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ScienceDirect

Procedia Chemistry 21 (2016) 453 – 460

Procedia Chemistry

5th International ATALANTE Conference on Nuclear Chemistry for Sustainable Fuel Cycles

Development of an opto-fluidic microsystem dedicated to chemical analysis in a nuclear environment

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Abstract

Micromachining techniques enable the fabrication of innovative lab-on-a-chip. Following the trend in chemical and biological analysis, the use of microsystems also appears compelling in the nuclear industry. The volume reduction of radioactive solutions is especially attractive in order to reduce the workers radiation exposition in the context of off-line analysis in spent nuclear fuel reprocessing plants. We hence present the development of an opto-fluidic sensor combining microfluidic channels for fluid transportation and integrated optics for detection. With the aim of achieving automated microanalysis with reduced response time the sensor is made compatible with a commercial microfluidic holder. Therefore the chip is connected to computer controlled pumps and electrovalves thanks to capillary tubing. In this paper we emphasis on the fluid handling capacities of the opto-fluidic sensor.

Peer-review under responsibility of the organizing committee of ATALANTE 2016

Keywords: Chemical analysis; microsystem; miniaturization; opto-fluidics, microfluidic; integrated optics

1. Introduction

Several nuclear energy policies encompass the reprocessing of spent nuclear fuel (SNF) as a way towards sustainable closed fuel cycle[1]. Thus the PUREX process is widely employed in commercial reprocessing plants[2,3]

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Peer-review under responsibility of the organizing committee of ATALANTE 2016
doi:10.1016/j.proche.2016.10.063

such as the one of La Hague. SNF is hence dissolved into a nitric acid solution in order to extract the reusable part, namely uranium and plutonium, from fission products and minor actinides. The extraction process involves a significant analysis amount either for process monitoring, material balance or safety[4]. However, due to the high radiation intensity of SNF the measurement have to be performed in hot cells. Optical spectroscopic techniques, especially the ultra-violet, visible and near-infrared (UV-Vis-NIR) spectrophotometry, have shown potential applicability for on-line monitoring[5] of SNF solutions. In this case, the measurement probe is located inside the confinement enclosure thanks to optical fibers. At the same time, the volume reduction is also appealing to lower the operational constraints, especially regarding workers exposure to irradiation. Indeed, the radioactive dose, and doing so the required radiological protection, is reduced accordingly to the volume reduction[6]. Through the manipulation of small volumes of liquid samples, the analysis can then be carried out in a glove box[7]. The combination of optical techniques and fluids microvolumes is suitable for at-line or off-line analysis[8] for which the measurement can be isolated from the harsh environment unlike in-line analysis. This approach leads to the need for opto-fluidic sensors. In the past, some preliminary work concerning a detailed study of the light/fluid interaction has been carried-out[9]. However if the structure has proven to be effective to measure absorption spectra of neodymium in nitric acid solution, many points concerning the microfluidics remain to be studied. For instance, to which extend is it possible to control the fluid flow inside the nano-scale channel? Is it possible to effectively rinse the nanochannel? How much time is required for the operation? The aim of this paper is to explore those aspects, which are of paramount importance in the case of a remotely-operated sensor operating in a glove box.. The evolution from microsystems to integrated opto-fluidic sensors is briefly depicted in Section 2. The current work focuses on a chip co-integrating optical and fluidic functions whose design and fabrication are described in Section 3. The hydraulic behavior of the opto-fluidic sensor is then studied in Section 4. Finally the perspectives are drawn in Section 5.

2. From microsystems to opto-fluidic sensor

The quantitative microanalysis is by itself a quite old concept, as illustrated by the pioneer work of Pregl[10] in the early twentieth century, driven at that time by the rare availability of the compound under study. Nonetheless, only the emergence of microelectronic derived fabrication methods several decades later, allows designing microsystems dedicated to analysis at the micro- and sub-microscale.

2.1. Microsystems for sensing

Microfluidics, regarding transportation and processing of liquid samples in microscale channels, has induced a revival of the microanalysis in the 90s[11], indeed enabling the realization of lab-on-a-chip or micro-total analysis systems[12]. Among the required components[13], the detection is essential to achieve quantitative microanalysis and optical methods are thus relevant for co-integration on the same chip to perform remote analyses. Integrated optics, introduced by Miller[14] in the 60s, plays a major role in the effort for an "on-chip" approach[15]. These technologies take benefit of microfabrication techniques to implement either optical or fluidic functionalities on planar substrates. The merge of microfluidics with integrated optics leads to opto-fluidic devices[16,17]. Sensors relying on opto-fluidic present both compactness and mechanical robustness since the functions are integrated on a single chip while also offering reliability thanks to self-aligned optics. Consequently opto-fluidics have found applications in chemical analysis as reported in review papers[18-21].

2.2. Previous works

Since small amount of radioactive solutions are required for the analysis, opto-fluidic devices are also promising for the nuclear industry. Therefore the CEA and IMEP-LaHC have started a collaboration aiming to design a dedicated sensor using microfluidic and integrated optics. The analysis toolkit is realized using a glass platform, chosen for its high chemical resistance, pronounced ionizing radiation sustainability and thermal stability. The technological know-how is mastered by the IMEP-LaHC and the fabrication process flow is described in Section 3. At first, a thermal lens based sensor has been investigated[22]. The chip comprises a channel crossing both arms of an integrated Young interferometer. An excitation laser is focused on one arm and partially absorbed by the analyte