Fiber-Optic Inclinometer Based on Taper Michelson Interferometer

L. M. N. Amaral, O. Frazão, J. L. Santos, and A. B. Lobo Ribeiro

***Abstract*—A compact fiber-optic inclinometer based on a fiber-taper Michelson interferometric sensor is constructed and demonstrated. The sensor consist of a single symmetrically taper waist of 80 μm distanced 30 mm from the single-mode fiber end-tip right-angled cleaved. The amplitude of the bending angle of the fiber taper interferometer is obtained by passive interferometric interrogation based on the generation of two quadrature phase-shifted signals from two fiber Bragg gratings with different resonant wavelengths. Optical phase-to-bending sensitivity of $\sim$1.13 rad/degree and a bend angle resolution of $\sim$0.014 degree/$\sqrt{}$ Hz were achieved.**

***Index Terms*—Fiber Bragg gratings, fiber taper, inclinometer, modal sensor, tilt measurement.**

I. Introduction

FIBER-OPTIC interferometric sensors has been an attractive choice for high-resolution sensing devices, in particular, fiber-optic Fabry–Pérot interferometers due to their inherent miniaturization and point sensing capability [1]. Generally, this type of fiber interferometer is created with two fiber ends with an air-gap in between them (also known as low-finesse Fabry–Pérot cavity), whereas it is associated an optical transfer function close to that of a two-beam interferometer [2]. The particular physical quantity to be measured (that is, the measurand) acts on the optical path difference (OPD) of the interferometer cavity. To recover the interferometric phase signal that contains the measurand information, two types of approaches have been used. One of them, relies on the white-light interferometry concept (or low coherence interferometry), where the light returning from the low-finesse Fabry–Pérot cavity, which is illuminated by an optical source with a coherence length smaller than the cavity OPD, is processed by a second interferometer [3]. The other approach, conceptually more elegant than the first one, is based on the generation of two quadrature phase-shifted interferometric signals through the use of dual-wavelength illumination by two optical sources [4], or by two fiber Bragg gratings [5]. Although, low-finesse Fabry–Pérot cavities have been widely used to measure several physical parameters (such as, displacement, temperature, strain, acceleration, etc.), some engineering design constrains exist when one is interested to measure tilt angle (or rotation/bend angle) using this type of fiber cavity. Recently, a new concept to measure rotation angles based on a fiber-optic modal Mach–Zehnder interferometer by using a non-adiabatic taper cascaded with a long-period fiber grating (LPG) has been demonstrated [6]. This versatile fiber-modal interferometer has a low insertion loss and no optical core discontinuity (that is, a self-aligned cavity itself) when compared to the low-finesse Fabry–Pérot interferometer. Nevertheless, this combined taper-LPG cavity needs to have the LPG to create the Mach–Zehnder interferometer, which imposes some fabrication control effort, and it will only operate in transmission, which in some applications where the sensor needs to be remote, is not very practical. A more recent bending sensor approach [7] using a non-adiabatic taper concatenated with a tilted fiber Bragg grating (TFBG), has shown a measurement capability of bend angles up to 12° with an accuracy of $\pm 0.15°$. Although the dynamic range seems large, the sensor head fabrication complexity is still high and the signal processing relies on optical power measurement with an optical spectrum analyzer (OSA). This intensity-based approach has associated the problems of signal referencing and the use of an OSA, highly convenient in a lab environment, brings some limitations in field applications.

In this work, we propose a simpler sensor design for a fiber-modal interferometer by using a fiber taper-tip combination (4% reflection coefficient due to Fresnel reflection on glass-air interface), originating this way a fiber taper Michelson interferometer that is very easy to fabricate by the arc-discharge technique [8] and can be used in a reflective configuration, allowing remote interrogation. To demodulate the interferometric phase signal from this inclinometer sensor, we have used an optical passive generation of two quadrature phase-shifted signals from two fiber Bragg gratings, following an interrogation configuration that has been previously demonstrated by one of the authors [5].

II. Principle

The fiber-taper Michelson interferometer is formed between the coupling region created by the fiber taper, and the low reflectance mirror of the fiber-tip distal end (4% reflection coefficient due to Fresnel reflection on glass-air interface). The inset drawing of Fig. 1 shows schematically the interferometric sensor arrangement. The taper couples a fraction of the core light to the cladding modes, which both will propagate along the fiber interferometer cavity length, being then reflected back at the fiber glass-air interface. The fraction of the light that is

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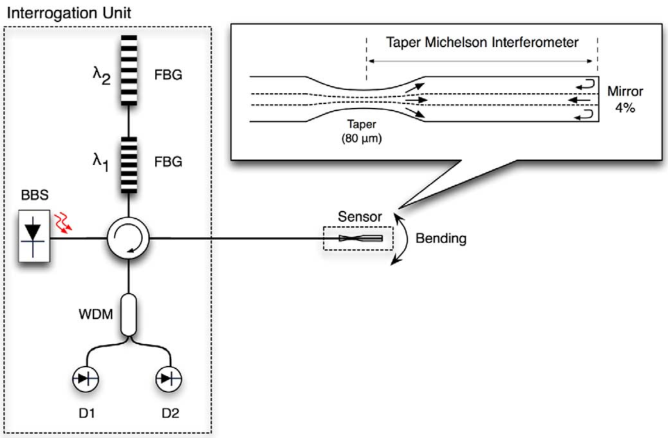

Fig. 1. Experimental setup for the optical interrogation of the proposed fiber inclinometer. Inset: schematic diagram detail of the fiber-taper Michelson interferometer.

coupled to the cladding depends on the length and waist of the fiber taper region. The optical interference between the back-reflected core and cladding propagation modes occur at the taper region originating a channeled spectrum. The interferometric phase of the light reflected from this fiber taper-tip Michelson cavity is a well-known function of wavelength. If two distinct wavelength discriminators with bandwidths narrower than the spectral response of fiber taper Michelson interferometer are used to optically process the back-reflected light, we can write the interferometric phase at each wavelength approximately as

$$\phi_j = \frac{4\pi \delta n_{\text{eff}} L}{\lambda_j} \tag{1}$$

where δn_{eff} is the effective refractive index difference between core and cladding modes of the fiber taper-tip Michelson cavity, L the cavity length, λ_j optical resonances of the two wavelength discriminators (with $j = 1, 2$). Thus, the relative phase between the two correspondent interferometric signals at two distinct wavelengths is given by

$$\Delta\phi = 4\pi \delta n_{\text{eff}} L \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right). \tag{2}$$

These two signals will be at quadrature when the wavelength separation between resonant wavelengths is an odd multiple of $\lambda^2/(8\delta n_{\text{eff}} L)$, where the approximation $\lambda_1 \approx \lambda_2 = \lambda$ was considered. This approximation is valid within 1% of error for cavity lengths higher than $\sim$20 μm. The output voltage signals at the two photodiodes (see Fig. 1), coupled to each output port of a WDM fiber coupler, measure independently the interferometric back-reflected light at each wavelength, and can be expressed by

$$\begin{cases} V_1 = G_1 \cdot [1 + \gamma_1 \cos\phi_1] \\ V_2 = G_2 \cdot [1 + \gamma_2 \cos(\phi_1 + \Delta\phi)] \end{cases} \tag{3}$$

where $G_{1,2}$ are constant voltages gains dependent on the optical power and gain in the detection electronics and $\gamma_{1,2}$ are the fringe visibilities at each wavelength. With proper gain adjustment (i.e., $\gamma_1 G_1 = \gamma_2 G_2$), the unambiguous interferometric phase recovery (that is, within the interval $-\pi$ to $+\pi$) can be obtained through one of the signals in (3) and by

$$\phi_1 = \tan^{-1}\left(\frac{V_2 - G_2}{V_1 - G_1}\right). \tag{4}$$

Due to the reason that the arctangent function signal is confined to the range of $\pm\pi/2$ (limiting the unambiguous measurement range), a simple phase unwrapping algorithm can be applied to solve this limitation, by adding or subtracting π to the extracted phase when it reaches $\pm\pi/2$ and changes abruptly in the amount of $\pm\pi$.

III. Experiment and Discussion

The schematic diagram of the experimental configuration is shown in Fig. 1. A broadband source (BBS), model FIBERAMP-BT 1400 from Photonetics, with central wavelength at $\sim$1550 nm and 100 mW average optical power was used to illuminate two FBG wavelength discriminators through a four-port optical circulator. The fiber-taper was fabricated in a Corning SMF-28 fiber by elongating it during a arc-discharge provided by a splicing machine (Fujikura's FSM-40S). The fabrication parameters were adjusted to reduce the fiber diameter of the SMF-28 from 125 to 80 μm in the taper waist. The length of the taper is $\sim$500 μm. The fused taper and the fiber tip-end are separate by a length of 30 mm. The insertion loss of these structures is typically 2–3 dB. The interferometric light signal reflected from the fiber-taper Michelson interferometer (sensor) was then coupled back through the same sensor port of the optical circulator. This back-reflected light is then spectral separated in each resonant wavelength by a WDM fiber coupler and monitored using two photodiodes (D1 and D2, model JDSU EPM5606). These signals were then acquired, demodulated, and processed using LabView™ software. As referred in the last section, the discriminator wavelengths must be properly selected to ensure that the relative optical phase between the signals is an odd multiple of $\pi/2$. In this experiment, the chosen resonant wavelengths were $\lambda_1 = 1554$ nm and $\lambda_2 = 1559$ nm ($\sim$0.2 nm bandwidth). Fine tuning was achieved by applying axial strain to one of the FBG, and both were kept in a temperature controlled environment inside the interrogation unit. Fig. 2(b) shows the spectral position of the two FBG discriminators before applying the strain for fine-tuning, and Fig. 2(c) shows the quadrature condition, after strain is applied. Fig. 2(a) shows the transmitted channeled spectrum response of the fiber-taper Michelson interferometer (i.e., the sensor). It can be observed that the response is not exactly of a two-beam interferometer, an indication that more than one cladding mode is excited by the taper structure. Our experience on these devices indicates that with fine tuning of the taper parameters (width and length) it is possible to achieve a condition very close to the co-sinusoidal situation, but in the present case the objective was to demonstrate the potential of this fiber device as an inclinometer, with optimizations to be considered later. Also, by fine adjustment of the taper diameter it is possible to tailor the sensitivity of the sensor head. The normalized output voltage signals obtained from the two photodetectors, D1 and D2 under the interferometric quadrature condition are represented in

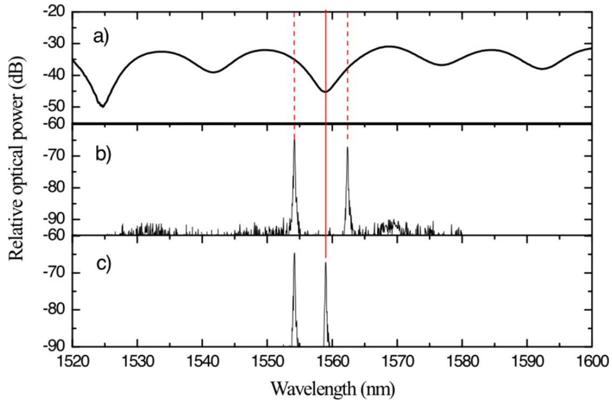

Fig. 2. Spectral responses of: (a) the fiber-taper Michelson interferometer and (b) the fiber Bragg gratings. (c) The spectral quadrature position.

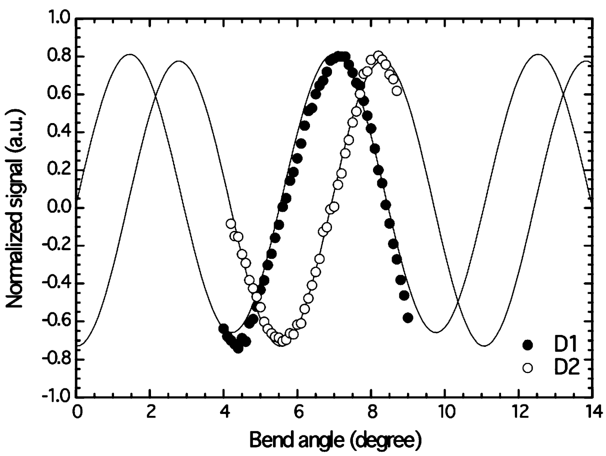

Fig. 3. Photodetected signals versus inclinometer bend angle (dots: experimental measurements, lines: fitting curve).

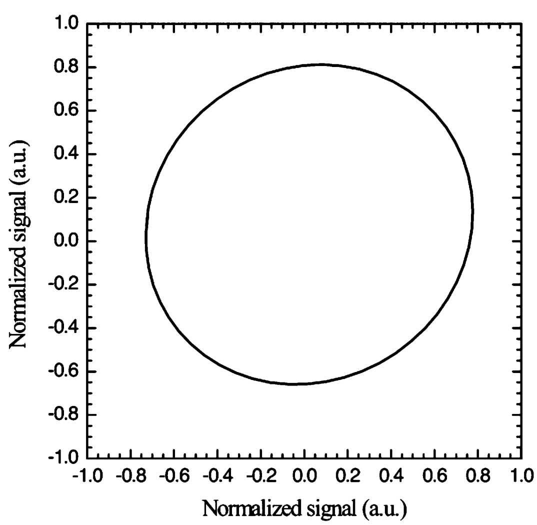

Fig. 4. X-Y signal representation of both photodetected signals (D_1—vertical axis and D_2—horizontal axis), illustrating the quadrature condition.

Fig. 3 for different values of bending angle of the fiber taper-tip cavity. Fig. 4 confirms the system is operating close to ideal quadrature condition in an exact two-beam interferometer.

The fiber-taper Michelson interferometer was applied to develop an inclinometer sensing head. The axis of rotation goes through the geometrical center of the taper. Therefore, when the angle measured from the straight position of the fiber changes, the curvature applied to the taper-tip cavity also changes due to the weight of the fiber after the taper, affecting the coupling of the core mode to the cladding modes. Thus, the OPD between the core and cladding modes alters, originating a phase shift of the modal interferometer, as shown in Fig. 5 for a bending angle between 0° and 7°. The figure at the bottom shows the interferometric phase after the phase unwrapping algorithm being applied. From this processed result, a sensitivity of ~1.13 rad/degree is obtained in the bending range between 4° and 7°. The small nonlinearity observed (~2%) was attributed to the mechanical relaxation of the translation rotating stage used to induce a signal variation on the inclinometer sensor, as well as to the deviation of the structure from an exact two-beam interferometer. It is interesting to note that the sensor bending angle sensitivity is quite low (~0.08 rad/degree) in the bending range between 0° and 4°. This behavior has also been observed by Shao *et al.* [7] and its explanation is not yet clear but it is a topic of ongoing research.

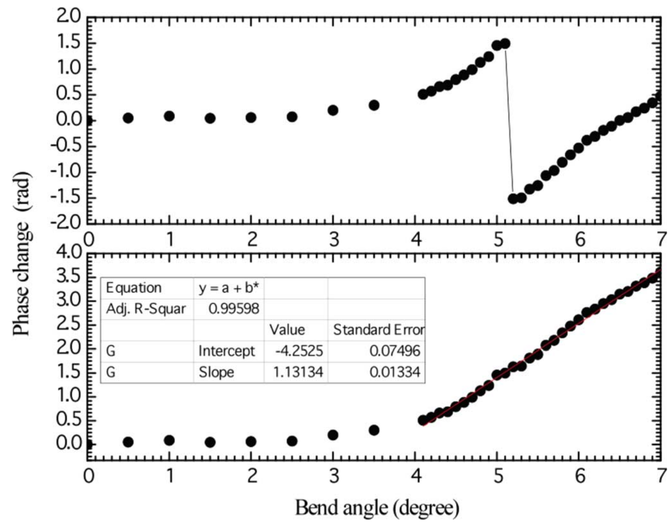

Fig. 5. Interferometric phase change versus inclinometer bend angle (on top), and the same result after the phase unwrapping algorithm (on bottom).

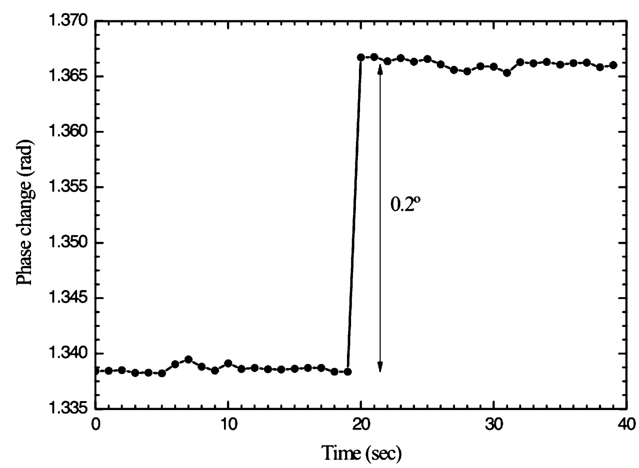

Fig. 6. Inclinometer sensor resolution (measurement bandwidth: 1 Hz).

Fig. 6 illustrates the system response for a small step variation of the rotation angle of ~0.2° when the sensor is operating in the high sensitivity region. The associated interferometric phase shift is ~ 0.028 rad and the observed RMS fluctuation is ~ 1 mrad. Taking into consideration the experimental detection bandwidth used (~ 1 Hz), it turns out a c-ystem static phase resolution of ~ 14 mrad/$\sqrt{}$ Hz. This result represents an accuracy on the angle measurement of about ~ 0.014 degree/$\sqrt{}$ Hz, which means more than ten times improvement over the inclinometer sensor reported recently by other authors [7]. These results indicate the potential of this interferometric structure to rotation sensing, in the case applied to achieve inclinometer functionality.

There is a large room for further studies and optimizations for the sensing configuration proposed in this work For example, for bending angles up to 4° from the vertical position, the sensitivity factor is smaller, as one can see from the results of Fig. 5. One possibility to increase this low sensitivity is to reduce the taper diameter. Also, the dynamic range being limited up to 7° was due to mechanical difficulties of the translation rotation stage used in the experiment, and therefore it is not a fundamental limitation of this sensing structure. Additionally, it should be pointed out that no temperature measurements were done with this device in view of the primary objective looked for which was the demonstration of the concept of an intrinsically simple fiber-optic interferometric configuration for high sensitivity bend measurement. However, it is possible to estimate its temperature sensitivity as ~ 2.3 rad/°C, based on the wavelength-shift dependence on temperature of about 10 pm/°C, which is typical for the sensors based on this taper fiber device [9]. This result means that the proposed inclinometer sensor must have a temperature compensation scheme in order to be used in real field applications. This can be achieved in different ways, one of them being the insertion of a FBG with wavelength λ_3 just before the fiber taper and with its temperature induced wavelength shift monitored by a dynamically matched FBG located in the optoelectronics processing unit. As a final note, the required fiber taper characteristics (width and length) to achieve the best performance as a two-beam interferometer, which shall optimize the operation of the quadrature phase demodulation technique, are being investigated. This development, together with the increase of the signal power level through silvering of the fiber tip of the sensing head, indicate the feasibility to substantially improve the measurand resolution already reported in this work.

IV. Conclusion

To summarize, in this work a compact inclinometer sensor based on a fiber-taper Michelson interferometer was presented. The proposed sensor head was interrogated with a passive interferometric demodulation scheme based on the generation of two quadrature phase-shifted signals from two fiber Bragg gratings. The concept was tested on the measurement of a rotation/bending angle of the fiber taper-tip cavity, being achieved a static phase resolution of ~ 14 mrad/$\sqrt{}$ Hz, from where results a bend angle resolution of ~ 0.014 degree/$\sqrt{}$ Hz.

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