Fibre Optic Inclinometer Based on the Combination of a Long-Period Grating and a Fused Taper

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Abstract: A new approach for a fibre optic modal Mach-Zehnder interferometer based on the combination of a fibre taper cascaded with a fibre LPG is presented. It is also demonstrated that such a structure can be applied for the implementation of a fibre optic inclinometer sensor.

OCIS codes: (050.2770) Gratings; (060.2340) Fibre optics components; (060.2400) Fibre properties

1. Introduction

A long-period fibre grating (LPG) is an optical device that couples the forward-propagating guided mode to forward-propagating cladding modes of a single-mode optical fibre, leaving in the transmission spectrum a set of attenuation bands [1]. This forward coupling is obtained by a periodic refractive index modulation along the core of the optical fibre. These devices turned out to be very valuable in both optical communication and fibre sensing. In this last field, they prove to be effective sensing elements of different measurands, such as temperature, strain, transverse load, curvature, pressure, refractive index, etc., [2].

LPGs can also be used to implement versatile fibre modal interferometers with enhanced parameter sensitivity. This is done cascading two equal LPGs with a fibre length separation between them, resulting in a single-fibre Mach-Zehnder configuration [3-5]. The first long-period grating couples part of the light to the cladding modes, where the light propagates down the fibre with an effective refractive index smaller than the one experienced by the remaining light that keeps propagating in the core. In this way, a differential optical-path length is accumulated between these two light waves. At the second LPG, the same fraction of the core light couples in the same cladding modes and it is lost after a propagation length much larger that the separation between the two LPGs; reciprocally, a certain amount of the light that was propagating in the cladding mode is coupled back into the core. Therefore, after the second LPG, two optical waves with a differential optical path delay propagates in the fibre core, resulting into an interference pattern that has the well-known channelled spectrum structure if broadband light is injected into the input fibre.

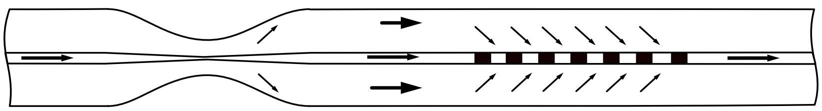
To have an interference pattern with good visibility it is required to combine two identical LPGs with a peak loss near 3 dB. However, the necessity of two identical LPGs can be avoided when a reflective configuration is considered. After light goes through the LPG and travels towards the mirror in the core and in the cladding modes, the reflection retraces their paths towards the same LPG. After it, the modes with a differential path length interfere in the core and an interference pattern is formed which can be analyzed with a suitable instrument. This fibre mode Michelson interferometer was explored by Lee and Nishii to implement a temperature sensor [6] and by Swart aiming refractive index measurements [7].

There are situations where it is necessary to operate in transmission and to keep the requirement of using a single LPG. With such objective, Dong *et al* reported a configuration where the coupling of the light from the core mode to the cladding modes is obtained through a misaligned splicing point [8]. This technique is globally effective but it would be desirable to have an alternative configuration without a core discontinuity and, therefore, with potential for an intrinsically smaller insertion loss.

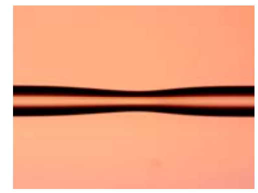
In this work we propose a new approach for a fibre optic modal Mach-Zehnder configuration with a single LPG. It is based on the fabrication of a taper that couples a fraction of the core light to the cladding modes, and a LPG, placed some distance after the taper, which re-couples the cladding modes into the fibre core. This concept is experimentally validated and applied to the implementation of a fibre optic inclinometer sensor.

2. Experimental results

The fibre optic modal interferometer explored in this work is schematically represented in Figure 1(a). It is constituted by a fibre taper, a length of fibre and a LPG. The non-adiabatic taper was fabricated in Corning SMF-28 fibre using a splicing machine combined with fibre elongation during the arc discharge. The fabrication parameters were adjusted in order to decrease the fibre diameter from 125 μm to 80 μm in the taper waist. The total length of this structure, shown in the Figure 1(b), was ~ 500 μm, and the insertion loss was ~ 1 dB. The effect of the optical taper is to expand the core field and to couple some light into the cladding modes which propagates down the fibre until a LPG located afterwards.



(a)



(b)

Figure 1. (a) Optical fibre modal interferometer based on a LPG combined with a fused taper and (b) photograph of the optical taper.

The LPG was written in the same type of fibre using the electric-arc technique described by Rego *et al* [9]. The fabrication process consists in placing an uncoated fibre between the electrodes of a fusion splice machine. One end of the fibre is clamped in a holder on top of a motorized translation stage controlled with a precision of 0.1 μm. At the other end a weight is attached to keep the fibre under a constant load, introducing therefore an axial tension. An arc discharge is then produced with a suitable electric current and duration time, exposing a short length of the fibre. After the discharge, the translation stage (computer controlled) displaces de fibre several times (N) by a distance that represents the grating period (Λ), until a required attenuation loss-peak is obtained. The LPG used in this experiment had the following fabrication parameters: weight = 5.1 g; period = 540 μm; electric current = 9 mA; arc duration = 1 s; N = 40. The resulting grating spectrum is centred at 1565 nm and has a peak transmission loss of 1.5 dB. The separation between the fused taper to the centre of the LPG is ≈ 80 mm.

Figure 2 shows the spectral response of the LPG before and after the fabrication of the optical taper. The presence of the channelled LPG spectrum is a clear indication that the taper couples light to cladding modes and that part of it is re-coupled again to the core by the LPG. The channelled spectrum, with a fringe periodicity of ≈ 12 nm, results from the interference of this light with the fraction that always propagated in the core. The fringe periodicity, together with the length of the fibre interferometer (≈ 80 mm), indicates a refractive index difference between the core and the cladding mode under concern of $\approx 2.54 \times 10^{-3}$.

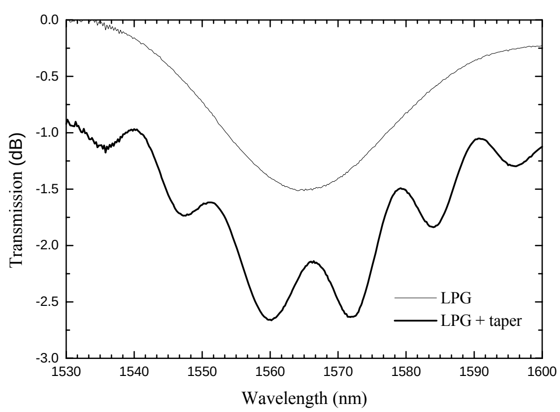


Figure 2. Output spectrum in the region of the LPG resonance before and after the fabrication of the fused taper.

This fibre modal interferometric configuration was applied to the implementation of an inclinometer sensing head, shown in Figure 3. As can be seen form this figure, the axis of rotation goes through the centre of the taper.

Therefore, when the shown angle α changes, the curvature applied to the taper also changes, which modifies the coupling of the core light to the cladding. The fibre after the taper is placed inside a capillary tube in order to assure that the fibre is kept straight for any value of α. In the experiment performed the angle was varied in the range between +10 and – 10 degrees.

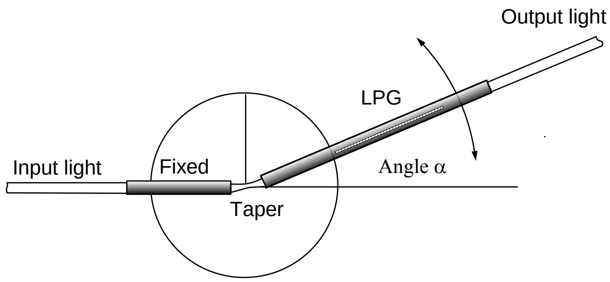


Figure 3. Structure of the proposed inclinometer sensing head.

The variation of α had no effect on the phase of the fibre interferometer. This was experimentally verified by the fact that the interferometric fringes in Figure 3 did not move in wavelength when the angle changed. This result was expected since the applied angles do no change the optical path length. However, the same does not happen when the rotation axis is slightly shifted relatively to the taper waist, as will be shown later.

Figure 4 shows the sensor response when positive and negative angles are applied to the proposed inclinometer sensing head. As can be seen, when the taper rotation increases, the coupling between the core mode and the cladding modes increases, resulting into larger amplitudes to the interferometric fringes, i.e., the interferometric fringe visibility increases and this behaviour is approximately symmetric relatively to the orientation of the rotation. Therefore, this configuration can only measure the absolute value of the rotation angle. Two aspects need to be addressed here: (i) with proper calibration, the non-linearity of the observed visibility versus rotation angle is not of too much concern; (ii) the fringe visibility is an absolute parameter, i.e., there is no need for any type of referentiation, which does not occur if other possibilities are considered (for example, removing the LPG and simply monitor the optical power propagating in the fibre core after the taper as a function of the rotation angle). This is an interesting and important feature of this sensing structure.

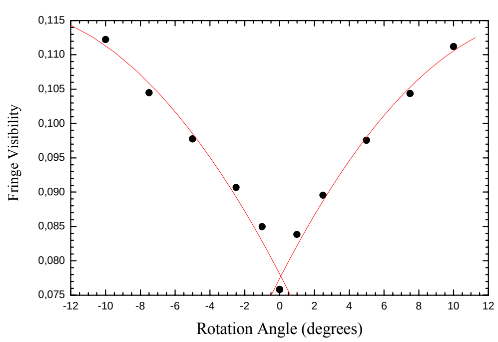


Figure 4. Fringe visibility of the fibre interferometer versus rotation angle.

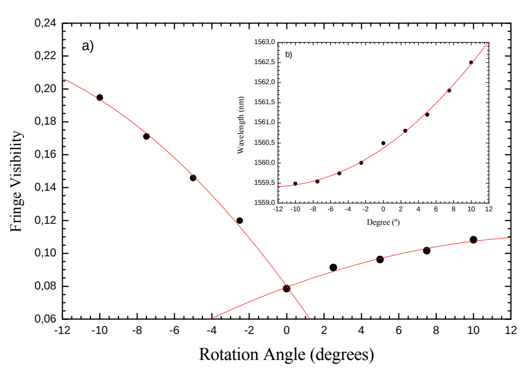


Figure 5. Visibility of the fibre modal interferometer versus rotation angle with a certain length of fibre not protected by the capillary tube (inset: variation of the peak wavelength of the interferogram central fringe).

The results given in Figure 4 are a particular case of the general one showed on Figure 5. In fact, the taper fabrication with the electric arc technique introduces a certain degree of azimutal variation of the fibre radius in the taper waist. As a consequence, there are different slopes for the variation of the fibre interferometer visibility with positive and negative rotation angles. The symmetric results shown in Figure 4 are indeed an exception, and they come from a particular orientation of the elliptical cross section of the fibre in the taper waist relatively to the rotation plane. Figure 5 illustrates the type of results that are obtained in general, where the asymmetry for clockwise and anti-clockwise rotation is evident.

It was mentioned before that the rotation angle did not introduce a phase variation in the fibre modal interferometer. This happens because the capillary tube that protects the fibre in the interferometer length extends up to the taper waist, which means all curvature associated with a particular rotation angle appears in that region. The situation would be different if the capillary tube is moved slightly away from the taper along the interferometer length (displacement to the right in Figure 3). In that case, to a certain extent, the curvature will also appear in the unprotected length of fibre, introducing a differential delay in the fibre interferometer that will be a function of the rotation angle. If the orientation of the elliptical cross section of the fibre in the taper waist relatively to the rotation plane is properly chosen, it shall be possible in principle to have a monotonic variation of the interferometer phase with the rotation angle within a certain interval (with positive and negative values). The inset in Figure 5 illustrates this possibility, showing the monotonic variation with the rotation angle in the interval [+10, – 10] degrees of the peak wavelength of the interferometric fringe in the central region of the LPG spectral resonance (the 3 nm variation of the channelled spectrum in this rotation range corresponds to an interferometric phase variation of ≈ 90 degrees; the two graphs in Figure 5 were obtained under the same experimental conditions, corresponding to an unprotected length of the fibre interferometer of ≈ 5 mm).

These results indicate that it is possible with the sensing configuration shown in Figure 3 to measure, not only the magnitude of the rotation angle, but also its sign. This can be done either from the measurement of the interferometer phase or from the measurement of the interferometer visibility, situation in which it is also required some additional information to overcome the sign ambiguity. The approach selected will essentially depend on the particular application under concern.

3. Conclusion

To summarize, in this work it was presented a novel concept to implement a fibre modal interferometer based on the combination of a fused taper and a long period grating. It was demonstrated that this structure can be effectively applied to measurement of rotation angle magnitude, being also possible in certain conditions to obtain information about the rotation sign.

4. References

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