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Multicore microstructured optical fibre for sensing applications

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ABSTRACT

In this contribution we present the sensing capabilities of a novel N-path Mach–Zehnder interferometer (MZI) that relies on a multicore microstructured optical fibre (MC-MOF) connected between two sections of standard single mode fibre. The modal properties of the MC-MOF structure are analysed experimentally by measuring near field profiles. The dependence of the N-path MC-MOF MZI sensitivity on temperature, tensile strain and bending is investigated. The results suggest that such an interferometer is a good candidate for a tensile strain or bending sensor.

1. Introduction

Optical fibre sensors belong to the most intensively studied subjects in photonics in recent years. The reason for this is that they can find many applications in biological, chemical and environmental industries. Furthermore, optical fibre sensors have many advantages, which include electromagnetic immunity, high sensitivity and simple and robust construction [1–3]. One of the most widely used types of optical fibre sensors is all-fibre Mach–Zehnder interferometers (MZIs) [1–4]. This is because connecting an all-fibre MZI with other optical fibre components is a simple and straightforward task. The operating principle of this device in essence consists in measuring the phase shift between two or more optical arms. The factors that change the phase shift can be related to some useful measurands like the mechanical strain, pressure, elongation, bending or temperature. In the literature a number of all-fibre MZI designs can be found. A specific type of the MZI is an in-line MZI whereby all interferometer arms are integrated into one optical fibre. For example in-line configurations can exploit twin core fibres [5,6], air hole collapsing of microstructured optical fibre (MOF) [7,8], core mismatch [9,10], a multimode fibre segment [11] or fibre tapering [4]. These configurations exhibit good performance when sensing strain, temperature and bending. Furthermore, in-line fibre MZIs are simple, cost effective and easy to assemble. These features are essential for the practical application of the MZIs.

Recently in the literature the realisation of novel types of in-line MZI, based on multicore fibres, has been reported by several research groups [12–15]. The multi-core microstructured optical fibre (MC-MOF) MZI acts as an N-path interferometer. It has been proven that multi-path interferometers have enhanced sensitivity when compared with conventional two path interferometers [16]. However, this is a very new topic and one which in our opinion has not been fully addressed in the literature. A bending sensor that utilises a seven-core MOF has been recently proposed in [15]. These authors used a lateral offset of the coupling fibres to invoke interference between two supermodes having different effective refractive index. In contrast, in this contribution we analyse the modal properties of MC-MOF using an experimental approach. Furthermore, results presented in the literature shows that in order to obtain equal intensity distribution in each core the careful optimisation of the multicore fibre structure is needed [17,18]. We have shown that we were able to achieve the equal intensity distribution for our MC-MOF by coupled the light with a SMF-28.

In this paper experimentally investigate the sensing properties of an N-path interferometer based on a multicore silica-based microstructured optical fibre. We also analyse the modal properties of the MC-MOF using an experimental approach. Whilst our fabricated MC-MOF waveguide structure is similar to the structure presented in [15], our waveguide lattice parameters are significantly different from the ones reported in [15]. In the present paper the N-path MZI was realized by inserting a section of a MC-MOF between two sections of a standard single mode fibre (SMF-28). Sensing capabilities for the temperature, tensile strain and bending of the MC-MOF were characterised. Unlike [15], we do not

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offset the coupling fibres; this simplifies the setup. The results obtained show that the proposed N-path MC-MOF MZI can provide good sensitivity for measurement of tensile strain or bending, with the benefit of low sensitivity to operating temperature. It retains the additional benefit of compactness that in-line MZIs offers over conventional MZIs.

The results are presented as follows: in Section 2 the procedures used for the fabrication and initial characterisation of the MC-MOF are described. Section 3 presents the experimental evaluation of the sensing behaviour of an N-path MZI based on the MC-MOF fabricated. Conclusions are drawn in Section 4.

2. Characterisation of MC-MOF

2.1. Fabrication of MC-MOF

The cross-sectional structure of the manufactured seven-core microstructured silica-based optical fibre is presented in Fig.1. The fibre was made using a stack-and-draw technique. The fibre preform was created by stacking capillaries around a solid rod. Each core was produced using a single rod. The MC-MOF has been polymer coated. Table 1 presents the parameters of the fabricated MC-MOF.

2.2. Near-field measurements

The mode field properties in MOFs strongly depend on the lattice parameters. Therefore, it is important to know the exact mode field profile of a MC-MOF. The near field mode intensity of the MC-MOF fabricated was measured experimentally at a signal wavelength of 630 nm. Each core in MC-MOF is endlessly single-mode because the ratio $d/\Lambda < 0.43$ [19]. The light from a laser was introduced into a 2 m length of the MC-MOF by connecting both ends of the MC-MOF to a single mode fibre SMF-28 using conventional a FC/PC fibre connectors. The near-field image at the MC-MOF output was captured using a CCD camera and the mode field profile obtained is shown in Fig. 2a. The intensity plot of the mode field profile is given in Fig. 2b. These results indicate that the light from SMF-28 can effectively excite all cores of the MC-MOF

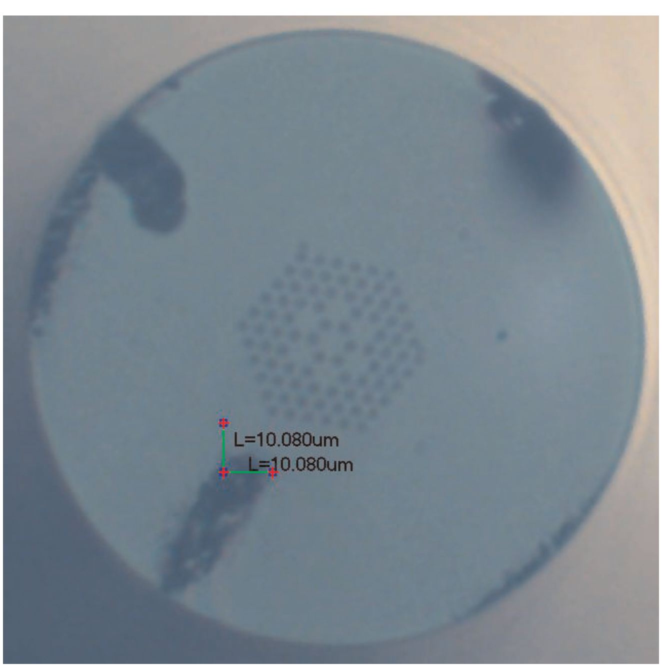

Fig. 1. Cross-section of the silica MC-MOF fabricated.

Table 1
Parameters of the MC-MOF fabricated.

Core diameter	5.15 μm
Air-hole diameter, *d*	1.5 μm
Lattice constant, Λ (pitch)	3.6 μm
Filling factor, d/Λ	0.413

without coupling a significant proportion of the input power to the cladding modes. It has been proven in the literature that is possible to achieve equal intensities in each core of 7-core MOF by careful optimisation of the fibre structure [17,18,20]. Each core is slightly different in practice due to manufacturing differences.

Therefore this simple configuration can be used to realise a sensor, which exploits the interference that occurs between the core guided modes. Based on this principle the MC-MOF-MZI was implemented. We excite all cores of the multicore fibre with the SMF-28 aligned with the centre of the MC-MOF.

3. The experimental results for N-path MC-MOF MZI

3.1. Principle of operation

Schematic and illustrative diagrams of the realised N-path MC-MOF MZI are depicted in Fig. 3a and b, respectively. The MC-MOF cores are not exactly identical due to fabrication inaccuracies this results in difference between the optical path length of the interferometers arm. The interferometer was fabricated by inserting 2 m section of MC-MOF between two sections of SMF-28 using conventional FC/PC fibre connectors. An overall MC-MOF length of 2 m was used in all experiments, however the MC-MOF section exposed to external factors (temperature, strain, bending) was slightly altered in each experiment. In each case the MC-MOF length exposed to temperature, strain or bending is specified. The fibre was coated in all experiments. The SMF-28 at the beginning and at the end of MC-MOF acts as an input and output coupler, respectively. The light from the SMF-28 excites several modes in the MC-MOF. A fibre with seven coupled cores supports seven supermodes [21,22]. At the end of the MC-MOF section the light from each mode is coupled back to SMF-28. Multi-mode interference occurring in this fibre. Each supermodes acts as a separate arm of a MZI. The coupling efficiency depends on the relative phase differences between the optical beams propagating in the cores of the MC-MOF, since each mode acts as a separate arm of a MZI. Spectrally, the interference generates a periodic transmission spectrum of the N-path MZ device. The fabricated MC-MOF MZI is simple and compact, in contrast to a conventional MZI assembly where the two optical fibre couplers and two fibre sections are needed.

In order to investigate the transmission properties of the MC-MOF MZI, broadband light from an erbium amplified spontaneous emission (ASE) source was introduced into the fibre. The transmission spectrum of the MC-MOF MZI was monitored using an Optical Spectrum Analyser (OSA), Yokogawa AQ6370C, with a resolution of 0.02 nm. The experimental set-up is shown in Fig. 4. Since SMF-28 is used at both ends of the sensor further coupling with standard fibre optic devices is straightforward. The insertion loss of the MCF device was obtained as 1.89 dB. Fig. 5 presents the interference fringe pattern observed at the output of the MC-MOF MZI near the wavelength 1550 nm. A maximum contrast of around 10 dB is observed. The measured spacing between the interference peaks was around 0.8 nm. It can be observed that the interference fringe pattern is not uniform like in a conventional two-path MZI. The sidelobes in the spectrum are characteristic of an N-path interferometer, and are due to the superposition of the multiple