Strain Sensor from Tapered Fibres

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Abstract. A new all fibre, and low transmission loss, digital optical strain sensor is proposed. This sensor behaves as a Coaxial Mach-Zehnder interferometer. Special depressed cladding single-mode fibre DCF was tapered down to the micrometer scale presenting FSR in the nm range. The sensor is modelled to probe up to ± 0.2% strain when under expansive or compression stresses, returning 20 optical Power Transfer Turning Points (PTTP) at 1575 nm transmitted wavelength.

1 Introduction

Devices fabricated by tapering optical fibres, enable additional effects and applications other than those reported using bulky optical fibres [1]. Analogue fibre optics sensing devices based on interferometer’s principles are crucial for many applications. Unfortunately, these sensors have as disadvantage a low linear dynamic range. On the other hand, the ease of fabrication of tapered fibre-based devices contributes to their use in applications such as: Brillouin optical sensors [2], tuneable acoustic-optical filters, super continuous radiation generation, among others applications [3], useful in Internet of Things (IoT). For these reasons, the concept of multimodal interference has been studied aiming at the development of different devices. Devices intrinsically manufactured from tapering single-mode fibres (SMF) allow the generation and propagation of selected super-modes, causing interference at the output of the multimode (MM) tapered section. As a result, low loss transmitted optical power may be observed at specific wavelengths. In addition, when this SMF has a Depressed Refractive Index profile (DCF), and the adiabatic condition holds at the tapered section, this structure behaves as a Coaxial Mach-Zehnder interferometer (CMZI) [3]. The interrogation of such sensor occur acting externally on either the MM optical path, or on the super-modes speed (external refractive index).

In this work, an all-fibre digital strain sensor based on a taper from a DCF is proposed. Our fabricated tapered-based CMZI senses external force fields acting on the optical path of the excited super-modes.

1.1 Materials, principles and methods

The DCF has been specified, and manufactured to enable HE11 HE12 mode coupling at the adiabatic tapering section [4]. The core and cladding radius and refractive index parameters of the DCF is shown in Figure 1. Determining which profile results from stretching a fibre into a given heat source with its own temperature distribution is a complex fluid mechanics problem.

\[ \rho(\alpha, L_0, z) = \rho_0 \left[ 1 + \frac{2\alpha(z - z)}{(1-\alpha)L_0} \right]^{-1/2\alpha} \]  
\[ L_w = L_0 + 2.\alpha Z_f \]  

Where \( \phi(\alpha, L_0, z) = 2\rho(\alpha, L_0, z) \) is the diameter of the fibre in the profile region. \( \rho_0 \) is the radius of the fiber outside the tapered region, \( \alpha \) is the linear rate of change in the length of the heated zone with the fiber extension. \( L_0 \) is the initial length of the heated zone, \( Z_0 = Z + L_0/2 \) the final extension of that region on the axial axis \( z \) of the fibre, and \( L_w \) the length of the waist region.

2 Experimental data and discussion

Three fibre tapers with different parameters, as shown in Table 1 were modelled and manufactured. A micro-torch, displaced in the longitudinal direction was used. The DCF was pulled using step motors.
Table 1. Tapers parameters, model and experiments

| Sample | α  | L₀ (mm) | D₀ (µm) | L₁ (mm) | Z (mm) | L_total (mm) |
|--------|----|---------|--------|---------|--------|-------------|
| 1      | -0.1 | 14      | 3.9    | 6.7     | 38.5   | 84          |
| 2      | -0.1 | 14      | 10.6   | 8.5     | 30     | 68.5        |
| 3      | -0.1 | 14      | 27.8   | 10.4    | 20     | 50.4        |

The resulting taper profiles, and fitting curves, according to Eqn. (1) and (2), are presented in Fig. 2.

During the heat-and-pull process a number of oscillations (inset of Figure 3) is observed in the transmitted optical power, and defined as Power Transfer Number (PTN). PTN presents an exponential dependence for different taper elongations. According to mode coupling theory, under adiabatic condition \[ \frac{1}{\rho} \frac{d\rho}{dz} < \frac{1}{z_b} \] where \( z_b \) is the beat length between HE₁₁ and HE₁₂.

The intrinsic sine square response in transmitted power (at 1575 nm) to external mechanical loads of sample #1 can be seen in the inset of Figure 4. The output power experiences a number of Power Transfer Turning Points (PTTP) when under stress, and this PTTP is directly proportional to \( \Delta L/L_0 \) (Figure 4). An intrinsic sine square transfer function has two PTTP per cycle. Submitted to 0.02 Newton it elongates by \( \Delta Z = 180 \, \mu m \), which is equivalent to an increase \( \Delta PTN = 10 \), and a number of PTTP = 2.\( \Delta PTN = 20 \). It can be clearly noticed from Figure 4 that the digital sensor operates counting the PTTP when under traction or compression along its longitudinal direction. Negligible hysteresis was observed between traction and compression.

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