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Poster

NANOPHOTONIC BIOSENSOR FOR SPACE EXPLORATION (PBSA INSTRUMENT)

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I. INTRODUCTION

One of the biggest challenges of Astrobiology is the search for clear signs of present or past life on other planetary bodies. Thus, this poster will describe the project "Photonic Biosensor for Space Application" (PBSA, www.pbsa-fp7.eu) founded by the Directorate-General for Enterprise and Industry (DG ENTR) within the European Commission and managed by the Unit S2 (Space Research) of the Research European Agency (REA).

There are a number of applications in space that requires rapid, robust, light and automatic biosensing techniques. For example, for checking the microbial contamination in space stations or to search for life in planetary exploration. The PBSA instrument aims to implement a Lab-on-a-chip (LoC) device based on a photonic immunosensor and to demonstrate its use for microbial monitoring and life detection missions. Advanced terrestrial technologies in the field of biosensors are combined for the development of a novel solution ready and tested for the space environment. This approach employs recent advances in antibody microarray-based immunosensors with two powerful technologies, photonic integrated circuits (PICs) and microfluidics.

The use of PIC enables the implementation of highly integrated solutions for the implementation of a LoC. Multiple detection can be integrated into a single chip for multiple parallel analyses. That is, multiple microbial targets or biomolecules can be detected simultaneously. This technology has shown to be very sensitive and improves the protocol simplicity compared to other techniques such as the fluorescent approach that requires labelling steps. The PIC based solution permits direct and real time measurement of the target analytes (molecules or whole microbes) in just a few minutes. This feature, together with microfluidics, makes PBSA suitable for remote sensing in space applications where savings in reagents are very valuable.

Both photonic and microfluidic systems optimize critical parameters in space applications (volume and mass) enabling new opportunities. These benefits apply also to terrestrial market, such as veterinary or biomedical purposes.

A compact PBSA device with integrated microfluidics, photonic components and biosensing elements (antibodies or other capturing molecules) will be constructed and tested. The subsystems and the whole device will be tested under space-relevant conditions: high energy radiation and Martian conditions.

II. SYSTEM LEVEL DESCRIPTION

The contribution of the PBSA project to the implementation of a life exploratory system is mainly focused on the implementation of an autonomous detection system based on a modified immunoassay technique. The immunoassay technique is inspired in the immune system of animals. The biologically synthesized antibodies show big recognition and binding capabilities towards odd external analytes. This effect is called affinity of the antibody ligand to the analyte. This technique has been widely spread in medical and Food & Beverage applications in different formats. Therefore it can be easily found immunoassay techniques in fluorescent approaches, radioimmunology or the most widely spread the ELISA (Enzime-Linked Immunoabsorbent Assay) format. These kinds of tests are typical in everyday medial determinations or laboratory test.

The modification to the conventional solutions is introduced by the use of the photonic technology for the implementation of the transduction system. The objective of introducing the photonic solution is oriented to achieve valid detection solutions for space applications with high performance features.

To explain the overall system concept Fig. 1 shows a bottom to top system element detail view. Fig. 1a shows the signal resonance shift in the biosensor while antibodies connect to a sample antigen. The antibodies are fixed on a solid surface of a sensing system. The sensing system has an entrance and an egress signal. The entrance signal is phase shifted due to the presence of material on the surface of the sensing ring resonator (Fig. 1b). To deliver the sample and additional buffer and assay liquids to the sensing material a fluidic channel is needed

(Fig. 1c). A method to integrate a biosensor into a microfluidic system was developed on the basis of the lab on a chip system depicted in Fig. 1d. Within the platform integrated pumps deliver a sample volume from reservoirs to an attached biosensor.

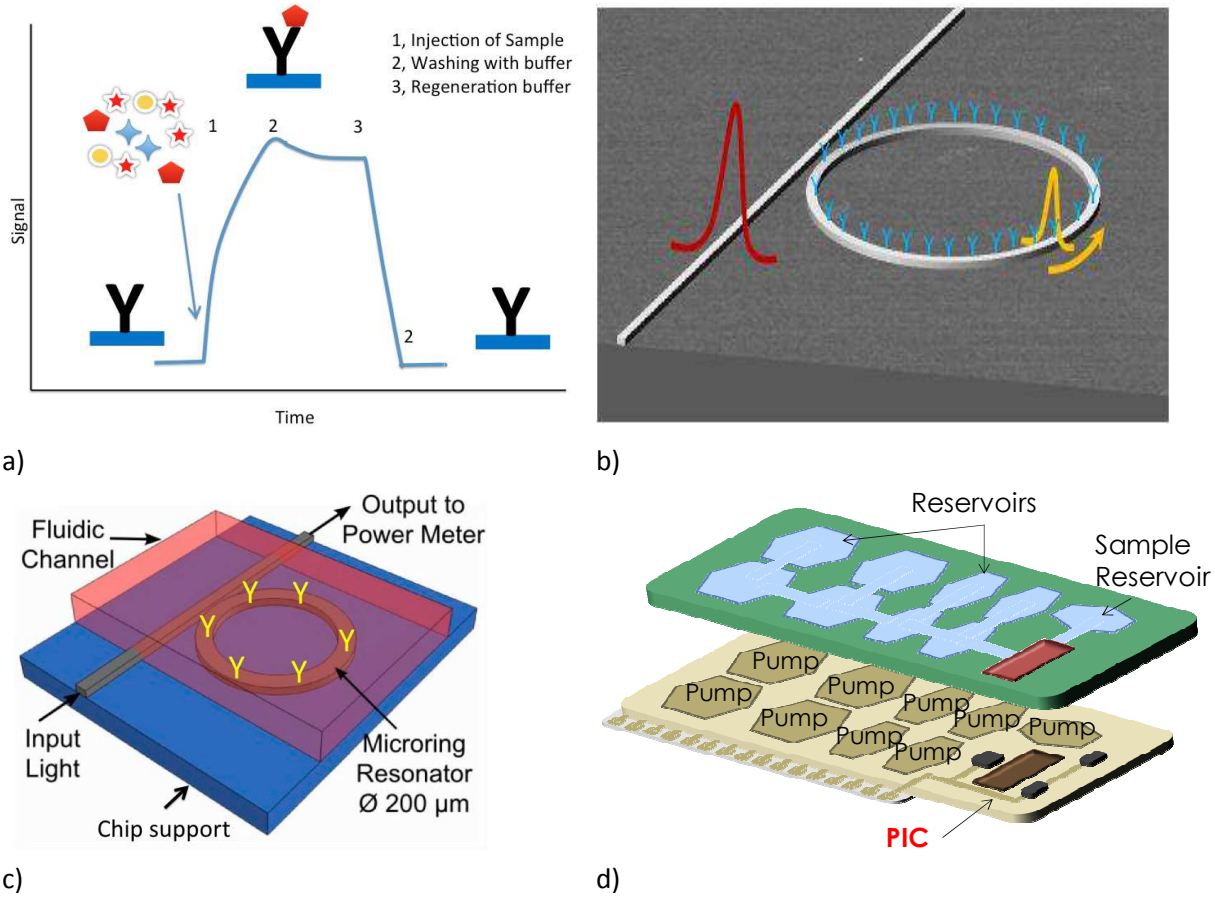

Fig. 1: (a) A sample graph of the signal shift within the biosensors signal while a sample antigen is attached to the sensing antibody and after a regeneration of the sensor system. (b) Schematic of an optical ring resonator structure with an entrance signal on the left and a sensing ring with antibodies and a shifted sensing signal on the right. (c) Chip structure with one optical ring resonator and a fluidic channel to deliver assay liquids on top. (d) Concept of a microfluidic platform with integrated pumps and an attached biosensor.

The photonic biosensor is the product of the conjugation of several disciplines such as biochemistry, photonics, microfluidics and electronics.

PBSA is composed by three main building blocks which can be distinguished as the Biosensor: A microfluidic subsystem, the Photonic transducer and the biomolecular probe. The microfluidic system is critical for the implementation of the sensing protocol since it contains the reservoirs for the required liquids and automates the sample preparation steps required in a lab. The samples are conducted with the microfluidic system to the PIC transducer. In the transducer, if the binding of the biomolecular probe to the analyte takes place, it is translated in a positive optical signal of detection. These three main building blocks will be controlled with the appropriate electronics for the readout system and control.

The PBSA system is a 10x10x11cm box (fig. 2a) with a weight below 1Kg that can be decomposed in 6 sub-systems (fig. 2b) that interact with each other in order to provide the desired result. The sub-systems are named as:

1. MicroFluidic Photonic System (MPS): Two parts - microfluidics and photonic chip boards.
2. Photodetector Signal Conditioner (PSC): Signal conditioning of the photodetectors output
3. Electronic control system (ECS): Interaction with the exterior for telecommand and telemetry data exchange and to manage the photonic biosensor system
4. Power distribution unit (PDU): Distribution of the secondary voltages from PSU to other boards. PSC&MPS LogAmps groups are protected in groups of 4. Current is measured on ECS.

5. Power supply unit (PSU): Power Conversion from 28Vdc to secondary voltages (+3V3, +5V, +15V and -15V) and ground references.
6. Laser: Laser module used to interrogate the system

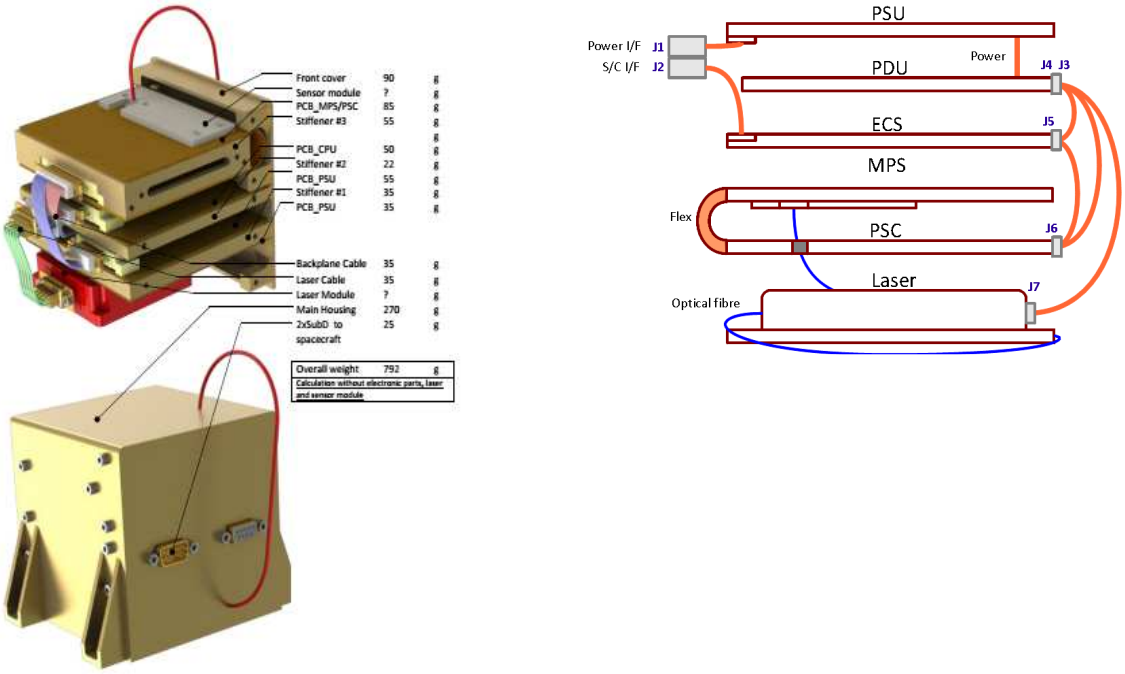

Fig. 2: (a) PBSA concept. (b) PBSA stack layers diagram.

III. PHOTONIC INTEGRATED CIRCUIT (PIC)

PICs are proposed as an emerging technology that may yield novel applications in the field of chemical detection in space. CMOS technology was employed for the implementation of the PIC. In this particular case the underlying target design also consists of high Q filtering structures (see Fig.).

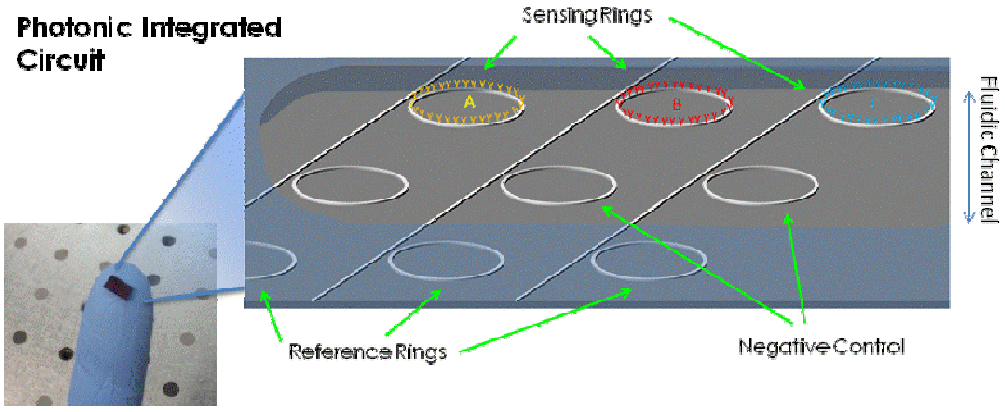

Fig. 3 Picture of the photonic transducer. Left: General view of a PIC device. Right: Detail of resonating structures (Ring resonators with radius ~100µm) used in the detection. In each circuit three rings are shown: one to compensate derivatives other for the negative control of the detection and a third one for the measurement. The molecular bioreceptors are represented in different colours to illustrate the multiple target capabilities of the technology.

The tight confinement of light in integrated structures leads to an increased light-matter interaction. Chemical or biological molecules will be identified and attached onto the PIC changing the optical properties of the photonic filters. The light transmitted through the underlying waveguide undertakes a change in its properties when the immobilized molecules bind the target analyte. Resonant effects taking place in the high Q designed structures are exploited to increase the sensitivity of the integrated structures. Sensitivities down to ng/ml scale with response times of less than half an hour are targeted. Multiple integrated detectors are allocated in a single chip, allowing the implementation of multi-assay techniques that improve the reliability of the detection and also allow estimations of the concentrations of the target analyte to be made. The PIC transducer does not require the use of a fluorescent label for the detection. Today's trend in biosensors is the simplification of the detection process to improve accessibility and robustness. This also leads to advantages in the space environment.

A. Overall Chip Layout

The photonic integrated circuit layout consists of a silicon substrate with outer dimensions of 9.5mm multiplied by 9.5mm and four major functional areas (see fig. 4). As general guidelines of the layout it can be observed that in the footprint of the fibre array (shaded in orange) there are three input ports. Two of them are connected and will be used to help in the alignment of the Fibre array. The other optical input is the only input port of the photonic structures. Only one input has been considered so only one laser source will be needed to interrogate in parallel to the sensing structures. In this way the external components requirements are lowered. The light power entering the input port is divided up into 16 parallel circuits. Two of them will be used for power monitoring and other two will be used in reference ring resonating structures. These references will be used to help in the detection algorithm for the detection of drifts of interfering effects with the detection. Finally 12 ring resonators structures, described below, will be used for sensing.

As can be shown in fig. 4, the *sample flow channel* contains multiple biological functionalised optical ring resonators. Before the light reaches the sensing elements it was distributed to them via optical splitters. The *light input port* and the *light-to-electrical signal interface* are connected through *waveguides* to the sensing area. The *light input port* contains *grating couplers* to deliver the light from an optical fibre into the integrated system. The *light-to-electrical signal interface* contains photodiodes, which deliver the electrical signals to the *electrical output port* (area of wire bonding pads).

Different PIC block:

The **optical power splitters** provide an equal distribution of the input power to two different optical waveguides. With a cascaded architecture the light is delivered to the multiple sensing structures within the sensing area. This design allows to have only one fibre attached to the devices making alignment easier and the system more robust. As captured within Fig. 4 (detail 5) a proper design of the power splitter is a symmetric "Y". In the chip design configuration light enters the Y splitter from the left side and the beam is divided into two waveguides. Basically the symmetry leads to equal power distribution. The angle between the arms of the Y splitter was designed in order to prevent back reflection of the incoming light to the input waveguide.
After a initial length, when it can be assumed that the light in both arms do no longer interact, the angle is opened introducing bended waveguides. Fig. 4 (detail 5) shows the simulation results of the proposed design.

Fig. 4 (detail 4) shows the design of an **optical ring resonator** used within this investigation. The difference between a waveguide and the ring resonator is that the cladding on top is not an oxide, but an open cavity making the bio-functionalisation selectively (Fig. 4 (detail 3)). Having the biology directly bound on a waveguide the light wave interaction enhances. The optical ring resonators induce a marked spectral response by introducing peaks into the resonant frequencies.

These peaks are the optical feature that is tracked by the electronics. The shift of the peak is proportional the refractive index. The variations of the refractive index taking place within the biological layer can be visualised through the movement of the peaks in the frequency spectrum. Moreover, in order to improve the robustness of the sensor to drifts in the measurement, two reference ring resonators (The uppermost ring resonators in Fig. 4) have been included. This ring resonators are protected by the uppercladding in order to be used as a reference to interfering effects such as temperature drifts.

The change of the refractive index in the biolayer is achieved directly by the binding of the antibody bioreceptors to the target analyte. Theoretically, in the limit of shot noise, the detection limit for RI (refractive index) is estimated to be in the order of 10^{-9} refractive index unit (RIU).

The literature describes several designs with different coupling efficiencies. All the approaches can be classified into horizontal and vertical coupling solutions. Well known solutions are the inverted taper and the **grating coupler**. Despite of the lower coupling efficiency a vertical, grating coupler solution has been chosen for the following reasons: It is more robust to misalignment, it is selective to the desired polarization which was chosen for the design of the ring cavities (transversal, electric polarized light). Additionally the vertical approach of the fibre allows a tighter and more robust assembly (Fig. 4 (detail 1)).

As an opto-electrical interface an integrated method with **photodetectors** placed inside the chips was preferred. This solution is more power efficient than collecting the output light of the chip with fibre arrays and externally photodetecting the light. Fig. 4 shows that the photonic waveguides terminate in arrays of 4 output ports. Over each output array a photodetector array will be placed for the opto-electrical conversion. The proposed photodetector arrays consist of arrays of large area InGaAs PIN diodes (Fig. 4 (detail 1)).

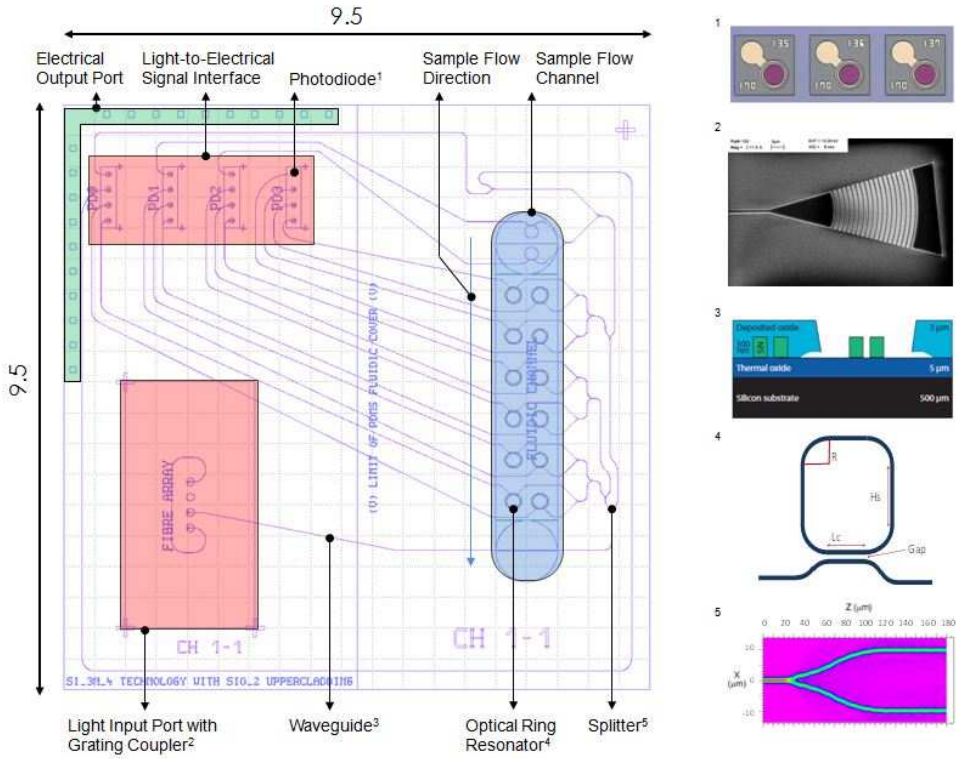

Fig. 4 Design of the photonic integrated circuit (PIC) with outer dimensions and functional sub-systems. The functional sub-systems are shown on the right in a detailed view.