Laser micromachining of optical fibre: an instrumentation enabler

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Invited Paper

Abstract

The use of lasers to process optical fibre at INO goes back in the early '90 when a team developed a CO₂ laser-based process to anneal fibre-end surface allowing the lowest back reflection-loss connectors commercially available at that time. Since then, INO has developed several processes for stripping, cleaving, polishing, end-shaping, machining, bending, welding, soldering and packaging optical fibres. More recently, INO has used laser micromachining of optical fibres in order to enable innovative instrumentation in the field of chemical sensors, flow cytometry and gas chromatography.

Keywords: laser micromachining; optical fibre; instrumentation

1. Introduction

Due to major and irreversible trends such as globalization and population aging in developed countries, the worldwide pressure on productivity and healthcare cost structure is tremendous. This has raised the need for reduced diagnosis and treatment time which, in turn, ask for low-cost compact instrumentation that can be brought out of large laboratories and deployed at point-of-care. Fibre-based instrumentations are well suited for such applications since they can be made compact and rugged.

Processing optical fibre is a demanding application, however, the thermo-physical properties of fused silica makes it particularly well suited for photothermally-based laser processing. The high purity and the low thermal expansion coefficient of fused silica [1,2] render microcracking and surface crazing negligible. Hence, high precision and limited thermal load allow to process optical fibres without affecting their optical properties.

Over the years, driven mainly by the telecommunication market, laser processing techniques have been developed for annealing, stripping, cleaving, polishing, end shaping, bending, welding, soldering, and packaging optical fibres. On its part, INO initiated work on laser micromachining of optical fibre in the early '90, by using a CO₂ laser to anneal fibre connector to reduce their back-reflection losses. Further work has included fibre welding to collimating GRIN lenses, fibre tip shaping for increased coupling efficiency and fibre stripping for automated fibre connector manufacturing [3-6]. More recently, INO has used laser processing to implement functionalities in

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microstructured optical fibres enabling innovative instrumentations such as all-fibered flow cytometer and gas chromatograph.

2. All-optical flow cytometer engine

2.1. Flow cytometry

Flow cytometry is a well established technology which has applications in various areas such as molecular biology, pathology, immunology, plant and marine biology as well as bio-threat detection and identification. In flow cytometer, a tightly focused stream of fluid is intersecting a light beam (see Fig. 1). When the targeted organic molecule or cell present in the fluid passes through the intersection, it absorbs and scatters light and eventually emits fluorescence. Both fluorescence and scattering can be detected to identify and count the cell or organic molecule under study.

![Fig. 1. Standard flow cytometry principle](image)

2.2. All-fibre engine

In order to reduce the size of the instrumentation and increase its robustness, an all-fibre engine has been developed [7-8]. In its initial version, an optical fibre is drilled perpendicular to its propagation axis and a capillary is welded to the fibre to bring the fluid to be analysed. Additional fibres may be welded to the arrangement to capture scattered and fluorescent light emitted by the sample. Figure 2 shows a basic all-fibre arrangement with a picture of original 100μm-core optical fibre drilled with a circular hole of a 100 μm.

![Fig. 2. All-fibre engine along with the original circular-hole fibre](image)

The coefficient of variation (CV) of flow cytometer is defined as the ratio of the standard deviation over the arithmetic mean of distribution of measured value of fluorescence or light scattering intensities from “nearly identical” particles [9]. It is usually expressed as a percentage. State-of-the-art flow cytometer have CVs of less than 2%. Large CV means that signal emitted vary considerably from one cell to the other which results in cell count

![Excitation fibre optic](image)
inaccuracies. Either a strong signal emitted by a single cell may be interpreted as a double count or weak signals emitted by two cells passing the interrogation region simultaneously will be seen as one count.

By using a circular waveguide with a perpendicular flow, the cell will experience a different excitation light intensity depending on its particular position in the flow. In order to reduce such dependence, a square-core optical fibre (250μm x 200μm) was used with a square hole of 100μm x 100μm. Hence, the cell will experience a uniform illumination independently of its trajectory in the interrogation region.

![Square fibre with perpendicular flow](image)

Fig. 3. Picture of the square fibre along with a picture of an all-fibre engine

2.3. Results

CV measurements were conducted using calibrated 10 μm BC Flow-Check™ beads at flow rate of 17 μl/min. Excitation was performed with a 488 nm laser while the fluorescence signals were measured at 90° at 520 nm with a bandpass filter of ± 30 nm. As it can be seen on figure 4, the CV obtained was of 3%, which is slightly higher than high-end flow cytometer but is of interest for ruggedized portable devices. For example, successful identification of harmful organisms has been demonstrated using such device [8].

![CV measurement graph](image)

Fig. 4. CV measurements realized with 10 μm reference beads

3. Chemical sensing

3.1. Liquid core fibre

Microstructured optical fibres (MOF) have been used to increase the sensitivity of spectroscopic techniques and to considerably reduce the amount of liquid required to perform the analysis. Hollow-core fibres were realized using standard MOF fabrication techniques. Air clad was collapsed at both end of the 1-m long fibre over a 1-2 mm length (see fig. 5), standard fibres were spliced and a CO₂ laser was used to perforate the liquid inlet and output. Using such an arrangement, it is possible to perform spectroscopic measurements (absorption, Raman, etc.) over increased interaction length (meaning increased sensitivity) with minimal liquid sample [10]. For example, using a 1-m long
fibre, spectroscopic measurements were realized with few microliters of liquid. Due to the confinement of the light in the core of the fibre, the measurements can be performed at high intensity allowing non-linear techniques as well.

![Liquid-core fibre: pictures of the core, the air-clad, the collapsed and spliced fibre-end and the liquid inlet](image)

**Fig. 5. Liquid-core fibre: pictures of the core, the air-clad, the collapsed and spliced fibre-end and the liquid inlet**

### 3.2. Gas Chromatography

Gas chromatography (GC) is a commonly used technique in analytic chemistry. A carrier gas is used to transport a mixture to analyze in a capillary. Each component of the mixture interacts differently with the wall of the capillary, resulting in a different transit time. The measurement and analysis of those transit times will provide the mixture content. Such a method is widely used in process and quality control.

### 3.3. Real-time gas chromatography

Using the MOF fabrication techniques and laser processing techniques for the microfluidics, it is possible to implement a polarization maintaining fibre with a capillary in close proximity of the birefringent core (see figure 6). When the mixture to be analyzed is propagating in the fibre, its interaction with the inner surface of the capillary (adsorption/desorption) induces coupling of the polarization modes due to core proximity. It is possible to measure the position of those coupling points along the fibre performing polarization interferometry. Furthermore, those measurements are performed in real-time opposite to standard GC requiring to wait the propagation of the sample over the full length of the capillary prior to measurements.

![Elliptical core](image)

**Fig. 6. Picture of the GC fibre which is composed of an elliptical core in close proximity of a capillary**
4. Vunerable plaque detection

4.1. Vulnerable plaque

Over the recent years, it has been determined that most of the heart attacks or strokes were caused by a coronary artery disease called vulnerable plaque. Vulnerable plaque distinguished itself from standard fatty plaque by the presence of inflammation, hence an increased metabolic activity. It has been, thus, suggested that vulnerable plaque can be associated with a temperature increase and a lower pH [13].

4.2. Temperature and pH sensor.

Due to the blood flow in the coronary artery and its large heat capacity, it is essential that the sensor material will be in direct contact with the artery wall and isolated from the blood flow. To achieve such an arrangement, the cladding is removed on a small portion of a multimode optical fibre. The cavity is then filled with the sensitive material which is composed of a dye sensitized polymer. Two dyes are utilized, one sensitive to temperature variation, the second one to pH.

![Fig. 7. Schematic of the Temperature and pH measurement endoscope](image)

5. Conclusion

The use of lasers to process optical fibre at INO goes back in the early ’90 when a team developed a CO$_2$ laser-based process to anneal fibre-end surface allowing the lowest back reflection-loss connectors commercially available at that time. Since then, INO has developed several processes for stripping, cleaving, polishing, end-shaping, machining, bending, welding, soldering and packaging optical fibres. In this paper, we have reported on how, at INO, we have used laser microprocessing in order to implement microfluidics in optical fibre allowing novel instrumentation, compact and portable. We have also exposed a new concept for vulnerable plaque detection.

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