# Optical inclinometer based on fibre-taper-modal Michelson interferometer

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## ABSTRACT

An inclinometer sensor based on optical fibre-taper-modal Michelson interferometer is demonstrated. The magnitude of the tilt (bending angle of the fibre taper interferometer) is obtained by passive interferometric interrogation based on the generation of two quadrature phase-shifted signals from two fibre Bragg gratings. Optical phase-to-rotation sensitivity of 1.13 rad/degree with a 14 mrad/√Hz resolution is achieved.

**Keywords:** Modal sensor, taper, fibre Bragg gratings, tilt measurement.

## 1. INTRODUCTION

All fibre interferometric sensors has always been an attractive choice for high resolution sensing devices, in particular, fibre optic extrinsic Fabry-Pérot interferometers due to their inherent miniaturization and localized sensing capability [1]. In general, this Fabry-Pérot interferometer is created with two fibre ends with an air-gap in between them (also known as low-finesse Fabry-Pérot cavity), whereas it's 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's contains the measurand information, two types of approach have been generally used. One of them relies on the white-light 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 quadrature phase-shifted interferometric signals trough the use of dual-wavelength illumination by two sources [4], or by two fibre Bragg gratings [5]. Although, the low-finesse Fabry-Pérot cavities have been widely used to measure physical parameters, such as, displacement, temperature, strain, acceleration, etc., some engineering design constrains, such as cavity alignment, exist when one is interested to measure tilt angle (or rotation/bend angle) using this type of cavity. Recently, a new concept to measure rotation angles based on a fibre-optic modal Mach-Zehnder interferometer by using a non-adiabatic taper cascaded with a long-period fibre grating (LPG) has been demonstrated [6]. This versatile fibre-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 also, will only operate in transmission which, in some applications where the sensor needs to be remote, is not very practical.

In this work, we propose a simpler sensor design for a fibre-modal interferometer by using a fibre taper-tip combination (4% reflection coefficient due to Fresnel reflection on glass-air interface) originating this way a fibre-taper-modal Michelson interferometer, which is very easy to fabricate by arc-discharge technique [7] and it can be used on a reflection configuration allowing remote interrogation. To extract the interferometric phase signal from this inclinometer sensor, we used a passive generation of two quadrature phase-shifted signals from two fibre Bragg gratings, following an interrogation configuration that has been previously demonstrated by one of the authors [5].

## 2. PRINCIPLE

The fibre-taper-modal Michelson interferometer is formed between the coupling region created by the fibre-taper region and the fibre-tip distal end, working as low reflectance mirror (4% reflection coefficient due to Fresnel reflection on

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glass-air interface), as schematically shown in the inset drawing of Fig.1. The taper couples a fraction of the core light to the cladding modes which both propagate through the fibre cavity length to the fibre glass-air interface, that reflects back this cladding and core modes which will interfere at the taper region. The interferometric phase of the light reflected from this fibre taper-tip Michelson cavity is a well known function of wavelength. If two distinct wavelength discriminators with bandwidths narrower than the spectral response of fibre-taper-modal Michelson interferometer are used to optically process the back-reflected light, we can write the interferometric phase at each wavelength as

$$\phi_j = \frac{4\pi nL}{\lambda_j} \tag{1}$$

where $n$ is the effective refractive index of the fibre taper-tip Michelson cavity, $L$ if the cavity length, $\lambda_j$ optical resonances of the two wavelength discriminators (with $j$=1,2). Thus, the relative phase between the two correspondent interferometric signals is given by

$$\Delta\phi = 4\pi nL\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \tag{2}$$

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

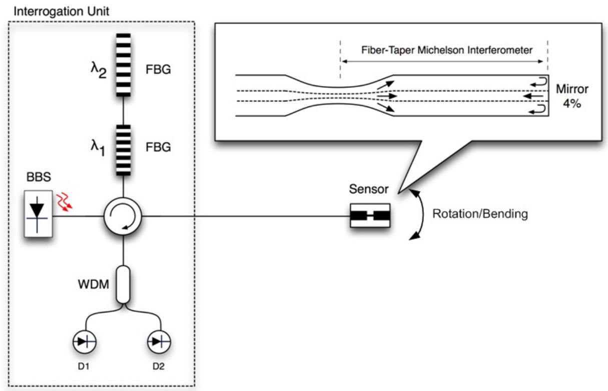
$$\begin{cases} V_1 = G_1 \cdot \left[1 + \gamma_1 \cos\phi_1\right] \\ V_2 = G_2 \cdot \left[1 + \gamma_2 \cos(\phi_1 + \Delta\phi)\right] \end{cases} \tag{3}$$

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 visibility at each wavelength. With proper gain adjustment (i.e., $\gamma_1 G_1 = \gamma_2 G_2$), the unambiguous interferometric phase ($-\pi$ to $+\pi$) recovery can be obtained through one of the signals in (3) and by:

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

## 3. EXPERIMENT AND DISCUSSION

The schematic diagram of the experimental configuration is shown in Fig. 1. A broadband source (BBS) with central wavelength at ~1550 nm and 100 mW average optical power was used to illuminate two FBG wavelength discriminators through a 4-port optical circulator. The fibre-taper was fabricated in a Corning SMF-28 fibre by elongating it during the arc discharge provided by a splicing machine. The fabrication parameters were adjusted to reduce the fibre diameter from 125 µm to 80 µm in the taper waist. The fused taper and the fibre 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 fibre-taper-modal 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 fibre coupler and monitored using two photodiodes (D1 and D2). These signals were then acquired and processed using LabView™ software. As referred on 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 (~0.2 nm bandwidth). Fine tuning was achieved by applying axial strain to one of the FBG. Figure 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.



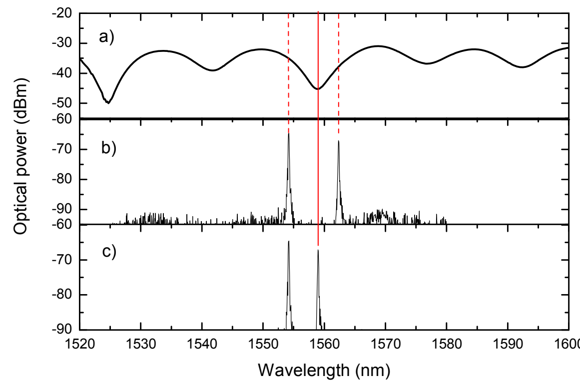




Figure 1. Experimental set-up for the optical interrogation of the proposed fibre inclinometer. Inset: schematic diagram detail of the fibre-taper-modal Michelson interferometer.

Figure 2 Spectral responses of (a) the fibre-taper-modal Michelson interferometer, and (b) the fibre Bragg gratings. (c) The spectral quadrature position.

Fig. 2 shows the spectrum response of the fibre-taper-modal Michelson interferometer (that is, 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 depth) 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 fibre device as an inclinometer, with optimizations to be considered later. Fig 2 also shows the two FBG spectral resonance signals, indicating a $\pi/2$ phase difference between the two interferometric signals. The normalized output voltages signals obtained from the two photodetectors, D1 and D2 (see Fig. 1), in this quadrature position are represented in Fig. 3(a) for different values of bending angle of the fibre taper-tip cavity. Figure 3(b) confirms the system is operating close to the ideal quadrature condition in an exact two-beam interferometer.

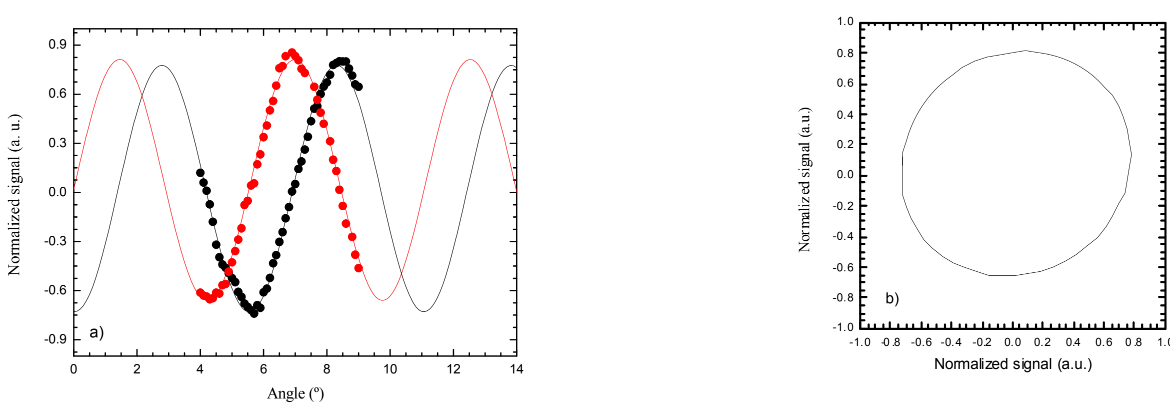



Figure 3 (a) Photodetected signals versus inclinometer bend angle (dots: experimental measurements, lines: fitting curve), and (b) *x-y* signal representation illustrating the quadrature condition.

The fibre-taper-modal Michelson interferometer was applied to develop an inclinometer sensing head. The axis of rotation goes through the geometrical centre of the taper. Therefore, when the angle measured from the straight position of the fibre changes, the curvature applied to the taper-tip cavity also changes due to the weight of the fibre 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. 4 for a rotation angle between 4 and 7 degrees ( From this result, a sensitivity of 1.13 rad/degree is obtained. 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. Fig. 5 illustrates the system response for a step variation of the rotation angle of ~0.2 degree. The associated interferometric phase shift is ~0.028 rad and an *RMS* fluctuation is ~1 mrad. Taking into consideration the experimental detection bandwidth (~1 Hz), it turns out a system static rotation resolution of ~14 mrad/√Hz.

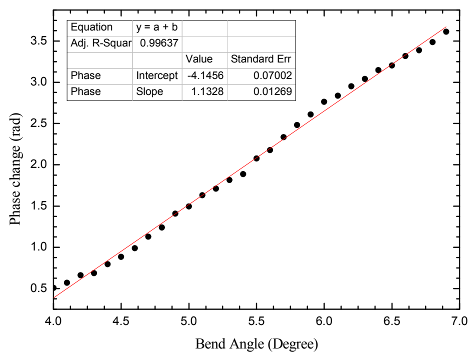



Figure 4 Interferometric phase change versus inclinometer rotation angle.

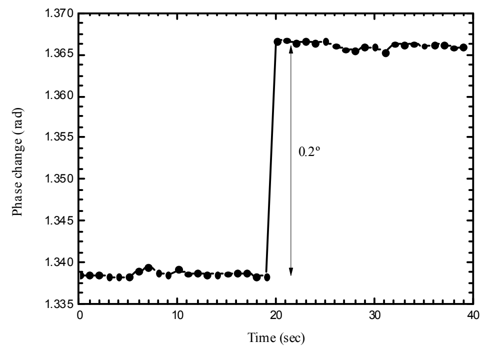



Figure 5 Inclinometer sensor resolution (measurement bandwidth: 1 Hz).

These results indicate the potential of this interferometric structure to rotation sensing, in the case applied to achieve an inclinometer functionality. Certainly, there is large room for further studies and optimizations. For example, we noticied that for rotation angles up to 3 degrees from the vertical position, the sensitivity factor is smaller than the one derived from Fig. 4. The reasons for that are being investigated, as well as the required taper characteristics to achieve the best performance as a two-beam interferometer, which shall optimize the operation of the quadrature phase demodulation technique. This development, together with the increase of the signal power level through silvering of the fibre tip of the sensing head, indicate the feasibility to substantially improve the measurand resolution already reported in this work.

## 4. CONCLUSION

To summarize, in this work a new inclinometer sensor based on a fibre-taper-modal 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 fibre Bragg gratings. The concept was tested on the measurement of a rotation/bending angle of the fibre taper-tip cavity, being achieved a static rotation resolution of ~14 mrad/√Hz.

## 5. REFERENCES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