Modal interferometer based on a single non-adiabatic fibre taper

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ABSTRACT

In this work it is presented a novel in-fibre modal interferometer based on a non-adiabatic biconical fused taper that couples light between the cladding and the core, combined with the Fresnel reflection at the fibre end. It is observed that the returned light from this fibre structure shows a channelled spectrum similar to that of a two-wave Michelson interferometer. The application of this device as a fibre optic flowmeter sensor is demonstrated.

Keywords: Fibre taper, modal interferometer, flowmeter.

INTRODUCTION

Fibre optic interferometric structures have been largely explored in sensing due to the high sensitivities that they exhibit on the measurement of a broad range of parameters[1]. Independently of their alternative topological configurations – Michelson, Mach-Zehnder, Fabry-Perot, Sagnac, etc. –, different implementations have been considered aiming to optimize the device performance for a particular set of measurands. The group of modal interferometers where the interferometric phase difference is built up considering the difference in the effective refractive index of different fibre modes has been widely researched in the context of environmental sensing, curvature sensing and others. These structures are attractive for several reasons, including small size and deployment flexibility, as well as the presence of a reduced thermal sensitivity in view of the usually small difference of the thermo-optic coefficients of the fibre modes under concern[2].

The most common modal interferometric structure is the two-wave Mach-Zehnder interferometer, where the reference path is along the fibre core and the sensing path is associated to a specific cladding mode excited by a long-period grating (LPG), with the interference induced by the recombination action of a second equal LPG placed some distance down the fibre[3]. It is also possible to have an LPG-assisted fibre modal interferometer in a Michelson configuration, by forcing the light to cross the same LPG twice by mirroring the fibre end some distance after the grating[4]. In general, this reflection approach is favourable considering it is simpler, shows increased sensitivity for similar fibre length, and also in view of its better adequacy to sensor multiplexing in many situations.

It would be advantageous to have a modal fibre interferometer with the coupling to the cladding of a fraction of the core light performed by a structure easier to fabricate than a LPG. It was reported recently that in a LPG-assisted Mach-Zehnder modal fibre interferometer, the first LPG can be replaced by a short non-adiabatic taper readily fabricated using a splice machine[5]. It was also published recently results on a fibre modal interferometer where the second LPG is replaced by a mirror, resulting in a Michelson configuration with the taper coupling light between the input standard singlemode fibre and a length of a two-core fibre which defines the sensing region[6]. In this work it is demonstrated that it is possible to achieve a reflective type modal interferometer with a single taper in standard singlemode fibre, having this interferometer a transfer function close to that of a Michelson. This sensing structure is then used to implement an optical flowmeter.

EXPERIMENTAL

The geometry of the sensing head is shown in Figure 1. The non-adiabatic taper was fabricated in Corning SMF-28 fibre using a splice machine combined with fibre elongation during the arc discharge. The fabrication parameters were adjusted in order to decrease the fibre diameter from 125 μm down to 80 μm in the taper waist. The total length of the taper and the maximum insertion loss were ~ 500 μm and 3 dB, respectively.

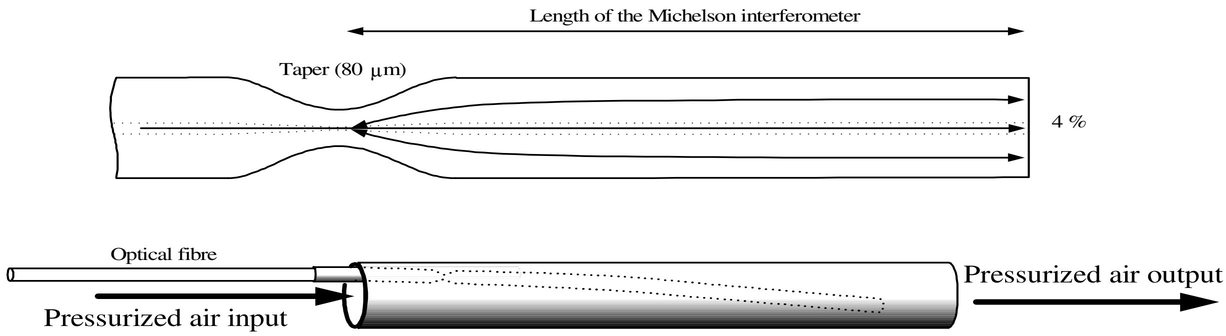

Figure 1. Geometry of the Michelson modal interferometer and the optical flowmeter design.

The fibre length after the taper is L≈100 mm and the reflection at the fibre end is that of an air-glass interface (~ 4%). The effect of the optical taper is to expand the core mode field and to couple light into the cladding modes, which propagates till the end of the fibre. The fraction of the light that is coupled to the cladding depends on the taper length and depth, and in the present case these parameters were chosen to have a high fringe visibility in the interferometric structure. The fraction of the light that is reflected back at the fibre end goes again through the taper, which induces a recombination effect originating interference between light coming from the core and the cladding regions in the sensing length. Due to the difference in the effective refractive indexes, the interfering waves accumulate an optical path difference of ~290μm, a value determined from the tuning of the receiver interferometer as described below. This value is substantially larger than the coherence length of the used optical source, which is a superluminescent diode emitting at 1320 nm with a spectral width of ~ 35 nm, resulting in L_c≈33 μm.
As shown in Figure 2, the returned light is injected into a receiver Michelson interferometer with an open air path in one of the arms, which is used to match the optical path difference of the sensing modal interferometer. In this way coherence addressing is performed and an interferometric signal appears at the input of the photodetector[7]. Applying a sawtooth waveform with proper amplitude to a PZT fibre stretcher in one arm of the receiving interferometer, an electric carrier can be obtained through electrical filtering, being its phase a replica of the phase of the tandem interferometric system[8]. This phase is then measured using a lock-in amplifier.

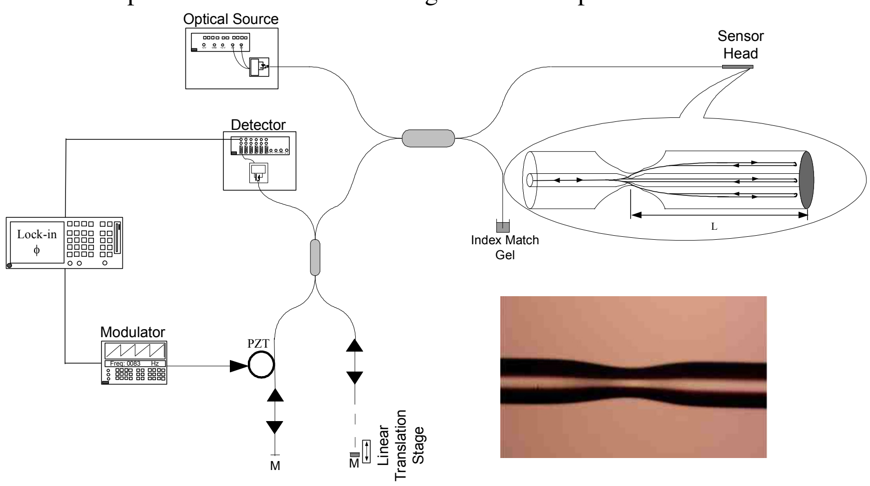

Figure 2. Sensing system set-up (inset: photo of the fibre taper).

Figure 3 shows the reflected power spectrum for the taper-assisted interferometer at the input of the receiving interferometer. Some important features can be drawn from this result. First, besides the presence of some fine structure in the spectrum, an indication of some degree of multiple-wave interference, it shows essentially the typical channeled spectrum pattern corresponding to a two-wave interferometer. Therefore, the recombination at the taper after reflection at the fibre end involves essentially the light from the core mode and from one of the cladding modes. Indeed, from the spectral periodicity of the fringes in Figure 3 (~6 nm) and the length of the sensing fibre (100 mm), it turns out that n_{core} -$n_{cladding}$ ≈ 1.45×10^{-3}, which means that the interference is mostly between the LP_{01} core mode and the LP_{02} cladding mode. Also, the visibility of the interferometric fringes reaches 75%, which shows the effectiveness of the short non-adiabatic taper to induce interference. Finally, the level of reflected power could be increased substantially by mirroring the end of the sensing fibre to reach a power reflectivity close to 100%.

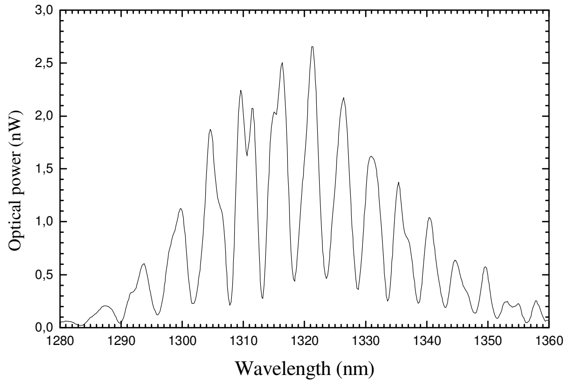

Figure 3. Reflected power spectrum from the taper-assisted modal interferometer.

It was further observed that the interferometric phase is highly sensitive to the bending in the taper region. Indeed, even the own weight of the fibre after the taper induces a change in the interferometric phase of the order of 150 deg, This structure can therefore be used as an highly sensitive bend sensor. In this work we decided to take advantage of this characteristic to build up a fibre optic flowmeter. The concept is illustrated in Figure 1. With the geometry shown, without flow of air the sensing device is under maximum bend due to fibre weight. This bend is reduced when the flow increases, or equivalently, with the increase of the input pressure. Therefore, the interferometric phase shall have a dependence on this pressure (compressed air in the range 0.5-3.0 bar), which is confirmed by the data shown in Figure 4, where it is clear a linear relation between the two parameters (slope of 69.8 degrees/bar, with a maximum error of ~3 %).

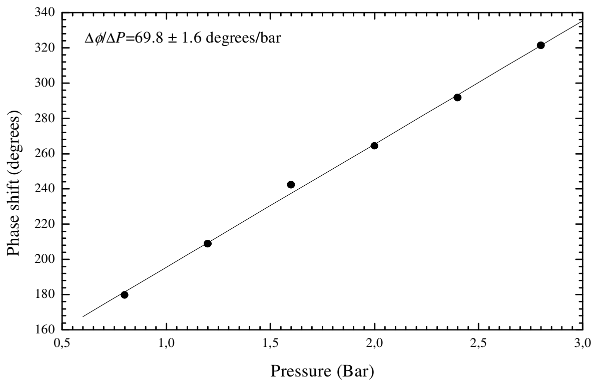

Figure 4. Interferometer phase change versus input pressure for configuration in Figure 1.

To characterize the optical flowmeter it is necessary to have calibration data between the input pressure, *P*, and the air flow. This was obtained using a conventional flowmeter which provided the following relation: *flow velocity in* (*ml/min*) = $-7845.8+12198.3\,P-1606.6\,P^2$, with P (Pressure) in bar (inset of Figure 5). With this information and the data of Figure 4, it is possible to have a relation between optical phase variation and flow velocity, which is given in Figure 5.

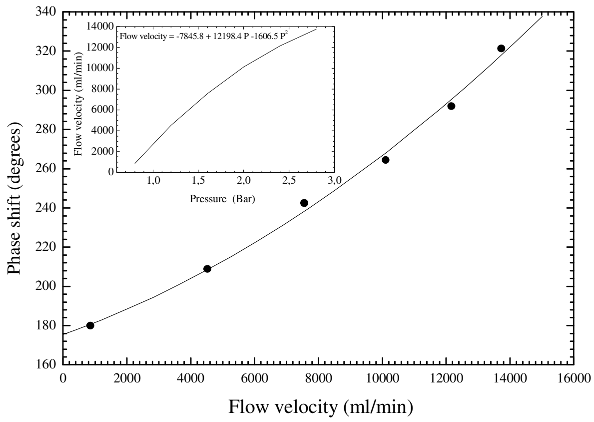

Figure 5. Interferometer phase change versus flow velocity (inset figure: calibration curve between input pressure and flow velocity).

CONCLUSIONS

It this work it was demonstrated a compact interferometric modal structure based on a length of singlemode optical fibre that includes a short-length non-adiabatic fused taper, combined with the Fresnel reflection at the fibre end. It was shown that the interferometric fringes have high visibility and the corresponding device transfer function is close to that of a two-beam Michelson interferometer. The modal interferometer was address ed in coherence with a matched receiving interferometer, and the phase reading was performed using pseudo-heterodyne technique. This type of modal interferometer is very simple to build, and has the potential for high sensitive measurement of a large range of parameters. In particular, it was demonstrated its application as a flowmeter.

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