strain in the tapered structure with a strain vector that is correlated with the tilt angle. Owing to the asymmetry of the dual tapers, the proposed tilt sensor can distinguish among horizontal, + θ and −θ tilt states by measuring interference spectral responses. Tilt angle sensitivities of 335pm/deg. and 125pm/deg. are achieved in the clockwise (−θ) and counterclockwise (+ θ) directions, respectively, when the proposed sensing scheme is used.

2. Configuration and operating principle

Figure 1 displays the developed ADTFMZI sensor, which is anchored on a rotation stage, and includes a set of iron balls with a total mass of about m = 12g that is fixed between two tapers. The two asymmetrical tapers were simply fabricated by a commercial fusion splicer (Ericsson FSU-975). For the first and second tapers, the lengths of the tapered regions were almost same and were measured as about 800µm, while the waist diameters were about 40µm (thin taper) and 50µm (thick taper), respectively. The two asymmetrical tapers were skillfully integrated on either side of the set of balls. Both sides of the asymmetrical tapered fibers were tightly straightened under tension and permanently fixed in the V-groove of a rotation stage using epoxy resin, as shown in Figs. 1(a) and 1(b).

(a)



(b)

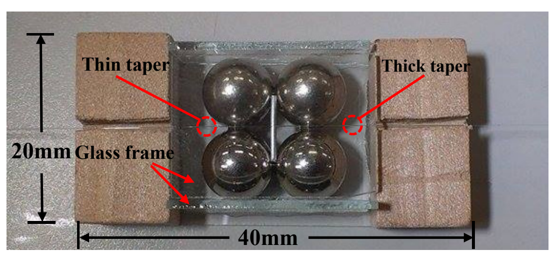


Fig. 1. (a) Developed directional ADTFMZI tilt sensor. (b) Top view of sensor structure.

Figure 1(b) presents the top view of the sensor configuration. The set of iron balls was centrally located between the two asymmetrical tapers and fixed in a flat frame. The iron balls were confined on all sides within a rigid trail with smooth glass walls to prevent them from obliquely gliding, as shown in the inset of Fig. 1(a).

The phase difference (ϕ_m) between the core and the interference cladding modes of such a Mach-Zehnder interferometer after propagation along path L in the ADTFMZI is given by $\phi_m = \frac{2\pi}{\lambda}\Delta n_{eff}^{m}\cdot L$, where Δn_{eff}^{m} is the effective index difference of the core mode and the m-th cladding mode. λ denotes the wavelength and L is length between the two tapers. Thus, the wavelength of the spectral minimum λ_p^m under the condition $\phi_m = (2p+1)\pi$ is given by the following Eq. (1), where p is an integer.

$$\lambda_p^m = \frac{2}{2p+1}\Delta n_{eff}^{m}\cdot L \tag{1}$$

Figures 2 (a) and 2(b) schematically depict the operating principle and the asymmetrical tapers that are forced by the strain vector, respectively. In Fig. 2(a), the applied force F(θ) acts on the sensor owing to the gravity of the set of iron balls, which depends on the tilt angle vector. Therefore, when the tilt sensor is almost equilibrated at θ = 0 (horizontal), the gravitational force F that acts on any of the fiber tapers is zero. However, when the device is tilted at –θ, the thin taper is stretched but the thick taper is squeezed. At a tilt of + θ, the thin taper is squeezed and the thick taper is stretched. Since the length of the interferometer is nearly constant, the axial strain is mainly responsible for changing the effective indices of the interference modes.

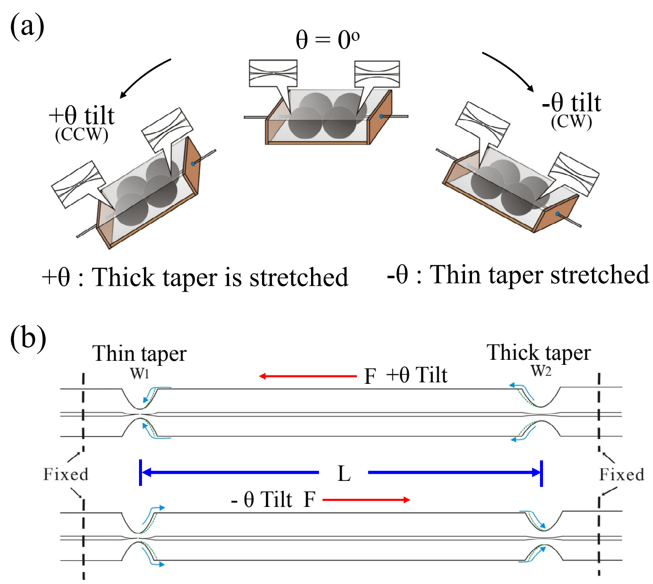


Fig. 2. (a) Operating principle of directional tilt sensor and (b) asymmetrical dual tapers, stretched under strain when sensor is inclined at + θ and –θ, respectively.

The strain vector $(\vec{\varepsilon}(\pm\theta))$ applied on the taper at a tilt of + θ or –θ can be easily formulated as follows.

$$\vec{\varepsilon}(\pm\theta) = \frac{mg\cdot\sin(\pm\theta)}{AE} \tag{2}$$

A is the cross-sectional area of the taper. The term g is the acceleration due to gravity so mg is the weight of the set of iron balls. E = 70G (Pa) is the Young's modulus of the fiber silica. The strain vector that acts on the sensor is determined using Eq. (2) and this equation can be

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simply expressed as a function of the tilt angle vector $(\vec{\theta}): \vec{\varepsilon}(\vec{\theta}) = mg\cdot\sin(\vec{\theta})/AE$. Since the structure of the sensor is asymmetrical, the asymmetrical strain on the fiber tapers at tilts in the directions + θ and –θ tilt are quite different. Furthermore, the optical response varies with the tilt angle θ. Most importantly, the proposed measurement configuration enables the easy determination of the angle of tilt and direction of inclination from the shift of the interference spectra, $\Delta\lambda$ which is thus a vector that depends on thetilt angle vectors and strain vector: $\vec{\varepsilon}$. In the scheme, the surfaces of the glass and iron balls are assumed to be smooth enough that friction is negligible. Accordingly, at a fixed temperature, by differentiating Eq. (1) yields the following equation,

$$\frac{\Delta\vec{\lambda}}{\lambda} \approx \frac{\partial L}{L} + \frac{1}{\Delta n_{eff}^{m}}\frac{\partial(\Delta n_{eff}^{m})}{\partial\varepsilon}\vec{\varepsilon} \tag{3}$$

Since both sides of the asymmetrical dual tapers are fixed, the change in the distance $(\partial L/L)$ between the two tapers can be assumed to be negligible. Thus the first term in Eq. (3) is ignored and the term $\frac{1}{\Delta n_{eff}^{m}}\frac{\partial(\Delta n_{eff}^{m})}{\partial\varepsilon} \equiv p_e$ can be defined as the effective photoelastic constant of the material. Generally, the vector $P_e\vec{\varepsilon}$ is negative (reduce the refractive index by stress) when the fiber is under stretching and is positive (increase the refractive index by stress) when it is squeezed. Therefore, the vector $\Delta\vec{\lambda}(\vec{\theta})$ of the wavelength shift that is caused by the competition of the two asymmetrical tapers thus can be determined as,

$$\frac{\Delta\vec{\lambda}(\vec{\theta})}{\lambda} \sim p_{e1}\frac{mg\cdot\sin(\vec{\theta})}{A_1 E} - p_{e2}\frac{mg\cdot\sin(\vec{\theta})}{A_2 E} \tag{4}$$

where , and are effective photoelastic constants and the cross-sectional areas of the thin and thick tapers, respectively. In this case, the A_1 and A_2 are approximately 400πμm^2 and 625πμm^2, respectively. When the sensor is horizontal $(\vec{\theta} = 0)$, no strain acts on the tapers so $\frac{\Delta\vec{\lambda}}{\lambda} = 0$ in the interference transmission spectra. However, when the sensor is tilted to an angle of $\vec{\theta}$, the strain vector affects the ADTFMZI, shifting the interference dips. Therefore, at a tilt of –θ, Eq. (4) yields $\Delta\vec{\lambda}/\lambda < 0$ since the sin(–θ) = – sin(θ) and $A_1<A_2$. Here, p_{e1} and p_{e2} are close to that of the fiber silica's p_e ~0.22 [4]. Thus, in the case of –θ tilt, when the thin taper (w_1) is stretched but the thick taper (w_2) is squeezed, the spectra are blue-shifted. On the other hand, at a tilt of + θ, the vector $\frac{\Delta\vec{\lambda}}{\lambda} > 0$ is producing a red shift. Based on the above analysis, the stain vector depends on the tilt angle and the direction of inclination. Accordingly, the red shift (Δλ/λ>0) and blue shift (Δλ/λ<0) in the optical interference spectra can be measured to determine whether the tilt angle is in the + θ or –θ direction, and its magnitude. In the proposed sensing configuration, a thinner waist of the used fiber taper yields greater sensitivity according to the strain-tilt related formula: $\varepsilon = \frac{mg\cdot\sin(\theta)}{(\pi w^2/4)E}$, where $\pi w^2/4$ is the cross-sectional area, A and w is the tapered waist. mg is the weight of the

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iron balls. By calculating the above stain-tilt related formula, we can obtain the relationship of the acting strain and the tilt angles for the proposed tilt sensor in different waist of the fiber tapers. The calculation results are shown in Fig. 3, the fiber taper with the thinnest waist, w = 40μm, received the highest strain for the tilt testing. The calculation results that are plotted in the figure reveal good linear responses for the operation with a tilt angle of θ between 0° to 60° but gradual saturation as θ approaches 90°.

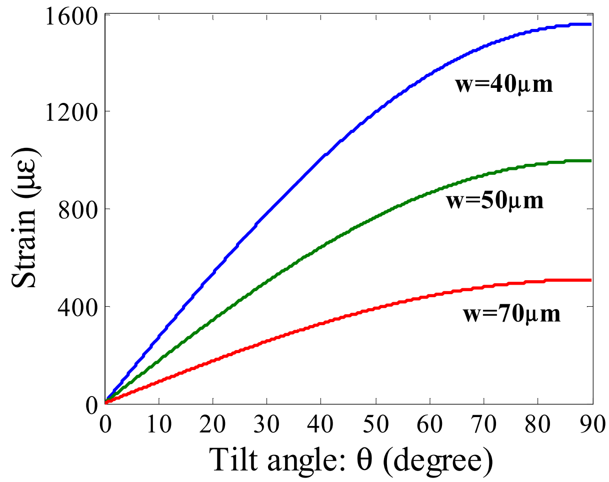

Fig. 3. Numerical calculation of micro-strain effect for different taper waists (w) with the sensor tilts from 0° to 90°.

3. Experimental results and discussion

To study the feasibility of the proposed method and the sensing structure, the ADTFMZI with the iron balls herein is confined inside a closed space that is formed by a smooth glass frame, to keep the set of balls moving only in axial directions. A wideband light source (WLS) is launched into the well confined ADTFMZI, and the spectral responses were obtained using an optical spectrum analyzer (OSA), as shown in Fig. 1(a).

Figures 4(a) and 4(b) display the experimental spectra of the proposed directional tilt angle sensor obtained for various angles with tilt directions of −θ (clockwise, CW) and + θ (counterclockwise, CCW), respectively. We can see that, the insertion loss of the proposed ADTFMZI is around ~22dB and interference fringes visibility can be higher to 30dB in the non-tilted situation. As previously mentioned, the interference dips shift to longer wavelengths (red shift) as the sensor tilts to a positive angle, + θ (CCW), and vice versa. In Fig. 4, the result of Δλ in the −θ case is more sensitive than it is in the tilt of + θ because the strain herein stretches the thin taper.

Figures 5(a) and 5(b) plot the fitted linear responses of the tilt angle sensitivities for the interference dips, Dip1 (λ~1465nm) and Dip2 (λ~1540nm), respectively. The insets in the Figs. 5(a) and 5(b) show the detailed spectral shifts in the wavelengths of Dip1 and Dip2 when tilts to + θ and −θ, respectively. In Fig. 5(a), the tilt angle sensitivities of 0.335nm/° = 335pm/° and 0.125nm/° = 125pm/° are achieved in the −θ and + θ directions, respectively, as plotted in the slope lines (black-dashed lines). The sensitivities (slopes) of the two λ dips to the tilt angle are shown and indicating a higher sensitivity in the −θ directions than in the + θ directions. The sensitivity slope lines are obtained over the tilt angle range of 0°~90° just by using the linear fitting regression in the Matlab program. It can be seen, except the result of Dip1 operating in the −θ inclination, strongly linear responses are obtained from a tilt angle of about 5° to 75°.

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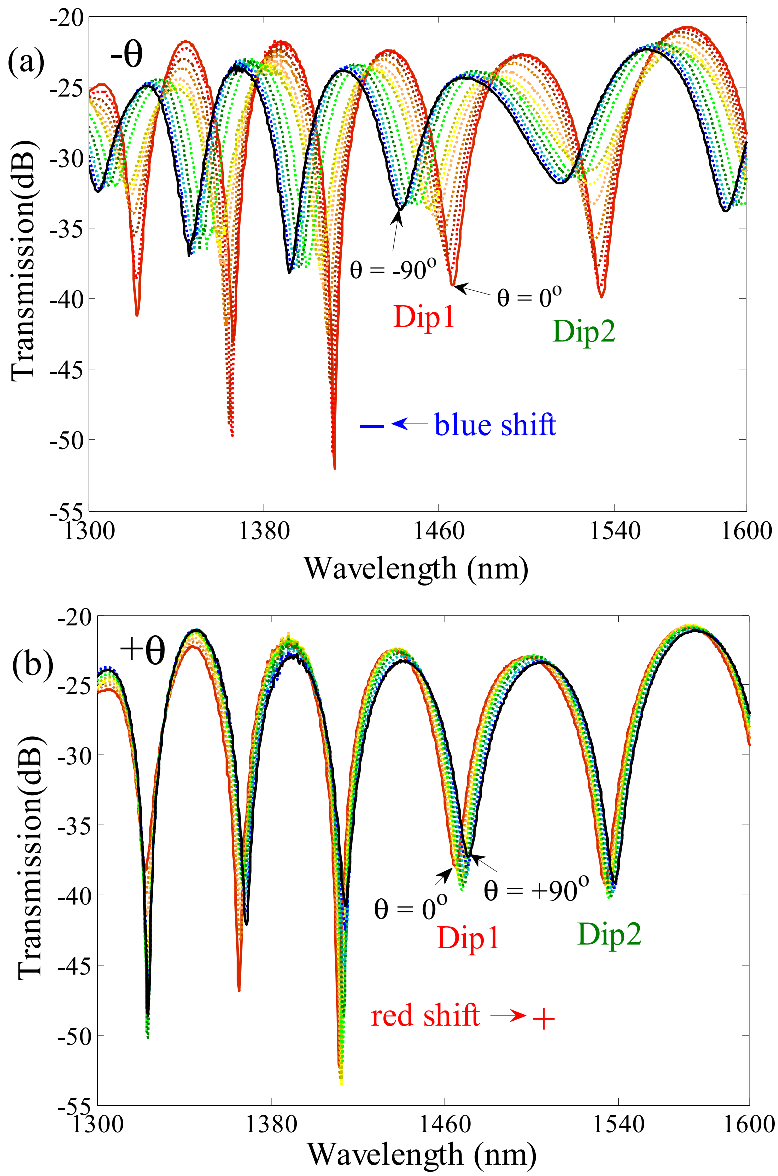

Fig. 4. Variations of transmission interference spectra of sensor as tilt angle to (a) −θ and (b) + θ, respectively.

The experimental curves clearly have a threshold angle, about 5° in the Dip1 (+ θ inclination) and also in the Dip2 (± θ inclination). The curve of the Dip1 in the −θ inclination shows a high threshold angle of around 10° that would be under an improper operation of the experiment. In the low tilt angles operation, the experimental results are not matched well with the fitted slopes and the sensitivities are not very good when compared with those of operating in the high tilt angles. We think that is because of slight friction force between the glass walls and iron spheres to affect the strain acting on the fiber tapers. The phenomenon is especially obvious in the low tilt angles operation since the friction force is high and the drag force from the iron-balls is small in the moment. To diminish the friction, the glasses and iron spheres can be further mechanically polished or adding a little lubricant to smooth the contacted surfaces. In this way, the sensitivity and accuracy of the sensor also would be improved. Even though, no matter the sensor is operated in the –θ or the + θ directions, the wavelength shift sensitivities of this kind of the proposed interferometric-based sensors are generally higher than those of the grating-based tilt sensors with the sensitivities of 54 pm/° [5], 39.5 pm/° [6], 12 pm/° [8], 62.6 pm/° [9] and 77 pm/° [10]. It is worth to mention that the measuring range of tilt angles from –90° to + 90° of the studied tilt sensor is greatly superior to those of the other published studies [1–17].

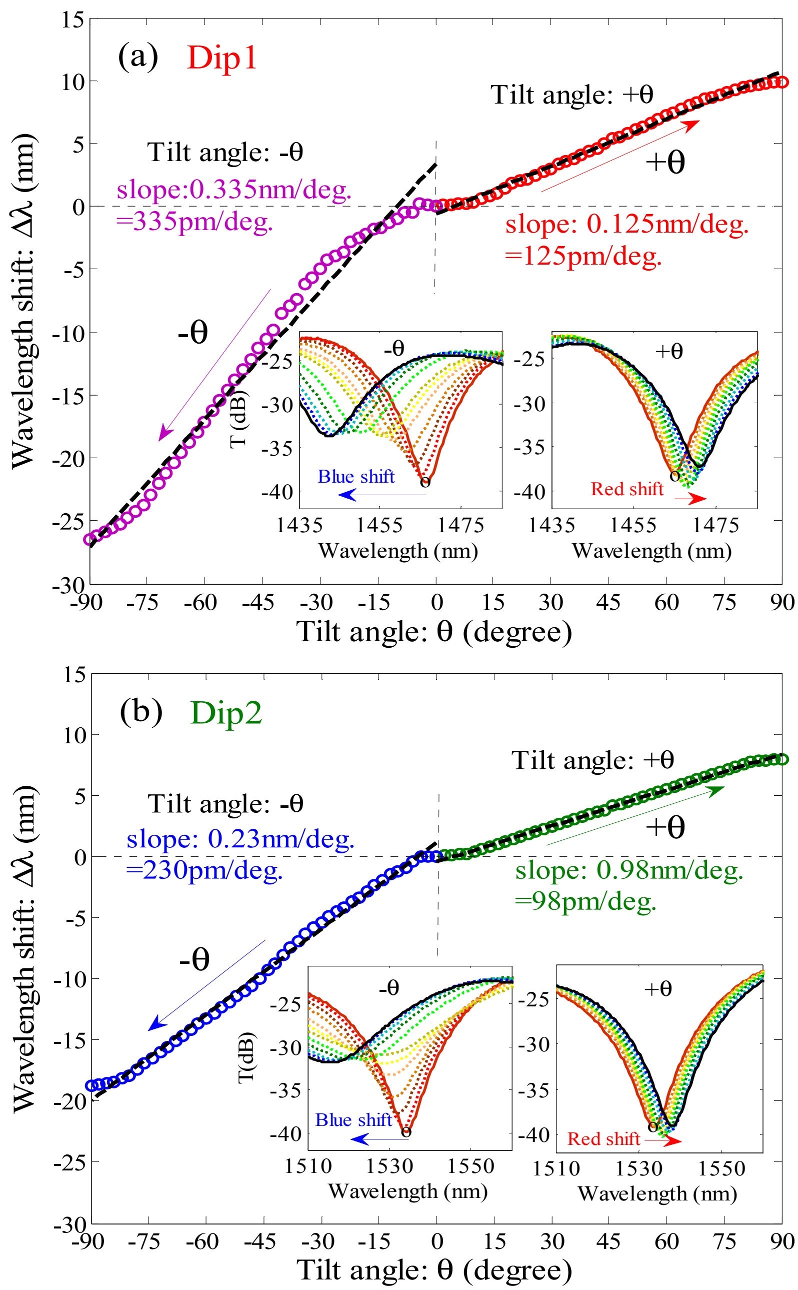

Fig. 5. Sensitivities of spectral shifts of (a) Dip1 and (b) Dip2 to the tilt angle (θ).

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4. Conclusions

This work proposed a directionally dependent, in-line fiber-optic tilt angle sensor that was based on an asymmetrical dual tapered fiber Mach-Zehnder interferometer (ADTFMZI). The sensing interferometer incorporates a set of iron balls to produce a strain vector that was correlated with the tilt angle and the direction of inclination. Experimental results demonstrate that the spectral wavelengths are red-shifted and blue-shifted when the sensor is tilted in the $-\theta$ and $+\theta$ directions, with directional angle sensitivities of around 335pm/deg. and 125pm/deg, respectively. Therefore, the direction of inclination and tilt angle can be determined from the shift of the interference spectra. A strongly linear response of the sensor is obtained from a tilt angle of around 5° to 75° by using the developed sensing structure. The advantages of the proposed sensor are its high direction-dependence, low cost, simplicity and ease of fabrication, in-line configuration, long-distance sensing and high sensitivity. The sensor has various potential applications, and can be further developed to improve its sensing capabilities with temperature-compensation. The proposed fiber-optic tilt sensor not only can measure the angles and directions of inclination but also can be used as an optical fiber level meter.

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