Integrated Fibre Optics for Sensing based on Whispering-Gallery Modes

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1 RESEARCH PROBLEM

In the field of photonics, optical fibres have shown to be a very versatile tool for multiple applications. Due to their high transmission, single-mode (SMF) and multimode fibres (MMF) have been widely used for manufacturing devices useful for different areas. Especially MMFs have been preferred for assembling fibre bundles because of their relatively easy light feeding and coupling compared to SMF; in addition to their low cost and strength. These fibre bundles manufactured with MMF are used for spectroscopy in areas such as Astrophysics (García-Lorenzo, et al 2008; Good, et al 2008) and Medicine (for optical coherent tomography). In both fields, having as lower losses as possible in a constantly changing medium is mandatory.

When the modes going along the fibre core reach the coating, due to bending losses or cladding coupling, the transmission of standard SMF (Harris & Castle, 1986; Faustini & Martini, 1997; Morgan, et al 1990; Sharma, et al 1990) and MMF (Padilla-Michel, et al in preparation) show an oscillatory behaviour. This behaviour is comparable to the Whispering-Gallery Modes (WGM) observed in photonic nano-cavities such as micro-resonators (Matsko, et al 2005). These WGMs have shown to be a very efficient tool for multiple applications covering from sensing (stress, temperature, refractive index and pH) to filtering (photonic filters).

WGMs in MMF have a double impact in the performance of finished devices. On one hand, the oscillatory effect on the spectrum has been an undesirable instrument footprint, for applications where a flat and stable reference spectrum is required (e.g. Astrophysics, Medicine or Pharmacy). On the other hand, with this thesis we want to prove that the WGM produced in MMF can be the base for a potential low-cost and profitable resonator. This will be achieved exploiting the helicoidal modes propagating along the coating of MMF, which resemble the WGM observed in the spectrum of a coil resonator.

2 OUTLINE OF OBJECTIVES

The present thesis project has two main objectives. First objective is to provide a solution to the so-called "fringing-like pattern" observed for example in fibre bundles made with circular-core MMF (Lagerholm, et al 2012). This will be achieved doing a complete characterization of the most used coating materials, including:

- Bending losses (Padilla-Michel, et al 2012);
- Intrinsic absorption bands of coating materials;
- Mechanical properties (accepted paper in Photoptics 2015);
- Effect of cladding-coating ratios (Presented abstract in EOSAM 2014, and accepted conference paper in NKW16 2015);
- Modelling the mode propagation in squared and circular fibre-core geometries.

These models will be of great interest to find the optimal geometrical properties, eliminate the fringing-like pattern mentioned formerly, and improving the performance of the MMF used for spectroscopy, tomography and laser surgery.

The second objective is to develop an innovative, efficient and profitable resonator, exploiting the WGM produced in MMF. This will be achieved characterizing the physicochemical properties of the coating material to produce a high quality WGM-based resonator.

All these results will be very useful for a better understanding of mode behaviour in MMF. For example, modelling the fringing produced by the modes propagation in an ideal MMF will be useful for detecting coating-thickness variations, turning into a quality test during the drawing of a MMF. This model will also be useful for explaining and solve the problem of fibre bundles performance such

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as the already mentioned fringing-like pattern reported in astronomical instruments such as the VIMOS-IFU (Lagerholm, et al 2012).

3 STATE OF THE ART

3.1 Scientific Background

According to Harris & Castle, 1986; when a SMF is bent, the fundamental mode is shifted outwards the fibre core and the outer portion of the evanescent field of this mode is guided through the cladding. This radiation bounces in the cladding-air interface and around the fibre bending, producing a WGM (see Figure 1).

Figure 1: Schematic of a bent SMF showing the generation of a WGM in the cladding. The schematic is taken from Harris & Castle 1986.

When the WGM is in phase with the fundamental mode, synchronized coupling occurs producing a maximum in the transmission, and vice versa.

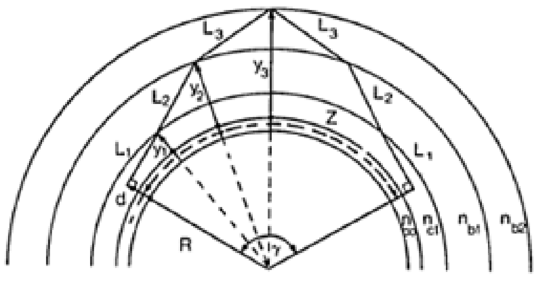

Figure 2: Schematic of the WGM interference model from Morgan et al 1990. The dashed line is the fundamental mode traveling along the fibre core, the continues line is radiation traveling from the core to the cladding until strike the second coating-air interface, and then going back to the cladding.

Morgan, et al 1990; noticed that when the refractive index of the coating is higher than that of the cladding, the evanescent field escaping from the core reaches the coating producing a WGM bouncing along the coating-air interface (see Figure 2).

In Sharma, et al 1998 it is reported the same oscillatory effect in straight SMF. In their experiment, the light source was coupled directly into the cladding. Therefore, when the cladding modes strike the cladding-coating interface these are refracted into the coating, because the refractive index of the cladding is lower than that of the coating. Afterwards, the coating modes are reflected from the coating-air interface and partially refracted into the cladding (see Figure 3).

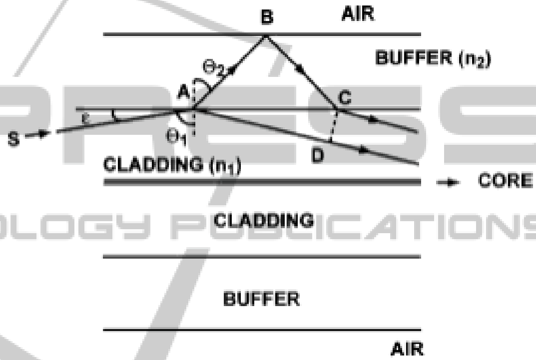

Figure 3: A ray-tracing model (taken from Sharma, et al 1998) which explains the spectral oscillations produced by modes interference along the cladding.

In Sharma, et al 1998; is also showed that removing the fibre coating, the oscillations are vanished (see Figure 4), proving that the oscillatory losses are produced in the coating.

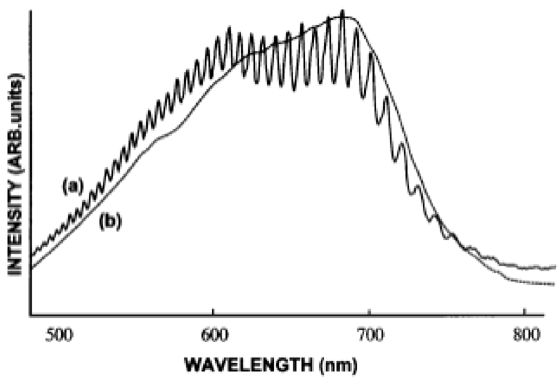

Figure 4: The plot taken from Sharma, et al 1998 is showing the spectrum of (a) the SMF with coating and (b) without coating.

This model is reported as useful for measuring the refractive index of the coating at different wavelengths as well as for sensing applications.

3.2 Existing Types of Resonators

In nature we can find WGM resonances in liquid droplets, but there is also a variety of fabricated resonators such as Fabry-Perot, micro-spheres, ring, disk, cylindrical, capillary resonators and those made based on optical fibre nanowires (for recent reviews, see e.g. Vahala, 2003, Matsko, et al 2005 and Brambilla, et al 2009).

Knot, loop and coil resonators, which are of most interest to this thesis project, are fabricated from optical fibres nanowires or microwires. This type of resonator produces the oscillatory losses exploiting its large evanescent field. Since the diameter of the nanowire is similar or even smaller than the wavelength of the feeding light, the evanescent field exceeds the physical boundary of the nanowire. Therefore, when the nanowire is coiled (see Figure 5), the mode propagating along the wire interferes with its own evanescent field, resulting in a resonator (Brambilla, et al 2009). The input and output couplings of these resonators are similar to those of a SMF. There is a wide range of techniques to manufacture nanowires, and every of them have challenging problems (Sumetsky, et al 2010a).

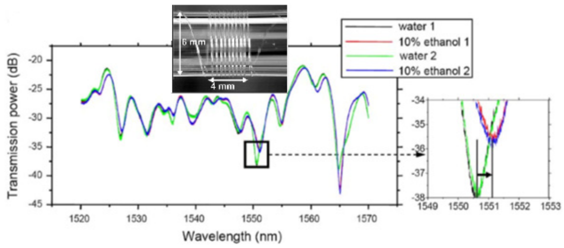

Figure 5: Variations of transmission of a micro-fibre coil resonator immersed in water and ethanol. The inset is the picture of the tested micro-fibre coil. On the right hand of the picture is a close-up showing the shift of the oscillations due to refractive index change of the measured sample. Picture adapted from Sumetsky, et al 2010a.

In analogy to coil resonators, the WGM observed in our MMF are produced when the modes trapped in the fibre coating bounce in the same manner as in a ring cavity, allowing the WGMs propagate along this layer (see Figure 6).

As well as in Figure 5, the way that a MMF will tell us if there is a change of stress or pH, it will be with a shift of the oscillatory spectrum as shown in Figure 7.

Up to the knowledge of the group, there is no public literature reporting, characterizing or modelling WGM in big MMF, i.e. with a core diameter bigger than 50µm.

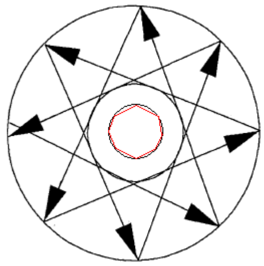

Figure 6: Schematics of helicoidal (skew) modes bouncing along a fibre coating. Figure modified from Su, et al 1992.

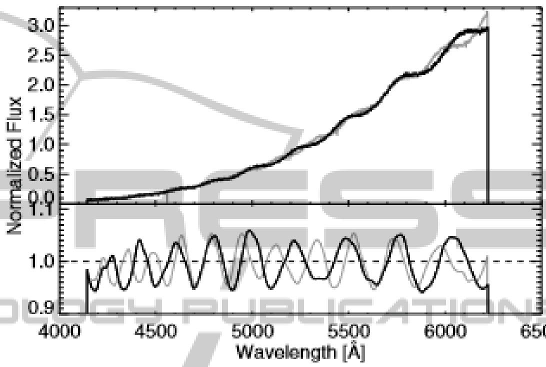

Figure 7: The fringe-like pattern observed in the VIMOS-IFU. On top, spectrum of one MMF clearly showing the effects of the WGM (black). On bottom, the corresponding normalized correction function for the same MMF (black). In grey, it is shown the spectrum and corrections function from the same MMF but observed in a different night, meaning that the MMF is being stressed due to the rotation of the telescope. The plot is taken from Lagerholm, et al 2012.

4 METHODOLOGY

As mentioned above, this thesis is divided in two parts. The experiments conducted in this first part will cover:

- Characterisation of changes in the fibre spectrum when using different type of light (monochromatic and broadband) for feeding fibres. This is to model and understand the interference process into the fibre coating;
- Transmission characterisation of square-core fibres to be compared with the performance of circular-core ones;
- Spectral characterisation of different coating materials;
- Theoretical modelling to develop equations that provide calibration curves for MMF performance and devices made with them;

- Method to minimize the modal dispersion characteristic of MMF.

The experiments conducted in the second part of the thesis will cover:

- Identifications of the optimal coupling parameters to excite WGM of high sensitivity;
- Increase the quality *Q* factor by doping the coating. In WGM-based sensors, the *Q* factor can reach the order of 10^6 (Nguyen, et al 2009), producing very narrow peaks in the transmission spectrum;
- Characterisation of the sensitivity of our WGM-based sensor under pH and stress changes;
- Modelling the sensitivity of the WGM-based resonator.

Finally, we will make test of our first prototypes in the laboratories of our industrial collaborator. This will give us the main measurable and quantifiable result of the project.

5 EXPECTED OUTCOME

5.1 Characterisation of Fibre Samples

The characterization tests will cover all the mechanical and optical properties. The mechanical properties tests will include environmental sensitivity (stress, temperature and pH), geometry (comparison between circular- and squared-core fibres) and coating texture (scattering control). Regarding optical properties tests, these will include focal ratio degradation, butt-coupling (refractive index), and transmission at different wavelength ranges.

5.2 Modelling of Fibre Components

For the present thesis, several types of MMF will be tested. On one hand, MMF with graded-index cladding to avoid cladding modes reaching the coating. As mention in section 3, coating modes are responsible of the WGM effect; therefore these fibres will have a flat and stable transmission spectrum. These fibres will be used to manufacture devices with high quality transmission and flat spectrum.

On the other hand, we will develop special MMFs to exploit the WGM effect. This will be achieved using step-index MMF coated with a polymer which refractive index must be as higher than that of the cladding as possible. The goal is to find the ideal refractive index difference between cladding and coating (Flaim, et al 2004). These fibres will be used as WGM-based resonators, for sensing purposes.

During this phase the group will make the corresponding simulations and modelling of the different types of fibres using COMSOL Multiphysics, which is a simulation software based on finite element analysis. Afterwards our industrial partner will take charge of the manufacturing of the prototype.

5.3 Simulations of WGM Propagation and Model Development

During this phase, we will develop a new model based on the existing WGM theory to explain the experimental results obtained from the fibres with doped coating. This model will be a milestone for the design and development of our MMF-based resonator.

This model will also be of great importance for all the research and industrial areas using MMF coated with high refractive index. These types of coatings are the most used in the industry because of their stripping properties. Also, this will be the first model explaining mode propagation in big-core MMF carrying thousands of modes.

5.4 Design and Modelling of MMF-based Resonator

Once the model obtained in section 5.3 give us the bases to understand and control WGM, we will find out the optimal fibre configuration to create our MMF-based resonator. As well as in the case of a coil or knot resonator, we will test different coil and knot configurations (see Figure 8) in order to increase the *Q*-factor and the finesse. Also we will control the free spectral range, exploiting the evanescent field of the fibres.

The advantage of our MMF-based resonator over these micro resonators is the very low price, easy manufacturing, in addition to its easy coupling due to the big core of the fibres used.

5.5 Characterisation of the First WGM-based Resonator

As well as in section 5.1, this MMF-based circuit will be characterized mechanically and optically. We will do the same test mentioned in that section.

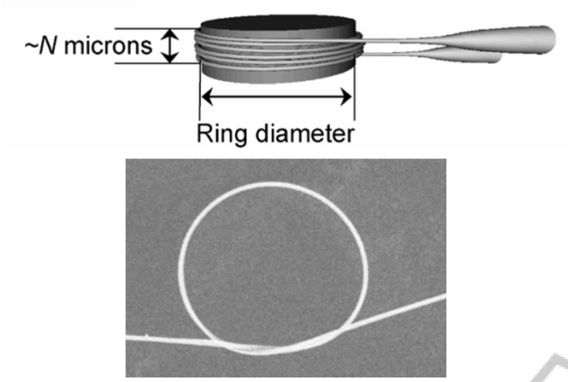

Figure 8: On top, example of a micro coil resonator taken from Sumetzki, 2008. On bottom, picture of a knot resonator made using an optical fibre microwire (Brambilla, et al 2009).

6 STAGE OF THE RESEARCH

During the first year of this thesis project, several characterisation tests on coating materials have been done. Some of the results have been already presented and published in conference papers (see references of section 2).

Based on the applied stress results presented in Padilla-Michel, et al 2012, we decided to make a Mechanical characterization of the same four coating materials reported in that paper. These materials are: fluorinated acrylate, acrylate, silicone and polyimide. The experiment consisted in calculate the Young's Modulus of these four coating materials using a Nanoindenter (Padilla-Michel, et al in press 2015a). Based on the obtained results, it is also discussed the impact of the Young's Modulus of these coating materials on the attenuation. In the same paper is also compared the impact of the Young's Modulus and the impact of the refractive index of these coating materials on the fibre performance.

We also carried out the spectral characterization of the four coating materials in the near infrared range (0.8 µm - 2.5 µm) using a Fourier Transform spectrometer, optimised for NIR. The results of this experiment are part of a paper in preparation regarding WGM in MMF.

The next step of the thesis is the modelling of modes propagation in the cladding-coating interface using COMSOL Multyphysics. The results will be compared with a ray tracing model made with the optical design program ZEMAX.

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